

Coastal Inundation due to Tide, Surge, Waves, and Sea Level Rise at Naval Station Norfolk

Honghai Li¹, Lihwa Lin², and Kelly A. Burks-Copes³

¹U.S. Army Engineer Research & Development Center, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199; PH (601) 634-2840; FAX (601) 634-3080; email: Honghai.Li@usace.army.mil

²U.S. Army Engineer Research & Development Center, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199; PH (601) 634-2704; FAX (601) 634-3080; email: Lihwa.Lin@usace.army.mil

³U.S. Army Engineer Research & Development Center, Environmental Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199; PH (601) 634-2290; FAX (601) 634-3080; email: Kelly.A.Burks-Copes@usace.army.mil

ABSTRACT

A coupled flow and wave model, the Coastal Modeling System (CMS), was developed to simulate synthetic tropical storms with the consideration of future sea level rise (SLR) scenarios and to evaluate the potential coastal inundation at Naval Station Norfolk, Virginia. The CMS capability for surge and inundation calculations was validated with Hurricane Isabel, a devastating hurricane landed on the Norfolk area in 2003. The CMS calculated water surface elevation and storm induced inundation for combined influence of tide, surge, waves, wind, and SLR. Associated with the storm surge and SLR, extensive inundation occurs at the Naval Station Norfolk. For the 100-year storm, the surge levels could inundate approximately 60-80% of the Naval Station Norfolk under the present sea level and different SLR scenarios.

INTRODUCTION

Recognizing the climate change and sea level rise threats to coastal residents and coastal military facilities, the US Strategic Environmental Research and Development Program (SERDP) funds a research initiative to develop technologies in quantitative risk assessment and to provide decision-makers with relevant guidance regarding existing and future coastal infrastructure development. Naval Station Norfolk, Virginia, is selected as a demonstration site for the risk assessment study.

METHOD

Numerical model. The Coastal Modeling System (CMS) was developed and applied to simulate storm surges with design SLR scenarios and to understand the effects of sea level rise and coastal storms on changes in both installations and natural systems. The CMS, consisting of a hydrodynamic model, CMS-Flow, and a spectral wave model, CMS-Wave, is an integrated suite of numerical models for simulating water surface elevation, current, waves, sediment transport, and morphology change for coastal and inlet applications.

CMS-Flow is a three-dimensional (3D) finite-volume model that solves the mass conservation and shallow-water momentum equations of water motion on a non-uniform Cartesian grid. Three sediment transport formulations are available: a sediment mass balance, an equilibrium advection-diffusion method, and non-equilibrium advection-diffusion transport. The model can run in a two-dimensional (2D) mode based on the depth-integrated continuity equation. The wave radiation stress and wave field information calculated by CMS-Wave are supplied to CMS-Flow for the flow and sediment transport calculations. Currents, water level, and morphology changes are feeding to CMS-Wave to increase the accuracy of the wave transformation predictions (Sanchez et al. 2011) (Figure 1).

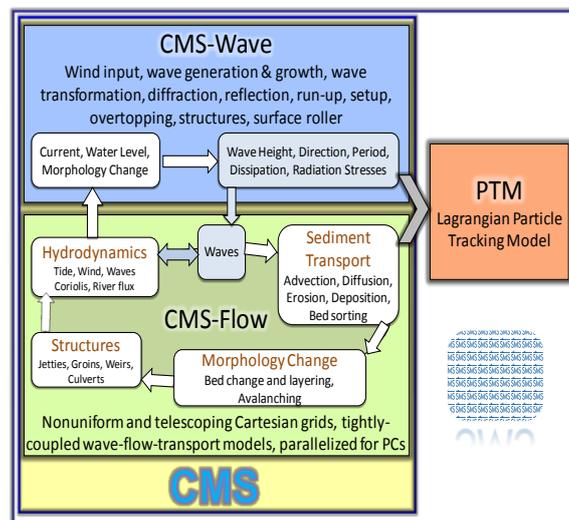


Figure 1. The CMS operational flow chart.

CMS-Wave is a two-dimensional spectral wave transformation model that solves the steady-state wave-action balance and diffraction equation on a non-uniform Cartesian grid (Lin et al. 2011). The model can simulate important wave processes at coastal inlets including diffraction, refraction, reflection, wave breaking and dissipation mechanisms, wave-wave and wave-current interactions, and wave generation and growth. It is a full-plane model with primary waves propagating from open boundaries toward inside domain. If the reflection option is selected from one open boundary, CMS-Wave will perform a backward marching for the boundary reflection after the forwarding-marching calculation is completed. The fundamental wave diffraction process is theoretically developed and calculated in the wave-action balance equation (Mase 2001). Additional model features include the grid nesting capability, variable rectangle cells, wave run-up on beach face, wave transmission

through structures, wave overtopping, and storm wave generation (Figure 1). CMS-Flow and CMS-Wave are coupled and operated through a Steering Module developed within the Surface-water Modeling System (SMS) (Zundel 2006).

Data. Coastline information is extracted from the shoreline database of the National Geophysical Data Center (NGDC) of NOAA. LIDAR network provides the land topography in Naval Station Norfolk. The 1-m resolution data allow the CMS to describe local land features, such as buildings, roads, airport, and other infrastructures in the area. Topographic information of other land areas and bathymetry for the water domain were provided by a 10-m resolution coastal Digital Elevation Model (DEM) of Virginia Beach (Taylor et al. 2008). Figure 2 shows water depth and land surface topography contours, relative to mean sea level (MSL), from the two datasets. The figure displays the deep-draft navigation channel running across north of the domain, the Norfolk Harbor entrance channel, and a few small channels to the military piers. The data ranges from the highest elevation of more than 10 m on land (negative values) to more than 30 m in the navigation channel (positive values). The detail land features, such as grass, forest, and roads, are described by land coverage data in Naval Station Norfolk. Based on these data, corresponding hydrodynamic conditions are specified in the CMS.

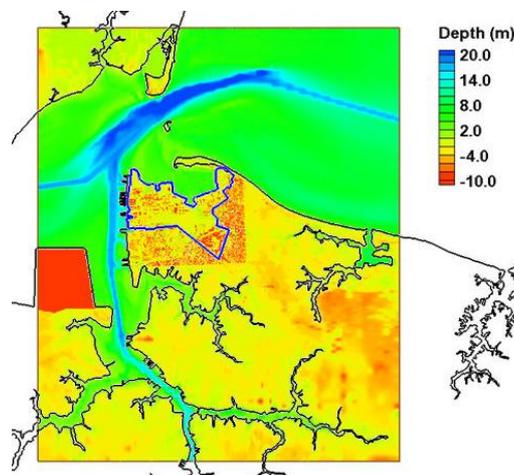


Figure 2. Topographic map of the study area. The blue line outlines the Naval Station Norfolk.

Based on extensive literature review, the sea level rise scenarios are prescribed as 0 (existing condition), 0.5, 1.0, 1.5, and 2 m over a 100 year period between 2000 and 2100. The selection of storms includes two synthetic hurricanes (tropical) with a 50-year and a 100-year return period.

The large scale storm surge and wave models, ADCIRC (Melby et al. 2005) and SWAN (<http://www.swan.tudelft.nl>), provide information on storm development and progression at the regional scale. Forcing to drive the model includes tide, surge, wind and waves. The regional model provides synthetic storms with 50-year and 100-year return periods (Burks-Copes and Russo, 2011). Tidal data at Sewells Point, VA, are available on the NOAA website, <http://tidesandcurrents.noaa.gov>. Four-day water surface elevation was downloaded during a spring tidal period and incorporated into

the surge of the 2-m sea level rise scenario for the CMS. The combination of the surge and the tide was used to drive the CMS at the open boundaries (Figure 3). Figures 4 and 5 show wind and waves for the 100-year return storm, respectively. As passing over the study area, the tropical storm has a peak wind speed of 33 m/sec (74 miles/hour) and a peak wave height greater than 4 m.

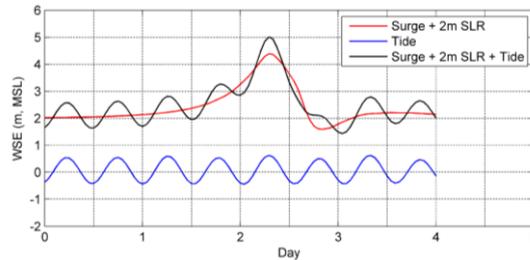


Figure 3. Surge, 2 m sea level rise, and tide at NOAA Gage 8638610 (Sewells Point, VA).

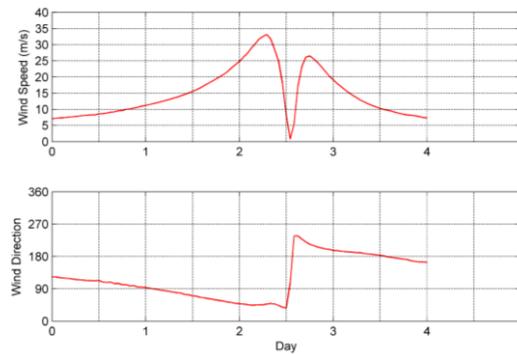


Figure 4. Wind speed and direction of the 100-year return storm.

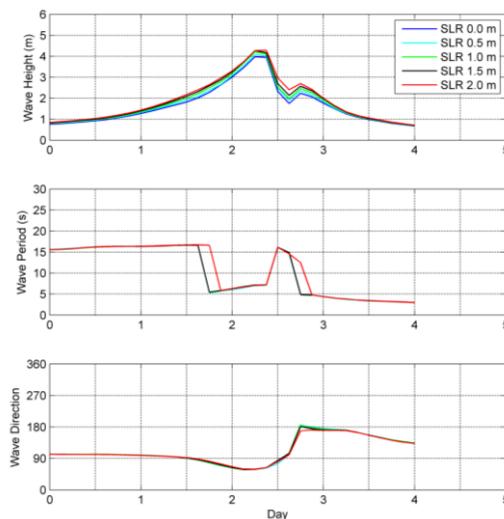


Figure 5. Wave parameters of the 100-year return storm under the existing condition and four sea level rise scenarios.

Considering that sustained sea level rise will increase the area of water coverage and create new wetlands along coastal regions, bottom friction in a nearshore hydrodynamic model ought to be adjusted corresponding to different sea level rise

scenarios. Based on land coverage types, spatially varying bottom roughness through Manning's n coefficients is specified in both the regional model and the CMS under four sea level rise scenarios. A small Manning's n of 0.02 is specified for ocean bottom and the value increases to as large as 0.15 on concrete covered land areas.

CMS domain. Figure 6 shows the CMS domain, which covers the mouths of the James River and the Elizabeth River, and the part of the lower Chesapeake Bay in the Hampton Roads, and extends approximately 20 km from east to west and 24 km from north to south. The western open boundary is located in the mouths of the rivers and the northern and eastern open boundary in the Chesapeake Bay. A non-uniform rectangular grid system with more than half million grid cells was created to discretize the entire installation and the nearshore region. The grid system permits much finer resolution (10 m) in areas of high interest such as Naval Station Norfolk. The mesh of the regional model, also shown in Figure 6, overlaps the CMS grid and the hydrodynamic forcing generated by the regional model has been passed to the CMS through data mapping.

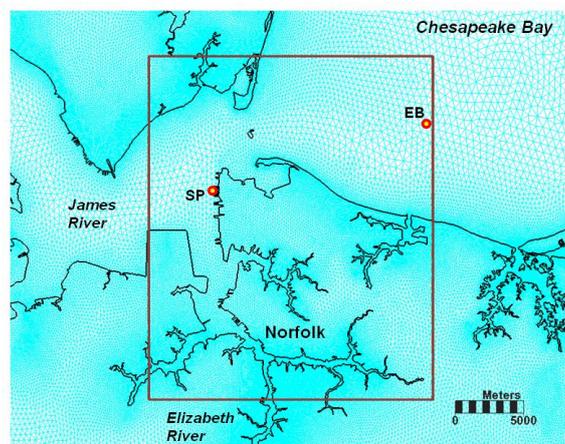


Figure 6. The CMS domain and the regional model mesh. Cycles are time series sites at Sewells Point, west of the Naval Base (SP), and the eastern open boundary (EB).

RESULTS

Hurricane Isabel. Hurricane Isabel made landfall on the coast of North Carolina in September 2003. It passed over the Norfolk area and resulted in the most devastating damage in the Hampton Roads area. The data collected during the hurricane were used to validate the CMS for surge calculations.

The CMS simulated Hurricane Isabel for the period from September 15 to 19, 2003. Figure 7 shows the calculated and measured water surface elevation at Sewells Point, Virginia. The peak water surface elevation due to the hurricane reached 2.0 m above the MSL. The correlation coefficient between the CMS calculated and the measured water levels is 0.99. The root mean square error (RMSE) and the relative RMSE (RMSE/data range) are 7.6 cm and 3.6%, respectively.

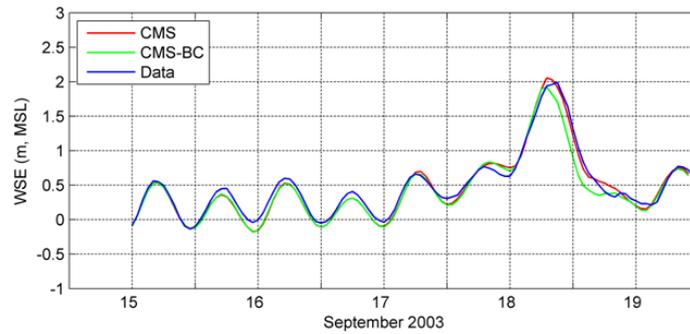


Figure 7. Calculated and measured water surface elevations at EB and SP during Hurricane Isabel.

Figure 7 also shows the synthesized water surface elevation at the CMS open boundary (EB). Comparing the calculations at EB and SP, it can be seen that the storm surge propagates from the eastern open boundary as indicated by the phase difference between these two locations. As the surge waves approach nearshore and water piles up against coast, the water surface elevation shows an amplitude increase of approximately 10 cm and a one-hour phase lag. The coastal effects on the tidal waves are well represented in the CMS.

Figure 8 shows the areal variations and areal percentage proportional to the total area of Naval Station Norfolk (the blue line polygon in Figure 2) as a function of the variations of land elevation. 80% of the Naval Station has a land elevation of less than 5 m and 70% between 1 and 4 m.

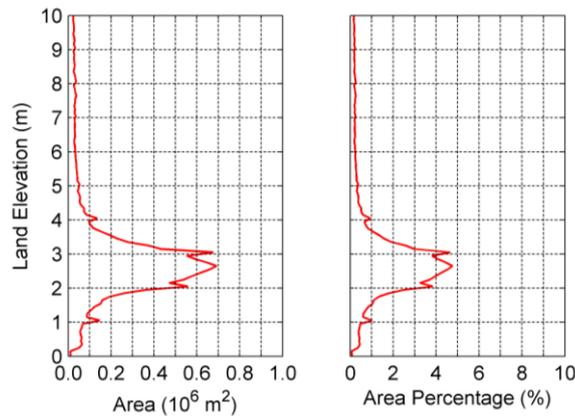


Figure 8. Areal distribution as a function of land surface elevation (relative to MSL) in Naval Station Norfolk.

Figure 9 shows the hurricane induced maximum water surface elevations around Naval Station Norfolk. The calculations indicate that about 6% of the land area was inundated due to the passage of Hurricane Isabel. Additional land areas can be flooded due to wave effects. The calculations show that the averaged significant wave heights at the flooded area is 0.08 m. Based on the peak surge level of 2 m and the relationship between the change in land elevation and flooded area percentage (Figure

8), a 0.04 m increase in water level corresponds to an area change of 1.0% of the total area.

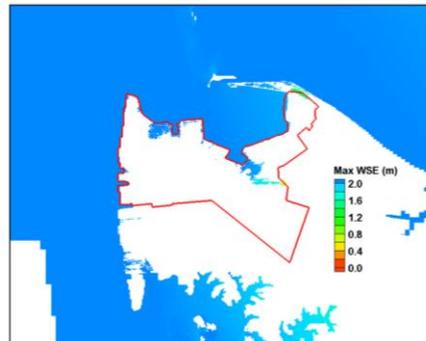


Figure 9. Hurricane Isabel induced maximum water surface elevation.

The post-Isabel flooding damage at Naval Station Norfolk was described by A. Schedel and E. Lambert (personal communication, June 5, 2012). Three inundated areas, located in the northern side of the base, by the storm surge were shown in Figure 10, which well correspond to the calculated results in Figure 9. Figure 11 is the latest hurricane storm surge inundation map of Naval Station Norfolk. The light green, dark green, and light yellow colors indicate the areas flooded by Category 1, 2, and 3 hurricanes, respectively. The CMS calculations show that the Hurricane Isabel induced land inundation is equivalent to the flooding by a Category 1 storm.



Figure 10. Land inundation due to Hurricane Isabel at Naval Station Norfolk (A. Schedel and E. Lambert, personal communication, June 5, 2012).

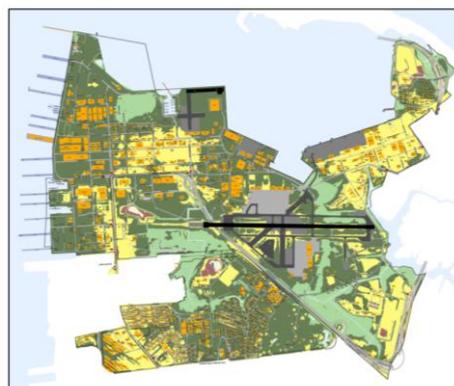


Figure 11. Storm surge map of Naval Station Norfolk (A. Schedel and E. Lambert, personal communication, June 5, 2012).

Synthetic storms. The CMS simulated the existing condition (0 m SLR) and four other SLR scenarios (0.5, 1, 1.5, and 2 m) for Naval Station Norfolk with two selected tropical storms with the 50-year and 100-year return periods.

Surge level is an important indicator of land inundation. Figures 12 show the maximum water surface elevations under the existing condition and the 2-m SLR scenario for the 100-year return storm, respectively. Because Naval Station Norfolk has land surface elevations generally less than 4 m above MSL, most areas could be under the maximum surge level for the simulated storm. Table 1 presents a list of areas inundated due to the 50-year and 100-year tropical storms with different sea level rise scenarios for Naval Station Norfolk. The results show that the flooded area expands as the SLR increases from 0 to 2.0 m. Among the simulated storms, the 100-year storm inundates more than 60% of the area for different SLR scenarios. Both storms cause inundation approximately 60-80% of Naval Station Norfolk under the 2-m SLR scenario.

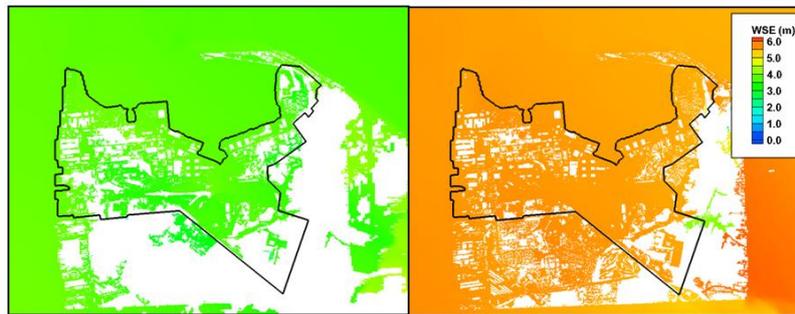


Figure 12. The maximum water surface elevation due to the 100-year return tropical storm under the existing condition and the 2.0-m sea level rise scenario.

Table 1. Area and area percentage flooded in the Naval Station Norfolk (10^6 m²) for two tropical storms under the existing condition (0 m) and four different sea level rise scenarios.

SLR (m)	50-Year Return Storm		100-Year Return Storm	
	Area	%	Area	%
0.0	1.176	8.11	9.076	62.57
0.5	2.720	18.75	10.219	70.45
1.0	4.948	34.11	10.762	74.20
1.5	8.198	56.52	11.078	76.37
2.0	10.014	69.04	11.317	78.02

Wave and wind setup/setdown. Physical processes associated with water level change and land inundation are wind and wave driven setup/setdown, tide elevation, and wave breaking and runoff/overtopping in nearshore areas. Table 2 presents the

land inundation corresponding to wave- and wind-induced water surface elevation changes. The wave setup has a minor impact on the change (less than 0.5%) in flooded area of Naval Station Norfolk. Wind-induced water level changes are much larger and result in an increase of inundated area of 6% under the existing condition. The flooded area reduction at this surge level seems more sensitive to and more closely related to wind setdown.

Table 2. Area flooded (10^6 m^2) for the 100-year storm under the existing condition (0 m) and the 2 m SLR sea level rise scenario and for Hurricane Isabel in the Naval Station Norfolk .

Scenario	100-year (0-m SLR)	100-year (2-m SLR)	Isabel
Flow + Waves	9.076	11.317	0.849
No Waves	9.029	11.307	0.834
No Wind	8.525	11.308	0.903

CONCLUSION

The CMS was applied to simulate nearshore surge and waves, to estimate inundation, and to examine potential effects of sea-level rise and storm surge surrounding Naval Station Norfolk. The CMS was validated for water elevation and land inundation induced by Hurricane Isabel and the calculations showed good agreement with measurements. Additional model simulations were conducted for two synthetic tropical storms (50-year return and 100-year return periods) under the existing condition (the present MSL) and four SLR scenarios, 0.5, 1, 1.5, and 2 m.

The model results indicated that Hurricane Isabel produced a maximum surge of 2 m MSL along the coast and inundated 6% of the Naval Station Norfolk. The maximum surge levels induced by the 100-year storm result in approximately 60-80% of Naval Station Norfolk flooded under different SLR scenarios.

The CMS study evaluated coastal inundation caused by storm surge, waves, and wind with sea level rise. Surge level changes induced by waves could increase the inundation by 1% of the total area in Naval Station Norfolk for Hurricane Isabel. Wave and wind effects on storm surge were examined using Hurricane Isabel and the 100-year storm. Wave setup/setdown is related to less than 0.5% of changes in flooded area in Naval Station Norfolk. However, wind setup/setdown corresponds to greater than 1% and 0.3% of total area changes under the existing condition and the 2-m SLR scenario, respectively.

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