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Chapter 6
Predicting and Visualizing Storm Surges and Coastal Inundation: A Case Study from Maryland, USA

Ming Li, Xiaohong Wang and Peng Jia

Abstract Many low-lying coastal regions are vulnerable to both chronic hazards associated with inundation by sea-level rise, and episodic storm surges generated by hurricanes and typhoons. Using Maryland's coast as an example, we provide an overview of a recent effort in the development of a state-of-the-art coastal inundation prediction system. We use a suite of atmospheric and hydrodynamic models to obtain an ensemble forecast of storm surge and overland inundation. Advanced graphic software such as ArcGIS and Google Earth is used to generate high-resolution images and animations of inundation in flood-prone areas. Such an end-to-end inundation prediction system can be applied to any coastal region. Given the accelerating sea-level rise and projected increases in the frequency and intensity of extreme weather events in a warming climate, we discuss how sea-level rise, changing tidal ranges and storm surges combine together to generate dangerously high surges in coastal regions.

Keywords Storm surge · Inundation · Hurricane · Typhoon · Tropical cyclone · Geographic information systems · Google earth · Graphic visualization

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6.1 Introduction

In the United States, approximately 50 % of the population lives within 50 miles of the coast. The human presence in the coastal zone drives an economic engine that produces more than one-third of the U.S. gross national product. The physical infrastructure in the U.S. Gulf of Mexico and Atlantic coastal regions alone is worth about \$3 trillion (Marra et al. 2007). Globally, three-quarters of the world population now lives within 50 km of the sea. The vulnerability of coastal communities to the impacts of natural hazards is well known. Storm surge induced by tropical cyclones is one of the major threats to the life and property of coastal regions. On average, roughly 5 tropical cyclones every 3 years would strike the U.S. coastline, causing 50–100 casualties and billions dollars of property damage (http://www.nhc.noaa.gov/HAW2/english/basics.shtml).

Coastal regions are not only vulnerable to flooding due to episodic storm events but also to chronic hazards associated with climate change and sea level rise. Global sea level rose at a rate of 1.6 ± 0.2 mm year^{-1} from 1961 to 2003 and 3.4 ± 0.1 mm year^{-1} from 1993 to 2007 (Domingues et al. 2008). Climate models predict that the rate of sea-level rise will further accelerate in the 21st century (Meehl et al. 2007), with global-mean increases by 2,100 of 0.5–1.4 m, depending on greenhouse gas-emission scenarios and climate-model sensitivity (Rahmstorf 2007). Currently, sea level is rising at a rate near the upper end of the projections (Church et al. 2011).

In this paper we provide a review of recent progress in predicting and visualizing coastal inundations due to storm surges and sea-level rise. We use Maryland, USA. as an example of low-lying coastal regions prone to flooding and draw heavily from our own work in modeling Chesapeake Bay. Storm surges and coastal inundations are active research topics that have attracted wide attention in recent years. We apologize in advance for omitting many interesting studies in this short review.

6.2 Maryland's Low-Lying Coastal Areas: A Case Study

Maryland's coast is vulnerable to both chronic hazards associated with inundation by sea-level rise, and episodic storm surges generated by hurricanes/tropical storms and nor'easters. Due to its geography and geology, the Chesapeake Bay region is considered the third most vulnerable to storm surge and coastal inundation in the U.S., behind Louisiana and southern Florida.

As demonstrated by Hurricane Isabel (2003), Maryland's coast is extremely vulnerable to storm surges. With a semi-enclosed geometry, Chesapeake Bay can trap and amplify storm surges under certain conditions (Boicourt 2005; Li et al. 2006, 2007; Shen et al. 2006a, b, c). Bays' enclosed reaches offer protection from tropical storms that pass on the ocean side. Northeast-to-northerly winds in the

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western semicircle of a cyclone drive water away from the bay's head, even though they may cause dangerous sea-level setup and storm surges on the open coast. In contrast, when a storm passes on the land side, the confined nature of the bay becomes a liability and storm surges exceed those on the open coast. This shift from protection to vulnerability arises because southeasterly winds in the right-front quadrant of the storm blow water into the bay and pile water up against its head. This interesting scenario happened in September 2003 when Hurricane Isabel made landfall at the Outer Banks of North Carolina and moved north on the west side of Chesapeake Bay, creating widespread flooding in several populated areas including Washington, D.C., Baltimore, Annapolis and Maryland's Eastern Shore (Fig. 6.1). A similar scenario happened in August 1933 when Hurricane Chesapeake-Potomac caused extensive flooding over the Eastern Shore of Maryland and Virginia, and damaged agricultural fields by salt contamination. Over the past couple of decades, tropical storms have shown elevated activity on the U.S. East Coast: 16 storms have pounded Chesapeake Bay since 1996, including Hurricane Fran (1996), Floyd (1999), Isabel (2003), Ernesto (2006), Irene and Lee (2011). This pattern is expected to continue and may increase due to global warming (Goldenberg et al. 2001; Emanuel 2005; Webster et al. 2005). Nor'easters can also cause extensive flooding, as demonstrated during Nov. 2009 when the surge heights approached those of Isabel in southern Bay.

With the projected increases in the frequency and severity of storms and accelerating sea level rise, Marylanders and their properties are facing ever-increasing risks. Especially vulnerable are those on the Maryland's Eastern Shore: Talbot, Dorchester, Wicomico, Worcester and Somerset counties (Fig. 6.2). Slope is a primary variable controlling the magnitude and range of sea-level rise impact over time. In Maryland's Eastern Shore where elevation change may only be as much as one foot per mile, gradual submergence of a large geographic area is quite likely over time. Land inundation due to sea-level rise is already occurring along low-lying coastal areas in Dorchester and Somerset Counties (IAN 2008). Two to three feet of additional sea-level rise will result in a dramatic intensification of coastal flood events and submerge thousands of acres of tidal wetlands and low-lying lands. Sea-level rise and storm surges also pose a significant threat to resources and infrastructure in Maryland's coastal zone. As growth and development continues in coastal areas, these impacts are likely to escalate. Figure 6.2 provides a graphical illustration of low-lying land areas in Maryland that are likely be subject to coastal inundation and flooding over the next 100 years.

To address the coastal inundation issue confronting Maryland, we recently participated in the development of Chesapeake Inundation Prediction System (CIPS). CIPS is a collaborative effort involving meteorologists, oceanographers, hydrologists, economists and information technologists. We use a suite of atmospheric and hydrodynamic models to develop an ensemble forecast of storm surge and inundation with graphic visualization of model results including forecast uncertainty (Stamey et al. 2007). Advanced graphic software such as ArcGIS is employed to create high-resolution animations of inundation in flood-prone areas, which are used to quantify the economic impacts. CIPS provides an end-to-end,

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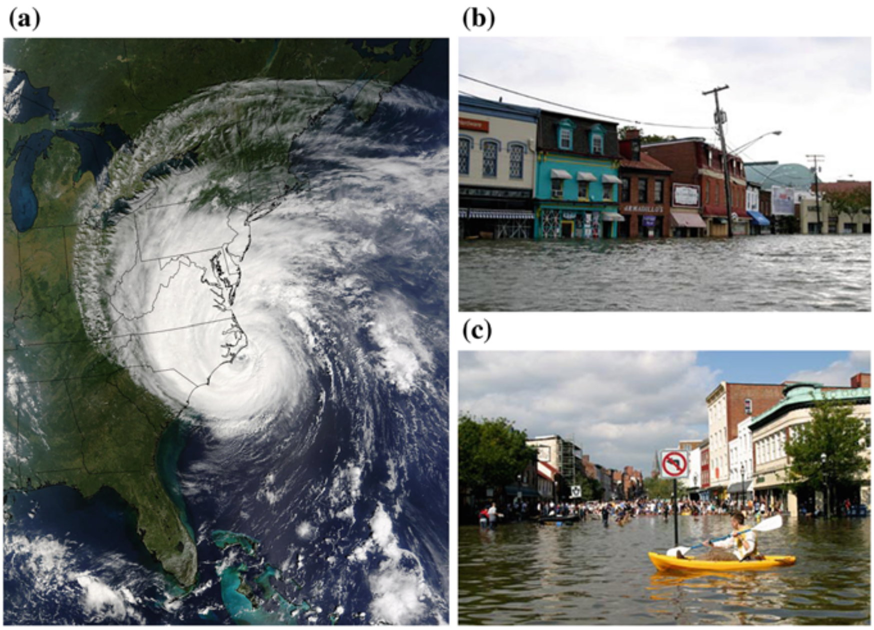

Fig. 6.1 **a** Satellite Isabel (2003) at landfall. Photos of flooded streets (**b**, **c**) in the Greater Washington D.C. Area

state-of-the-art, quantifiable storm surge and inundation forecast tool, and can be applied to other coastal regions in the U.S. and around the world.

6.3 Coupled Atmospheric-Hydrodynamic Models

Storm-surge models include atmospheric and oceanic submodels. The wind and pressure fields obtained from the atmospheric model are used to drive the hydrodynamic model for making storm-surge predictions. The atmospheric model ranges from simple parametric vortex models to mesoscale atmospheric forecasting models. Parametric surface winds are estimated either by assuming an idealized stationary, symmetric tropical cyclone with the observed path, surface pressure drop, and radius of maximum wind (Holland 1980; Peng et al. 2004), or by the planetary boundary layer model (Scheffner and Fitzpatrick 1997). Its operational utility has been limited by its sensitivity to errors in input parameters, such as the storm track, intensity and size (Rappaport et al. 2009). NOAA/Hurricane Research Division (HRD) has developed more accurate hurricane winds in real time (Powell et al. 1998; Houston et al. 1999); these winds are based on all available surface wind observations from buoys, coastal-marine automated

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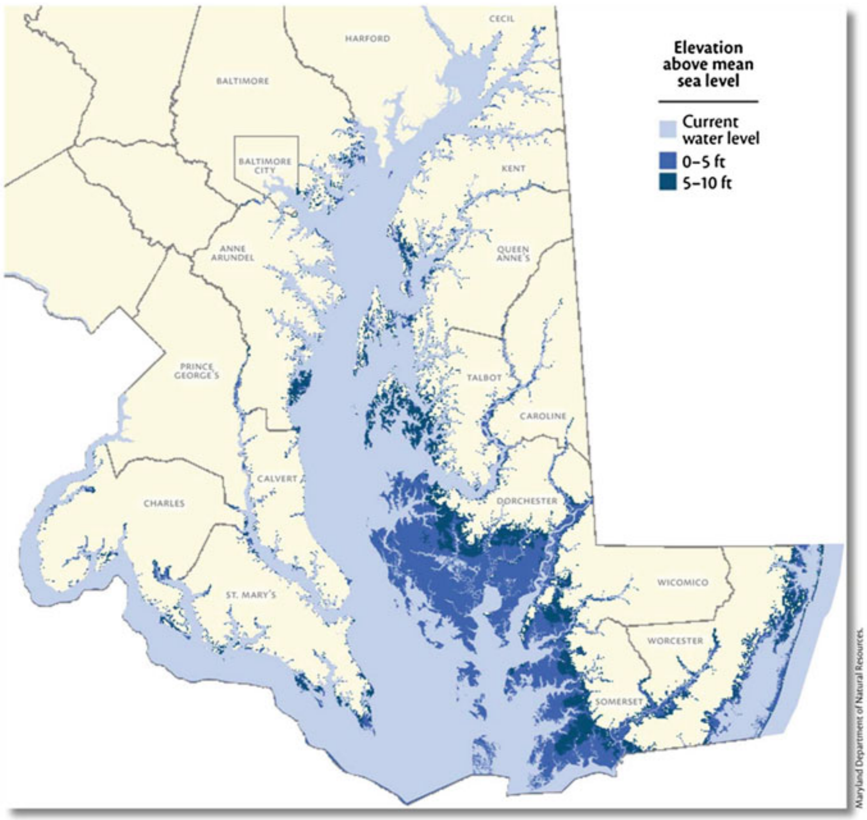

Fig. 6.2 Sea-level rise vulnerability in coastal areas of Maryland, calculated using LIDAR elevation data (from IAN 2008). Chesapeake Bay is shown as the *light blue area*

observation platforms, ships, and other surface facilities. However, the HRD surface winds are only available prior to the hurricane's landfall.

Several high-resolution mesoscale atmospheric models have been used to make forecasts for tropical storms over coastal regions. The MM5 model is an earlier version of the mesoscale atmospheric model. A nested-grid (36/12/4 km) version of the MM5 has been used in real-time daily forecast mode at the University of Maryland (UMD) to provide hurricane prediction. Figure 6.3a–c show the MM5 forecast for the wind field during Hurricane Isabel. After making landfall at the Outer Banks in North Carolina, Isabel moved along a track to the west of Chesapeake Bay. The southeasterly winds in the right-front quadrant of the storm were the dominant winds over the Bay. The MM5 model predicted reasonably well the trajectory and intensity of Hurricane Isabel as well as the other meteorological fields (Li et al. 2006). The surface winds at a mid-Bay station appear to be slightly overpredicted, but the model accurately captured the shifts in the wind direction from the southwesterly to southeasterly during the passage of Isabel.

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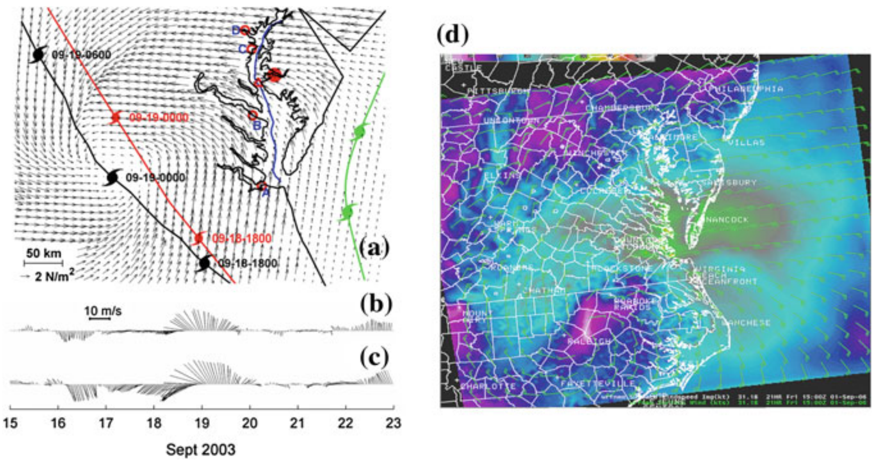

Fig. 6.3 **a** MM5-predicted surface wind stress over Chesapeake Bay during Hurricane Isabel (September 2003), superposed by observed (*red*) and predicted (*black*) Isabel's track and a hypothetical track for a storm moving on the ocean side of the Bay (*green*). *Red* open *circles* are used for tidal gauge stations (A-Hampton Road, VA; B-Lewisetta, MD; C-Annapolis, MD; D-Baltimore, MD), a *red* triangle for CBOS mid-Bay buoy and a red solid circle for a mid-Bay weather station. Comparison of observed (**b**, **c**) predicted horizontal wind vectors at the weather station. **d** WRF forecast of surface winds during Tropical Storm Ernesto

The Weather Research and Forecasting (WRF) model is a next-generation mesoscale numerical weather prediction system. It features multiple dynamical cores, a 3-dimensional variational (3DVAR) data assimilation system, and a software architecture allowing for computational parallelism and system extensibility. National Weather Service at Wakefield, Virginia runs a high-resolution (4 km) WRF model tailored for the Chesapeake Bay region (Fig. 6.3d). The model is able to resolve convection and produce detailed banding structures in tropical systems. the Regional Atmospheric Modeling System (RAMS) is another state-of-art mesoscale atmospheric forecasting model. Weatherflow Inc. employs a fine-resolution (2 km) RAMS to make operational forecasts for the Chesapeake Bay region. Global weather forecasting models such as Global Forecast System (GFS) and North American Mesoscale model (NAM) may be used to set up the initial and boundary conditions for the regional models.

Various 2D/3D hydrodynamic models have been developed and used to simulate storm surges, including the SLOSH (Sea, Lake, and Overland Surges from Hurricanes, Jelesnianski et al. 1992), ADCIRC (Luettich et al. 1992; Westerlink et al. 1992), ELCIRC (Stamey et al. 2007; Wang et al. 2008), SELFE (Shen and Gong 2009), CH3D (Sheng et al. 2010), Princeton Ocean Model (POM, Peng et al. 2004) and Finite Volume Coastal Ocean Model (FVCOM, Weisberg and Zheng 2008). These models use orthogonal curvilinear grids (SLOSH and POM), non-orthogonal curvilinear grids (CH3D), or unstructured triangular grids (ADCIRC and FVCOM). While a storm surge model usually simulates the wind-driven and

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pressure-induced surge and tide, wave-induced surge can be simulated by including the effects of waves on storm surge via one-way coupling or two-way coupling (e.g. Sheng et al. 2010) between a storm-surge model and a wave model such as SWAN. A few commonly used storm-surge models (ADCIRC, SELFE, SLOSH, FVCOM) are currently being compared in the SURA super-regional modeling testbed (http://testbed.sura.org).

Although unstructured models have the superior ability to fit complex coastlines easily, Li et al. (2006, 2007) and Zhong et al. (2010) used the structured-grid ROMS model to simulate storm surges in Chesapeake Bay. Regional Ocean Modeling System (ROMS) is a state-of-the-art regional ocean model (e.g. Shchepetkin and McWilliams 2005). It incorporates advanced modeling features such as high-order advection schemes, accurate pressure gradient algorithms, several subgrid-scale parameterizations, atmospheric, oceanic, and benthic boundary layers, biological modules and data assimilation (http://marine.rutgers.edu/po/). ROMS has found wide-ranging applications, including basin-scale ocean circulation (e.g. Haidvogel et al. 2000), shelf circulation (Marchesiello et al. 2003) and estuarine circulation (e.g. Warner et al. 2005; Li et al. 2005; Li and Zhong 2009; Zhong and Li 2006). Gridding techniques such as GRIDEN (Driscoll and Vavasis 1998; Zhong et al. 2010) and composite-domain method (Warner et al. 2010) provide reasonable approaches to refine grid resolutions in local regions for inundation predictions. The ROMS model was coupled to the MM5 model to predict the storm surge from Hurricane Isabel and the associated wind-driven currents. Figure 6.4a provides a 3D view of the sea-level distribution over the Bay at 0400 LST 19 September. The alignment of southeasterly winds with the long fetch of the lower Potomac River created the largest surge in Washington, DC, which reached 2.7 m above normal high tide. Sea levels in the northern Bay were also rising rapidly at this time. The observed temporal evolution of sea levels at 4 selected tidal stations was well captured by the model (Fig. 6.4b). The Root-Mean-Square (RMS) error averaged over 8 stations in the Bay is 0.13 m. The model's predictive skill as defined in Warner et al. (2005) has a high score of 0.96. It is worth noting that the storm surges reached 2.2 m at Baltimore and 2.0 m at Annapolis (Fig. 6.4b), causing flooding there.

To simulate overland inundation caused by storm surges, we have incorporated a simple wetting-and-drying scheme provided by ROMS. The formulation is based upon the concept of a 'critical depth' (D_{crit}) criterion (cf. Zhang et al. 2004; Oey 2005). As the model progresses, the total depth ($h + \eta$) is compared to D_{crit}. If $(h + \eta) < D_{crit}$, a 'flux blocking' algorithm is imposed to prevent transport out of that cell. Water can flow into any cell at any time, but the water cannot flow out if the total depth is less than D_{crit}. Cells become rewet if water flows back from adjacent cells. In our application, we choose $D_{crit} = 0.2$ m (Zhong et al. 2010). Recent model simulations suggest that storm-surge predictions are sensitive to bottom stress parameterization (Weisburg and Zheng 2008). Bottom stress is usually prescribed using a quadratic drag law. In 2D model, the drag coefficient C_D is prescribed as a constant or a depth-dependent function (cf. Daily and Harleman 1966; Luettich et al. 1992). The roughness height is related to sea bed types and

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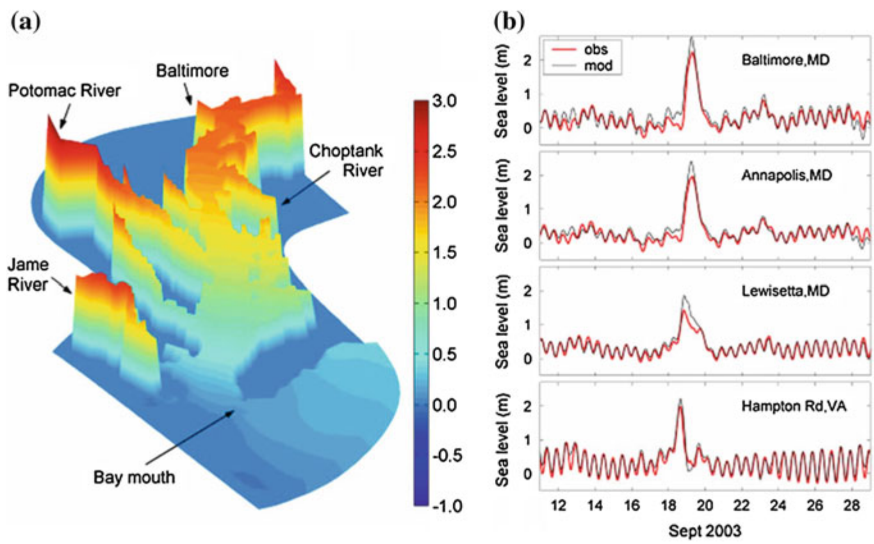

Fig. 6.4 ROMS validation for Hurricane Isabel: **a** 3D peak water levels at high storm surge; **b** observed (*red*) versus predicted (*black*) water levels at four tidal gauge stations

bed forms (Soulsby 1997). Different values may need to be used for intertidal zones and inundated shallow regions featuring salt marshes or other vegetative surfaces (Nicolle and Karptchev 2007).

6.4 Ensemble Forecasts

The magnitudes of storm surges are determined primarily by meteorological forcing, such as storm intensity, path, spatial and temporal scales, and topographic parameters such as the width and slope of continental shelf, geometry and character of local coastal and shelf features. For a semi-enclosed Bay such as Chesapeake Bay, Zhong et al. (2010) conducted a series of numerical sensitivity experiments for the storm surge generated by Hurricane Isabel. They found that small errors in the predicted hurricane parameters may lead to large errors in the storm surge prediction. Errors in the hurricane track and intensity mainly affect the model prediction on the surge height whereas errors in the translation speed change the prediction of not only the surge height, but also its arriving time and duration of high water. The surge height is more sensitive to the wind forcing in the upper Bay than in the lower Bay due to different response mechanisms in the two regions.

Ensemble forecasting has been shown to improve the weather forecasts and provide a means of conveying uncertainty. We have extended the ensemble forecasting technique to storm-surge predictions during the CIPS project. We use

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regional atmospheric models as well as global GFS and NAM models to generate an ensemble of atmospheric forcing fields: GFS, NAM, WRF-GFS, WRF-NAM, RAMS and MM5. The ROMS hydrodynamic model is forced by this ensemble of wind and pressure fields to produce an ensemble of storm surge forecasts.

We have tested the ensemble forecasting capability by comparing the model predictions of two historical storms (Hurricane Isabel in 2003 and Tropical Storm Ernesto in 2006) against observed sea levels. Figure 6.5 shows a comparison of sea level time series at several tidal stations between the observations and three model simulations: RAM, WRF-NAM (regional WRF forced with NAM boundary and initial conditions), WRF-GFS (regional WRF forced with GFS boundary and initial conditions). Because each atmospheric model produces slightly different forecasts for the wind and atmospheric pressure fields, the hydrodynamic model predicts a range of storm surge heights: some higher than the observed values while the others are lower. The forecasted surge heights fall into a narrow range at some stations (such as Cambridge, MD and Annapolis, MD) but spread over a wider range at other stations (such as CBBT, VA and Hampton, VA). We have also investigated how different models produce different predictions for overland inundations in a local region.

Figure 6.6 shows a comparison of the inundated area over the Eastern Shore of Maryland among six different models: MM5, RAM, WRF-NAM, WRF-GFS, GFS and NAM. We have included two coarse-resolution global weather forecasting models GFS and NAM for comparison. The inundated area is similar among WRF-NAM, WRF-GFS, RAM and GFS. NAM predicted least inundation area whereas MMS predicted the most. These model inter-comparisons have shown that the inundation prediction is highly sensitive to detailed wind field. For a flat area such as the Eastern Shore of Maryland, small differences in sea level predictions lead to substantial differences in the overland inundation. By conducting ensemble simulations, we are able to produce a range of predictions for the storm surges and overland inundations. Such information can help emergency managers to develop better response strategies.

6.5 Graphic Visualization of Overland Inundation

ArcGIS and Google Earth are two powerful software tools that can be used to display overland inundations due to storm surges. Prototype development has demonstrated that the storm-surge inundation output from the hydrodynamic model can be visualized to show the location, depth, and duration of inundation in static and animated products (Stamey et al. 2007). The overland inundation visualization was done at a spatial resolution of less than a city block ($\sim$50 m), vertical resolution of less than one foot ($\sim$30 cm or less), with a sequential time step of 1 h or less. Figure 6.7a shows the predicted inundation of Old Town Alexandria, Virginia during Hurricane Isabel.

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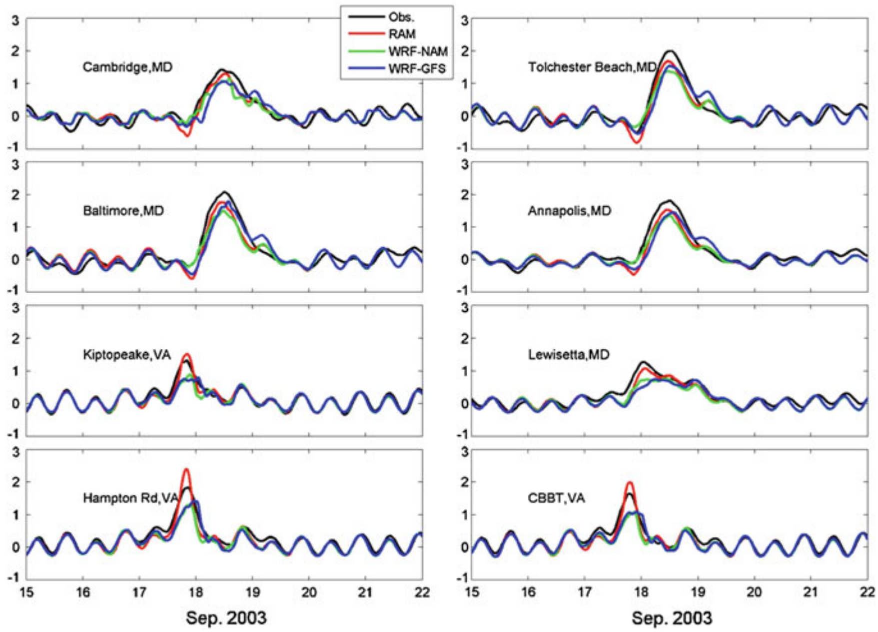

Fig. 6.5 Ensemble predictions of storm surges at tidal gauge stations during Hurricane Isabel

GIS provides a convenient environment for viewing, querying and analyzing data, and facilitates coastal planning and emergency management. The water-level data from the hydrodynamic model are imported and overlaid on GIS raster and vector data layers. Specially, raw high-resolution LIDAR digital elevation data are processed onto a regular grid which is used as the basis for visualization. The water levels from the hydrodynamic model cells are then interpolated onto this grid. Inundation depths are obtained by subtracting the land elevation from the water level in each grid cell. The result is a wet/dry profile of inundation. To improve the accuracy of the profile, a layer representing buildings is used as a mask if one is available for the local jurisdiction. The resulting grid is then converted into vector polygons and stored in the geodatabase. The polygons in the geodatabase can be visualized by ArcGIS or be converted into Google Earth KML files.

Inundation polygon layers and desktop GIS software such as ArcGIS are suitable tools for GIS professionals or trained emergency managers. However, there is also a need for a simpler delivery vehicle for dissemination to a wider audience such as the general public. Google Earth provides such as a tool and is free of charge. User-generated layers can be displayed onto the Google Earth client by importing KML files. One can publish the PostGIS polygon objects as KML and convert timestamp fields in the PostGIS records into the corresponding Time Stamp elements in Google Earth. Hence one can show animated inundation in

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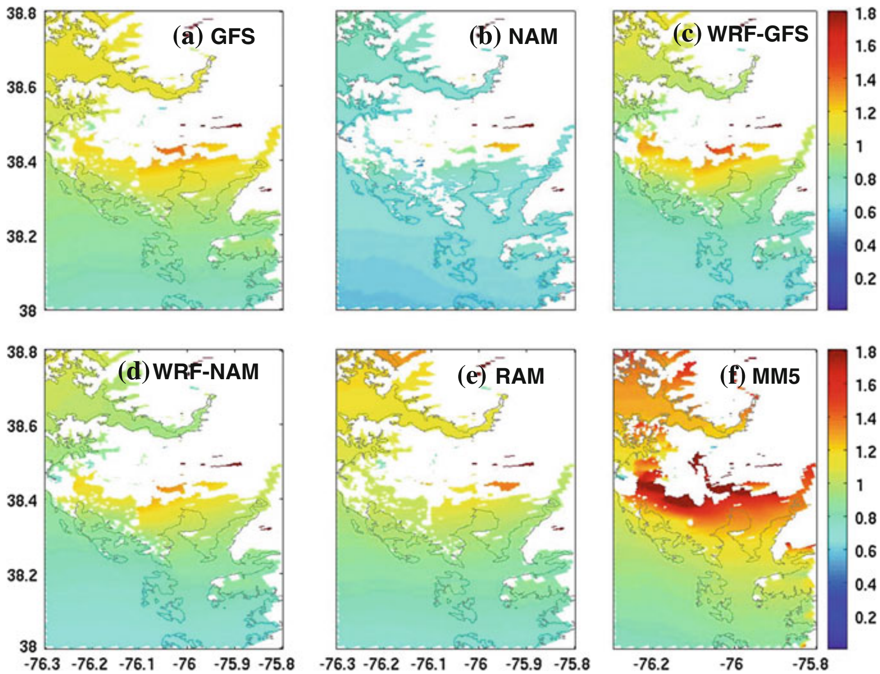

Fig. 6.6 Ensemble predictions of overland inundations over the Eastern Shore of Maryland during Isabel: **a** GFS; **b** NAM; **c** WRF-GFS; **d** WRF-NAM; **e** RAM; **f** MM5, all in unit of meters

specific local regions using Google Earth. Google Earth also allows users to add and view 3D buildings, thus enabling 3D views of inundations over buildings and structures. We have used ArcGIS and Google Earth to visualize inundations over Cambridge, Dorchester County during Hurricane Isabel (Fig. 6.7b and c). Both still images and animations were generated to display the area extent, duration and water levels in the city.

6.6 Effects of Sea-Level Rise on Coastal Inundation

Coastal regions around Chesapeake Bay are not only affected by episodic storm surges but also affected by sea-level rise. Global sea level rose a rate of 1.6 ± 0.2 mm year^{-1} from 1961 to 2003 and 3.4 ± 0.1 mm year^{-1} from 1993 to 2007 (Domingues et al. 2008). Due to the greater rate of absolute sea level rise in the middle latitudes of the Northwest Atlantic Ocean (Church et al. 2008) and regional land subsidence associated with the post-glacial rebound (Nerem et al. 1998), the sea level rise over Chesapeake Bay is particularly large. Tide-gauge records in Chesapeake Bay reveal that sea levels increased by 3–4 mm per year

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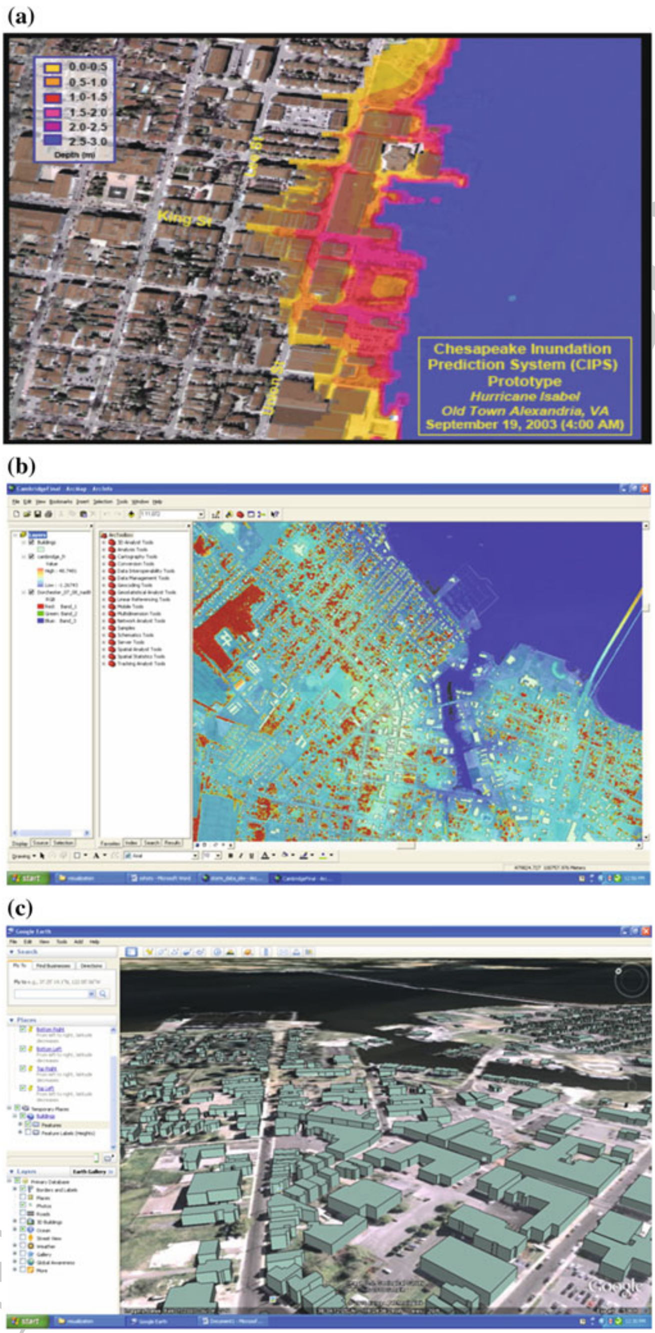

Fig. 6.7 Static GIS visualization of peak flooding in **a** Old Town Alexandria, Virginia (from Stamey et al. 2007) and **b** Cambridge, Maryland during Hurricane Isabel. **c** 3D visualization using Google Earth

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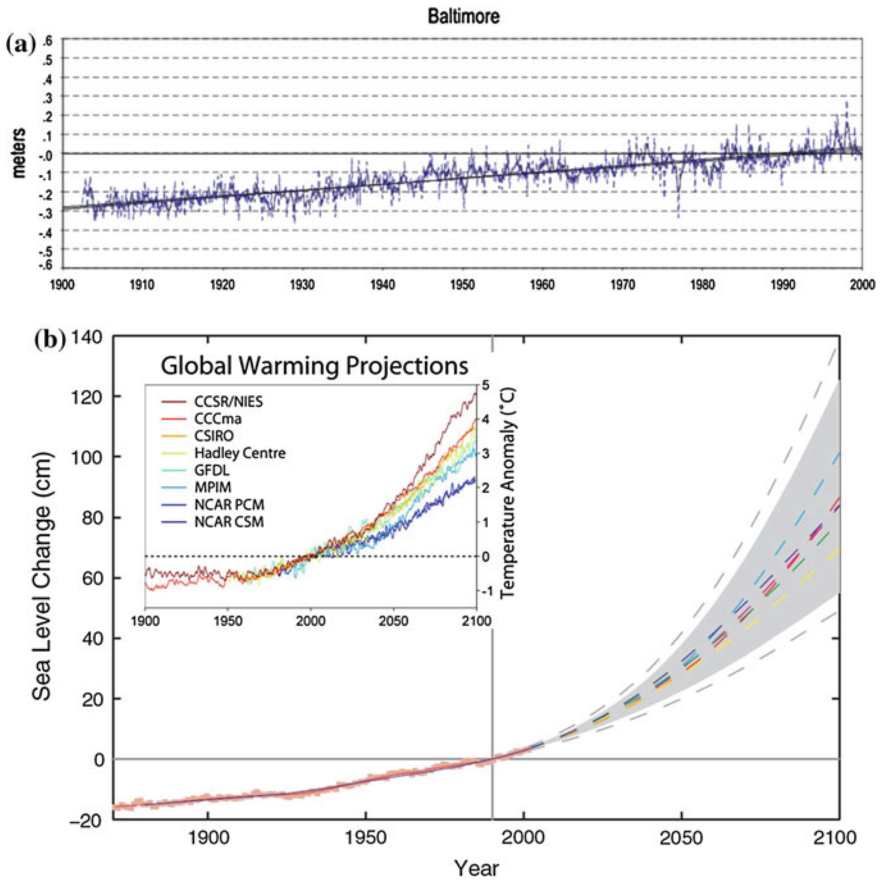

Fig. 6.8 **a** Time series of sea level at the tidal gauge station of Baltimore in the 20th century. **b** Global climate model predictions for the global-mean sea-level rise in the 21st century. The insert shows the model predictions for the global-mean temperature

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over the 20th century (Zervis 2001), which was nearly twice that of the global average over the same time period (Fig. 6.8a). For example, the sea level at the tidal-gauge station in Baltimore, Maryland rose by over 30 cm in the 20th century.

Climate models predict that the rate of sea-level rise will accelerate in the 21st century (IPCC 2007; Meehl et al. 2007), with global-mean increases by 2,100 of 0.5–1.4 m, depending on greenhouse gas-emission scenarios and climate-model sensitivity (Fig. 6.8b, Rahmstorf 2007). Currently, sea level is rising at a rate near the upper end of the projections (Church et al. 2011). Moreover, it is recognized that a catastrophic melt of ice sheets could occur and lead to 6 m rise in global sea levels (Bindschadler 2008), but robust methods for quantifying it are not yet available. The Scientific and Technical Working Group of Maryland's Commission on Climate Change assessed the 2007 IPCC global sea-rise projections, along

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with regional land subsidence variables, and provided a conservative estimate that by the end of this century, Maryland may experience a sea-level rise of 0.83 m under a lower-emission scenario, and 1.04 m under the higher-emission scenario (Boesch 2008).

With respect to coastal inundation during non-storm periods, the sum of local mean sea level and tidal amplitude, is more relevant. Tides are usually thought of as stationary, even though their astronomical forcing changes slowly (Cartwright and Eden 1973), and tidal datum levels are evolving in geographically variable ways that imply changes in both global sea level and tidal processes. A new study by Müller et al. (2011) has shown that the response of the oceans to tidal forces has changed significantly during the last century. Changes of tidal amplitude and/or phase have taken place in both North Atlantic and North Pacific (Jay 2009). Flick et al. (2003) examined long-term sea-level records around the U.S. coasts and found significant changes in the tide range, either in the diurnal tide range or mean tide range. For example, at San Francisco, the diurnal tide range increased by 64 mm from 1900 to 1998, while at Wilmington, N.C., the mean tide range increased at a rate of 542 mm per century from 1935 to 1999. Inside Chesapeake Bay, tidal stations in its upper part, notably Baltimore and Annapolis, showed an upward trend in tidal range whereas stations on the lower bay showed a downward trend (Flick et al. 2003). Semi-enclosed Bays such as the Bay of Fundy have extremely high tides because their natural resonance periods are close to those for semidiurnal or diurnal tides (e.g. Garrett 1972). At the current sea level, the resonant period in Chesapeake Bay is about 48 h. Raising the sea level by 1 m shortens the resonant period to about 36 h and moves it toward the diurnal tides (Zhong et al. 2008). Therefore, larger tidal ranges are expected to occur at higher mean sea levels. AQ1

Recent studies suggest that sea-level rise may greatly amplify storm surges in shallow coastal regions. Smith et al. (2010) examined the potential impact of sea level rise on coastal surges in southeast Louisiana. In shallow wetland or wetland-fronted areas of moderate peak surges (2–3 m), however, the surge levels increase by as much as 1–3 m beyond the sea level rise. Their study highlights the fact that surge generation and propagation over shallow areas are nonlinear processes and sensitive to changes in the water depth. Other studies have shown strong nonlinear interactions between storm surges and tides. For example, Horsburgh and Wilson (2007) showed that larger surges are usually encountered around 3–5 h before the high tidal water in the North Sea. Therefore, the cumulative effects of sea level rise, tides and storm surges on coastal inundations are not simple linear additions. Strong nonlinear interactions between them can produce unexpectedly high water levels in shallow estuaries such as Chesapeake Bay. Future research is warranted to understand the nonlinear interactions between sea-level rise, tides and storm surges.

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6.7 Conclusions and Discussions

Using the low-lying areas in Maryland, U.S.A. as an example of coastal regions prone to storm surges and coastal inundations, we have discussed how sea-level rise, changing tidal ranges and storm surges may lead to extremely high sea levels in a warming climate. We have also described the recent development of an end-to-end coastal inundation forecasting system that uses a suite of advanced regional atmospheric and hydrodynamic models to generate an ensemble forecast and employs the state-of-art software ArcGIS and Google Earth to produce high-resolution images and animations of overland inundations.

Many coastal regions in China are facing the same inundation risks due to sea level rise and storm surges. As a result of rapid urbanization, the Chinese coastal zone has become a region with highly developed economy and dense population. This coastal zone is inhabited by 42 % of the Chinese population and produces 51 % of the gross domestic product in China. For example, Shanghai, the largest city of China, lies in the Changjiang River Delta. During the period between 1978 and 2007, the mean sea level in Shanghai has risen 115 mm, as a result of global sea-level rise and local land subsidence (Xue et al. 2005). This large relative sea level rise, together with recent increases in the intensity and frequency of storms, has placed Shanghai at high risks of flooding and inundations. Computer models have been developed to evaluate these risks (Hu et al. 2007; Guo et al. 2009; Yin et al. 2011). Similarly, the southern Guangdong Province faces the high risks of typhoon-induced storm surges since much of the population inhabits low lying coastal regions. Each year over 3–4 named typhoons and tropical storms hit the coastal areas of Guangdong Province. With the continued urbanization, storm surges are a matter of great concern, particularly for the Pearl River Delta, where the physical geography (the southern part of the delta lies between −0.3 and 0.4 m relative to the sea level), and the urban development of the region render it extremely vulnerable (Zhang 2009; Zhang et al. 2011).

Given the same inundation issues facing the U.S. and Chinese coastal coasts, there is a great merit to conduct parallel investigations and develop collaborative projects between the American and Chinese scientists. Many numerical models of the atmosphere and ocean are open-source community models and can be applied to any coastal region around the world. By sharing the resources and experiences, we will all be better positioned to mitigate the impacts of storm surges and inundations in coastal regions.

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