PART V

Hydrological Aspects of Tropical Cyclones

Chapter 12

Storm Surge Modeling and Applications in Coastal Areas

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This chapter introduces the reader to a wide spectrum of storm surge modeling systems used to assess the impact of tropical cyclones, covering a range of numerical methods, model domains, forcing and boundary conditions, and purposes. New technologies to obtain data such as deployment of temporary sensors and remote sensing practices to support modeling are also presented. Extensive storm surge modeling applications have been made with existing modeling systems and some of them are described in this chapter.

The authors recognize the importance of evaluating river-ocean interactions in coastal environments during tropical cyclones. Therefore, the coupling of hydraulic (riverine) and storm surge models is discussed. In addition, results from studies performed in the coast of India are shown which generated maps to help emergency managers and reduce risk due to coastal inundation.

1. Introduction

Storm surges resulting from tropical cyclones expose the population in coastal areas to flooding and destruction. Accurate and understandable forecasts and flood information products play an important role in preparing for and mitigating these events, including flood protection and evacuation. The purpose of this chapter is to discuss theory for modeling tropical cyclone storm surge and the application of river flow and storm surge data for modeling flooding conditions in coastal areas.

Although numerous models are available for forecasting storm surge water levels in coastal areas, many of the models still remain in the field of research. One of the primary distinctions between research and operational models is that operational models must perform under all conditions, which constitutes an ongoing testament to their robustness. In the operational framework[a], there needs to be assurance that forecast products will be available at all times for use by emergency managers. Conversely, research applications are able to explore areas of technological advancement that benefits both future operations (operational models can be continuously improved by research) as well as other significant needs. These include but are not limited to calculations of long term risk, emergency planning, and coastal management and engineering.

Even though the authors recognize the importance of precipitation forecast due to tropical cyclones, this topic is not discussed in this section. This section will address only storm surge models and their coupling with hydraulic models for the application of coastal inundation.

2. Storm Surge Simulation

As a tropical cyclone approaches land, its impact on the sea leads to a rise in water level at the coast that can be extremely severe, inundating vast low-lying areas. This *storm surge* is defined as the rise in water level caused by the surface wind stress, atmospheric pressure deficit, and momentum transfer from breaking surface wind waves (wave setup). The term *storm tide* is commonly used to describe the water level change caused by the combined effects of the *storm surge* and the astronomical tide (Hicks *et al.*, 2000, p. 25). Both the *storm surge* and *storm tide* refer to a long gravity wave (so called because its wavelength is much greater than depth) that is of similar size to the storm itself. Wind-generated short waves (with wavelengths smaller than depth), while possibly devastating, are considered a separate phenomenon because of their short time and spatial scale. Figure 1 illustrates the relevant contributions to the total water level during an extreme storm surge event, and further description follows.

In deep water, storm surge is minimized because the effects of the wind stress are distributed over depth and counter currents can be generated in deep water. The primary water surface elevation response in deep water is the atmospheric pressure deficit which causes the so-called "inverted barometer" effect; the rise is approximately 1 cm for each hPa drop in pressure (see, e.g., Pugh, 2004). However, as the storm passes over the shelf, reduced bathymetric depths lead to a set-up of the water surface due to the currents caused by the surface wind stress. A large shallow shelf can therefore enhance surge generation. Local dynamics become increasingly important as the surge approaches the coast. The bathymetry, coastline, topography, and inundation barriers such as levees and dunes are capable of modifying the surge. Surges of several meters are commonly generated by land-falling tropical cyclones, and extreme surges approaching 10 meters can occur under certain conditions. The storm's strength, size, track/angle of attack and forward speed effectively determines the surge at any one location.

Other processes can affect the total water level and resulting damage caused by land-falling tropical cyclones. First, wind-generated waves can be severe and significant. They

[a]The term "operational" in the context used in this chapter, means executed in real time.

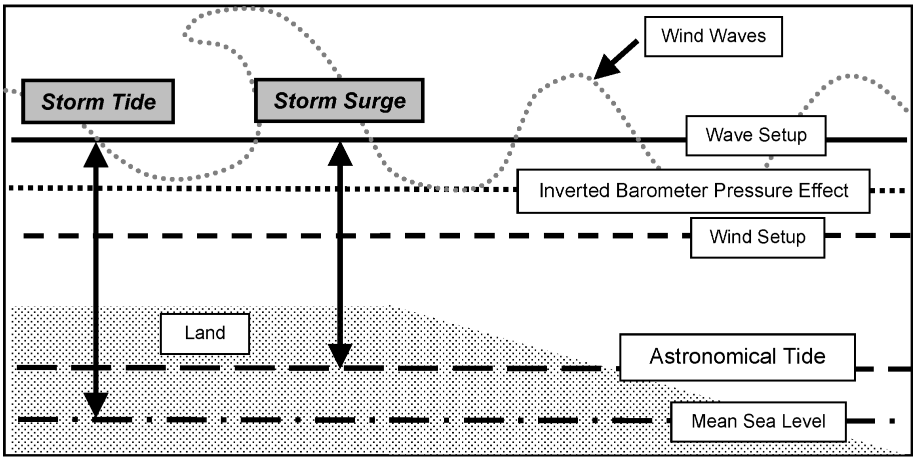


Figure 1. Contributions to the total water level during a severe storm surge event as it reaches land (gray shading). The individual effects vary significantly, depending on a variety of factors and this illustration cannot be construed as specific to any one case.

can contribute to the surge by a transfer of momentum, mainly when breaking, which is called wave set-up. They also are extremely destructive when impacting structures inundated by the surge. Second, flooding from rainfall can occur in conjunction with a storm surge. While there is generally a delay in the flooding caused by heavy tropical cyclone precipitation of a few days after landfall, saturated conditions and flooding caused by previous events can exacerbate inundation. Third, the total water level is also affected by seasonal and annual variations such as persistent (e.g., trade) winds and solar heating of the large ocean basins, which can cause a variation in water levels compared to the long-term mean.

Storm surge and the superimposed wind waves cause most of the damage from tropical cyclones at landfall. Extensive low-lying coastal areas (e.g., Louisiana, Bangladesh, and Myanmar) can be flooded, destroying communities, damaging property and infrastructure, and resulting in casualties. Furthermore, coastal development is rapidly increasing and population centers are growing (Crossett *et al.*, 2004). These factors are combining to raise the economic and social risk caused by severe storm surge. A clear example is the widespread impact that Hurricane Katrina had on coastal Louisiana and Mississippi, and on New Orleans in particular (Knabb *et al.*, 2006).

Considering the severe impact of storm surge, it is important to develop effective mitigation systems for supporting resilient coastal communities. This requires an analysis of the vulnerability due to storm surge activity at the coast. However, the frequency of severe storm activity at any particular location may be limited, hampering statistical analysis because of limited historical observations and precluding adequate in situ data acquisition (and thus effective data assimilation analysis strategies). Storm surge is so dependent upon the individual characteristics of each storm and geographical location that surge heights from a handful of historical hurricanes may not reliably predict future inundation risk. Predictive modeling capability is needed to study the potential threat due to storm surge as a function of meteorological forcing and geographic conditions.

A model capable of accurate storm surge simulation is important for minimizing risks to coastal communities. These simulations are needed to forecast potential flooding from an incoming hurricane, to develop and implement effective evacuation plans, to design flood protection and coastal management projects, and to assess surge risk for flood insurance programs. There are two distinct types of users of storm surge simulations: real-time responders and long-term planners. These users include emergency managers; meteorologists and forecasters; land-use, coastal zone, floodplain, and natural resource managers; engineers and public infrastructure managers; insurance companies; and commercial companies and non-governmental organizations. Their needs lead to a wide range of models and applications in use, and the most common are discussed below.

2.1. *Theory and Methodology*

The need for modeling storm surge and developing surge forecasting systems has led to a range of numerical modeling approaches utilizing an array of techniques. The predominant approach is to solve the two-dimensional (2-D), depth integrated form of the shallow water equations, which disregard baroclinic effects and variations in the velocity field over the vertical direction. The numerical techniques employed primarily include finite difference and finite element algorithms but other approaches have been used, such as finite volume schemes. The domains chosen tend to be regional, shelf based models, although some models use nested or large scale unstructured grids in order to apply far field boundary conditions (albeit with limited, if any, dynamic two-way coupling between domains). Bode and Hardy (1997) provides a review of developments in the field of storm surge modeling that identifies many approaches.

2.1.1. *Governing Equations*

Coastal ocean models are generally based on the shallow water equations (SWE). These governing equations are appropriate since they describe the dynamics in most free surface geophysical flow problems. The SWE are based on the principles of conservation of mass for an incompressible fluid, and the conservation of momentum as described by the Navier-Stokes equations subject to Reynold's averaging to describe the mean flow. Simplifications are made in the formulation of the SWE which lead to a more manageable set of equations: the hydrostatic approximation makes the vertical acceleration and associated viscous terms in the vertical momentum equation unimportant, the Boussinesq approximation allows gradients of fluid density to be ignored, and the shallow water assumption leads to a depth-integrated set of 2-D equations. The diffusion and dispersion of momentum due to unresolved lateral scales of motion as well as the effects of depth-averaging are accounted for by a turbulence closure model. The resulting SWE are applied to simulate ocean and estuarine circulation. When these equations are applied on a scale appropriate for geophysical flow problems, the Coriolis term is included to account for the rotational acceleration of the earth, and they can be solved in a spherical coordinate system (with horizontal dimensions of longitude and latitude) in order to more accurately account for the earth's curvature. For further detail on the derivation of the SWE see, for example, Pedlosky (1987), Cushman-Roisin (1994), or Weiyan (1992).

The SWE describe 2-D, depth-integrated circulation, which is a valid approach for modeling storm surge since the response due to hurricane forcing is of a relatively short time scale. This limits the generation of three-dimensional (3-D) circulation (namely, a return flow opposite to the surface gradient). Rather, storm surge propagates as a shallow water wave with height on the order of 10 meters and length on the scale of hundreds of kilometers. This satisfies the condition describing shallow water conditions: horizontal scales of flow are much larger than depth. When computations of vertical variations in currents are required a 3-D model can be used. However, 2-D models are much more economical and describe the dominant characteristics for storm surge simulations.

In order to improve model efficiency, nonlinear terms are omitted within some surge models. In particular, the nonlinear advective terms can pose a constraint on computational efficiency (namely the numerical time step size) of a surge model algorithm. (The nonlinear bottom friction and water surface elevation terms are more generally included.) It is in principle preferable to implement a fully nonlinear model, but linearizing the equations can be an acceptable choice if the compromise in accuracy is minor compared to the improvement in simulation cost. In practice the uncertainties inherent in the forcing, parameterizations, and grid design (including elevation specification) limit many gains in accuracy possible through use of a fully nonlinear model.

2.1.2. *Numerical Methods*

Computational models of the SWE have been in existence for over three decades, employing various numerical methods for simulating storm surge. The earliest numerical techniques employed finite difference (FD) schemes. The modeling community's experience with FD modeling of the Navier-Stokes equations led to its early application to the SWE. The resulting computational codes have proven to be efficient and robust and are widely applied. However, a disadvantage of FD methods comes from their use of structured grids. This hinders their ability to refine the complex coastal geometries and localized flow patterns near the coast and over floodplains. Because these features significantly affect surge height, accuracy can be affected by the grid resolution and orientation.

The application of the finite element (FE) method to the SWE has allowed use of unstructured meshes able to map complex geometry quite accurately. This produces domains that minimize computational effort while maximizing accuracy by varying nodal spacing over several orders of magnitude (Blain *et al.*, 1998; Westerink *et al.*, 1994). This allows for high resolution of coastal features such as inlets and barrier islands while using much larger node spacing further away in what may be very large grids. The method that proved to be most successful and widely used for FE modeling of the SWE is the wave equation formulation, due to its suppression of spurious oscillations (Lynch and Gray, 1979; Kinnmark, 1986). However, it has been established that for shallow, nonlinearly dominated flows there can be mass balance error, as the continuity equation is not being satisfied in the wave equation, but rather its time derivative (Walters and Carey, 1984; Kolar *et al.*, 1994). Additionally, this FE approach has been found to require very small time steps below the Courant condition, leading to costly simulations. When combined with the highly resolved grids that FE models generally apply, the computational resources required for FE storm surge simulations can be significantly more than FD models, limiting their use in time-constrained applications.

Recent research has been focused on combining the strengths of FD (mass conserving) and the strengths of FE (high resolution unstructured grid) methods. This has led to various forms of finite volume (FV) techniques, but use of these models has not yet been widespread although results have been reliable. The same cost issues regarding the size of highly resolved grids in FE modeling also apply to FV models as well.

Considering the cost of storm surge applications, which can rely on large, highly refined grids and time-consuming numerical schemes, state-of-the-art computational techniques are required to make these simulations feasible. For example, parallel processing techniques are being used to run models on distributed memory computers. With these approaches computational platforms among the most advanced available can be utilized, and wall clock times are reduced by a factor close to the number of processors.

2.1.3. *Grid Design*

Storm surge elevations can be impacted by complex local geometries, as flooding is controlled by geographic features. Therefore, simulations capturing these features improve storm surge prediction, and the corresponding model requires fine resolution. However, the size and resolution of the model domain must be balanced by consideration of the computational requirements. For example, forecasts are constrained by timeliness requirements, but pre- and post-storm investigations for engineering and risk determination purposes can benefit from more complex approaches that require greater computational resources.

FD storm surge models apply structured computational grids with regularly spaced discretization points. Curvilinear FD models provide fine resolution near the coastline and coarser resolution as the grid extends away from the coast. These grids can be cost efficient but if the boundary location is not extended far enough, these models may not correctly capture the dynamics of the basin-shelf interaction. However, nested modeling techniques can be employed which couple high resolution coastal grids with coarser larger scale domains. These larger basin effects can produce a set-up on the shelf which is not known *a priori* and therefore cannot be specified as a boundary condition. Additionally, structured grids can have difficulty sufficiently resolving irregular coastal features or may poorly represent them because of the regular structure of the grid. Flood amplitude and propagation are controlled by details such as the shoreline, inlets, and levees, so it is important to ensure the coast is resolved as accurately as possible. Therefore, some models link to subgrid-scale one-dimensional (1-D) models to represent flooding barriers, conveyance, or storage at a resolution higher than permitted by the native grid. Figure 2 shows an example of a structured orthogonal curvilinear mesh for the Northwest Florida Panhandle, including a close-up of the model resolution around Pensacola Bay. This model domain contains approximately 63,500 cells.

A storm surge model that uses an unstructured grid methodology can apply fine resolution of the coastal region along with far-field boundary conditions in the deep ocean. The paradigm recommended is a large domain/unstructured grid strategy that couples the ocean, shelf, and coastal floodplain while resolving local features. However, this methodology typically leads to costly model grids and it requires sufficient bathymetric and topographic detail to support its high resolution. Figure 3 shows a finite element mesh from a storm surge model of coastal Alabama and the Northwest Florida Panhandle. Detail of the model grid is shown for the inlet to Pensacola Bay, Florida, along with the view of the larger model domain and the increased resolution for the inundation region. This model grid has resolution of approximately 100 m at the coast but expands out to tens of kilometers in the deep basins, where the open ocean boundary conditions are applied. It has a total of approximately 450,000 nodes.

Key to any numerical storm surge simulation is the representation of the bathymetry, topography, and coastal features. The configuration of bathymetry (sea floor depth), its resolution, and its age/correctness is a critical factor in surge generation. Similarly, the topography (land elevation) of a coastal region is essential to correctly simulating the overland surge. This is because flooding depths over land are defined in part by the shape of topographic contours and features impacting inundation (e.g., levees, barrier island dunes, raised roadways). Waterways can propagate surge well inland, while concave coasts focus and amplify surge. Bathymetry and topography can change quickly due to both natural and anthropogenic causes, so it needs to be regularly updated. Considering the accuracy (errors reaching less than one-third of a meter) and resolution (reaching less than 100 meters) of widely used storm surge models (Jarvinen and Lawrence, 1985; Westerink *et al.*, 2008), data

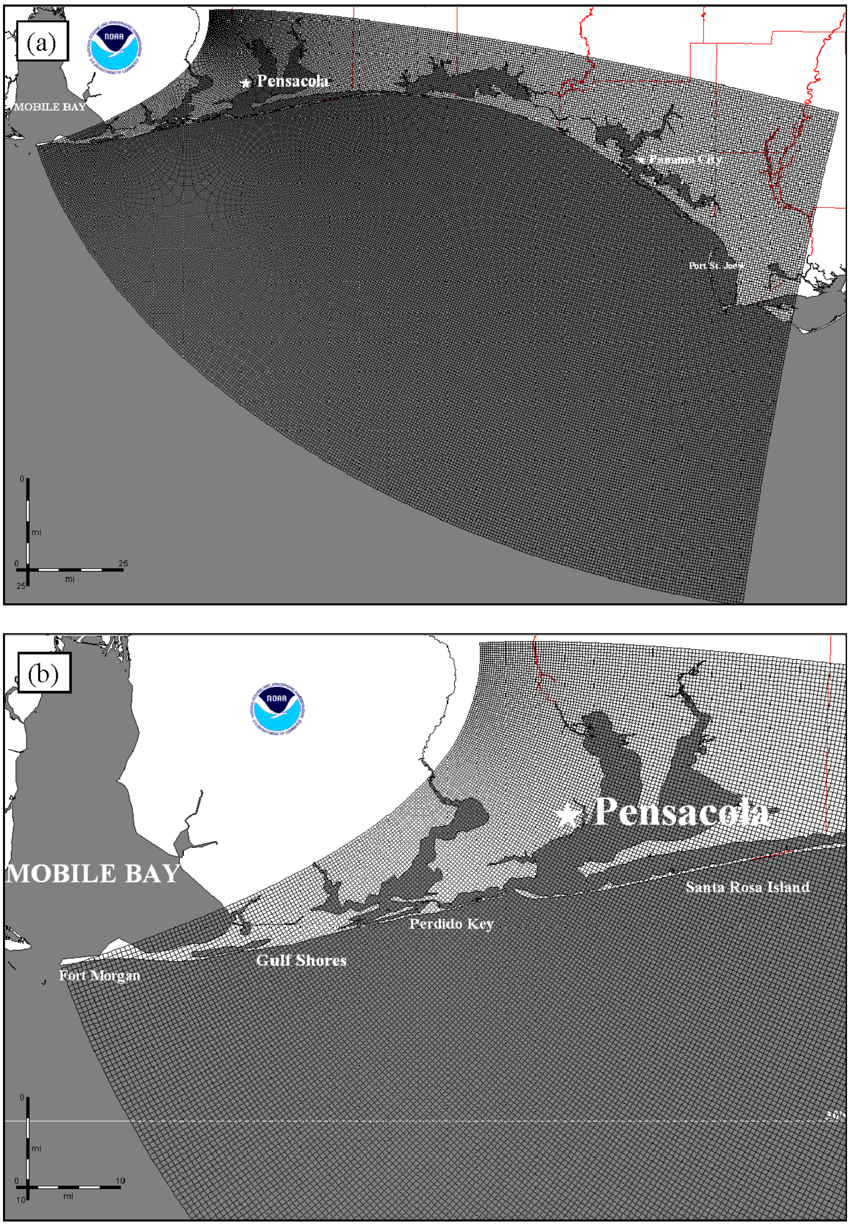


Figure 2. Finite difference storm surge model grid: (a) orthogonal curvilinear grid domain and (b) grid detail around Pensacola Bay. Figures provided by the US National Oceanic and Atmospheric Administration National Weather Service.

collection and processing need to meet or exceed these constraints. Many new remote sensing technologies are being employed for bathymetric and topographic data collection (e.g., sidescan and multibeam sonar, Light Detection and Ranging (LiDAR), interferometric radar). It is important that expensive data collection efforts include: necessary ties to vertical datums; accurate post-processing to produce bare-earth data sets; and appropriate collation into a useful Digital Elevation Model (DEM) or similar product.

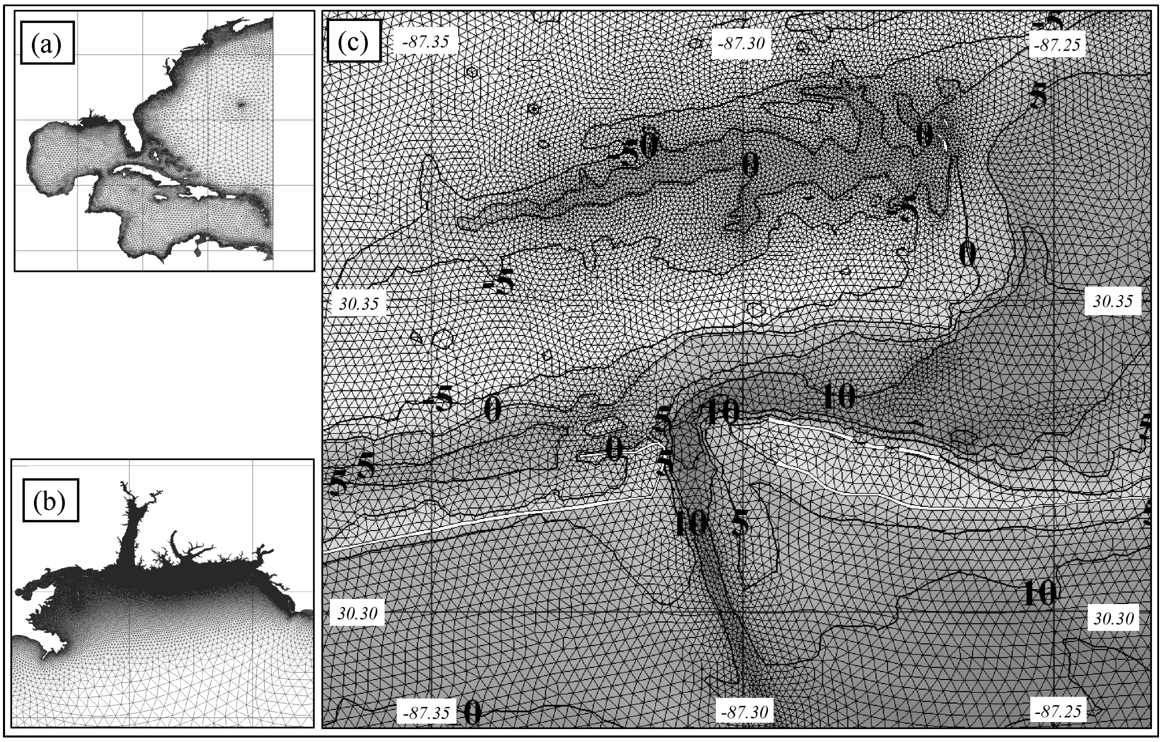


Figure 3. Finite element storm surge model grid: (a) unstructured grid domain, (b) high resolution grid in project region, and (c) model grid and bathymetry for the inlet to Pensacola Bay (m NAVD 88). Figure provided by the US National Oceanic and Atmospheric Administration National Ocean Service.

There are often a number of vertical datums used as a reference for elevation measurements. Bathymetry is generally referenced to a tidal datum, which is determined by computing the mean of a stage of an observed tide. For example, in the US, bathymetry is generally provided relative to Mean Lower Low Water (MLLW). Topography is usually referenced to a land-based geodetic datum, which is determined by surveying techniques from a national set of established benchmarks. In the US this geodetic datum standard is the North American Vertical Datum of 1988 (NAVD 88). While NAVD 88 is constrained to Mean Sea Level (MSL) at one location along the US/Canadian border, the difference between NAVD 88 and MSL varies along the US coast. Water level observations are generally collected relative to a tidal datum but peak surge values can be referenced to another datum. Finally, vertical datums also include 3-D ellipsoidal datums used by global navigation satellite systems. Storm surge simulations require consistent referencing of all data at the coast, where tidal, orthometric, and ellipsoidal datums are all used. Therefore, adjusting all datasets (bathymetry, topography, and water level observations) to a common vertical datum is required when building a surge model which describes propagation of water level from offshore to the coast and inland. This can be done by careful examination of data at locations where ties to multiple datums are provided, commonly at tidal gauges which have geodetic benchmarks. For example, the US National Oceanic and Atmospheric Administration (NOAA) is developing a vertical datum transformation tool called VDatum (Myers 2005) based upon these datasets to provide these adjustments for all of the US coastline (see http://vdatum.noaa.gov).

2.1.4. *Boundary Condition Specification*

The boundaries to a storm surge model have a significant influence on model response. For example, forcing at lateral boundaries (e.g., astronomic tides, river inflow, and inverted barometer pressure signal) requires accurate boundary conditions in order to generate the proper surge. Many models also employ specialized boundary conditions to characterize geographic features that can not be adequately modeled at the mesh resolution (e.g., levees, streams). Finally, storm surge simulation has the special case of a moving boundary at the wet/dry interface which must be handled in a way that correctly models inundation and recession.

Initial conditions specify the water level before the storm arrival. Models generally apply an elevation-specified boundary condition at the open ocean to define water level variations occurring outside the domain. Tidal constituent data from global ocean models or satellite altimetry can be applied if tidal forcing is desired. However, care must be taken to ensure that the constituents provided at the open ocean boundary are sufficient and accurate, since global databases are often not accurate in shallow water and many areas of the world lack adequate shallow water observations. Storm-induced set-up in the water level surface can be applied as well, if known. Also, the inverted barometer effect of the hurricane's low pressure system can be readily applied if known.

A model can define river inflows or a no-normal flow condition for land boundaries. However, a simple specified flux at river inflow boundaries can reflect surface gravity waves back into the domain, so use can be made of a wave radiation boundary condition that allows such waves to pass out of the domain.

Modeling inundation requires simulation of wetting and drying fronts. However, this is a challenge because the size of grid resolution (hundreds to thousands of meters) is coarse compared to features which locally impact flooding. Generally, the inundation front is described by allowing a region to flood if a sufficient volume of water can enter it from neighboring grid cells.

During hurricane flooding conditions, storm surge may overtop levees, dunes, road systems and similar features which are local barriers to flood propagation. However, these barriers generally fall below grid scale and represent a non-hydrostatic flow scenario. Therefore, it may be effective to treat these structures as subgrid scale objects within the domain, generally using boundary conditions which apply weir formulae. Similar techniques have also been applied for subgrid scale hydraulic features such as small streams and channels.

2.1.5. *Surface and Bottom Boundary Specification*

The specification of boundary conditions defines the forcing entering a storm surge model domain. However, the simulation also requires the stresses at its surface and bottom boundaries that guide the circulation. Due to the significance of the storm as a forcing mechanism, meteorological conditions provide the most significant contribution to model accuracy. Tropical cyclone wind and pressure fields input to the hydrodynamic model essentially control the generation of storm surge. A hurricane's track, strength, and size are critical factors which determine storm surge height. A shift in track location to either side of a river, for example, will significantly alter the impact that the storm has on that waterway.

The dominant forcing mechanism for storm surge is the surface wind stress (the inverted barometer and wave set-up effects generally contribute less than a meter of what may be a several meter surge). Therefore, accurate definition of the wind field (including its strength, size, and shape) as well as parameterization of the wind stress at the water surface critically affect accuracy. While an analysis of closely spaced observations can produce an accurate, objectively analyzed wind field (Powell *et al.*, 1998), this approach is not viable for forecast or hypothetical storm simulations, but only for hindcast scenarios. Therefore, meteorological tropical cyclone models are applied for these scenarios. Considering the importance of the wind field, the quality of the tropical cyclone model is very important to the surge prediction. Therefore, validation of the wind fields should be undertaken when possible, and probabilistic approaches may be employed during forecast scenarios to account for uncertainty in tropical cyclone predictions.

There are two primary classes of atmospheric models used to generate tropical cyclone wind and pressure fields. The first class solves the 3-D mathematical equations describing the dynamics of the atmosphere, and they are therefore called dynamical models. Dynamical models benefit from their fully 3-D solution of the governing equations but are costly to run and require extensive initial and boundary conditions. This type of model is used to guide forecasts of a tropical cyclone's track (and also intensity from some models); the wind and pressure fields computed during these predictions can also be used to drive a storm surge model. Three predominant dynamical models used by US National Weather Service (NWS) are the Global Forecast System (GFS; Global Climate and Weather Modeling Branch 2003; see http://wwwt.emc.ncep.noaa.gov/gmb/STATS/html/model_changes.html for the latest version), the Geophysical Fluid Dynamics Laboratory hurricane model (GFDL; Bender *et al.*, 2007), and the Hurricane Weather Research and Forecasting model (HWRF; see http://www.emc.ncep.noaa.gov/HWRF/index.html). The GFS is a suite of global model products produced for numerical weather prediction at about 35 km resolution. It has an incomplete description of the tropical cyclone and therefore is only relied upon for track predictions. The GFDL and HWRF models both use high resolution nested grids (smaller than 10 km) to represent the storm's dynamics and can predict the storm's track and intensity variation.

The second class of atmospheric tropical cyclone models develops an idealized representation of the storm based on a few key input parameters to characterize its location, size, and intensity; these are referred to as parametric models. This type of model is effective when estimated storm conditions are desired despite a lack of specific data about the event. This makes them good candidates for simulating hypothetical storms or when dealing with forecast uncertainty (e.g., ensembles of predictions). Parametric wind models include the one incorporated with the Sea, Lake, and Overland Surges for Hurricanes (SLOSH) storm surge model (Jelesnianski *et al.*, 1992), the tropical cyclone model of the planetary boundary layer from Thompson and Cardone (1996), and the Holland model of the gradient winds in a storm (Holland, 1980), among others. Typical input parameters are the track (to define location and translational speed), peak wind speed or minimum central pressure (to characterize intensity), and the radius to maximum winds (to define size). While each parametric model approaches the calculation of the tropical cyclone wind and pressure fields from a different basis, the resulting wind and pressure fields tend to be simplified, fairly uniform approximations that do not account for the variations in structure that occur in individual storms. Parametric models also lack meteorological conditions outside the storm. However, they solve simplified equations and therefore are very efficient and are often used to run large numbers of hypothetical storms (e.g., for planning purposes or as ensembles of possible land-falling tracks).

Air-sea interaction governs storm surge generation caused by the wind field. The surface shear stress parameterization is particularly important since this is the predominant forcing mechanism for surge generation. Wind shear stress at the water surface causes momentum transfer from the hurricane wind field to the water column, causing a gradient in the elevation of sea surface (set-up). Use of a wind drag law dictates that shear stress is governed by the wind velocity and the wind drag coefficient. The drag coefficient is defined by empirical data collected to define the relationship between wind velocity and surface roughness. Examples of drag coefficient relationships include Garratt (1977) and Large and Pond (1981), although recent research (Powell *et al.*, 2003; Makin, 2004) indicates that the generally linear correlation these laws provide for drag as a function of wind speed may not apply as winds reach hurricane strength, where drag may level off. Finally, overland regions have increased roughness in comparison to marine conditions, reducing the wind speed and the surface shear stress. Overland roughness can vary from relatively low values for open terrain to high values in heavily vegetated and urban regions. However, drag coefficient relationships are developed based upon data collected under open marine conditions. Therefore, surge models which are applying parametric-type tropical cyclone models which assume open marine conditions often reduce wind speeds according to land type classification (Jelesnianski *et al.*, 1992; Westerink *et al.*, 2008).

In addition to wind shear stress, the action of wind-generated short gravity waves can affect the surge through several mechanisms and, in consequence, the total water level. First, waves directly impart moment to the water column. This action can be described by radiation stresses which are applied at the water surface, leading to a localized wave-generated set-up in areas where waves are breaking sharply. However, when wave breaking occurs gradually and energy is dissipated by bottom friction it does not produce a significant increase in water elevation. Second, the sea state is characterized by the condition of the wind waves (e.g., height and steepness), which depends on their age. Changes in sea state therefore affect the roughness of the ocean surface and thus the drag coefficient. Modeling efforts which vary the drag coefficient dependent upon wave conditions improve momentum transfer from wind to water (e.g., Mastenbroek *et al.*, 1993). Third, waves affect local bottom friction effects, which impacts hydrodynamic circulation. Therefore, provided that good quality nearshore land and seabed elevation data is available, surge simulations might be improved when combined with wave models that describe the wave field.

Accurate representation of bottom shear stress is also important in governing the propagation of the surge inland. In 2D models the bottom shear stress is generally defined as a quadratic function of the depth-averaged current and a coefficient of friction. Bottom shear stress parameterization is especially significant during flooding processes due to shallow water depths and complex variations in topographic roughness (e.g., from sandy beaches and parking lots to grassy fields and wooded areas). While there can be a lack of empirical data for characterizing bottom friction under this range of conditions, many models do allow variable friction coefficients spatially to account for land cover type, such as by applying varying Manning's n values (e.g., see Chow, 1959). One advantage of 3D models is their ability to describe the bottom boundary layer according to local roughness heights, which can be more accurate than parameterizations used in the 2D equations.

2.1.6. *Calibration and Validation*

Hindcasts of recorded historical tropical cyclones are used to validate and calibrate surge model implementations. Ideally large datasets from multiple storms are used so that calibration and validation can be conducted independently. Considering the model grid's important role in representing coastal geometry, this process needs to be done separately for each model domain.

In order to validate storm surge models, observations of water level variations caused by tropical cyclones are required. Most valuable are time series observations of water level, generally from a preexisting water level gauge. It is important that the datums for these gauges be accurately tied into a common, documented datum such as a national network of benchmarks so that adjustments can be made to match the model's datum. The design and location of a water level gauge is normally intended to filter out short gravity wind waves, leaving the remaining storm tide signal. Unfortunately, water level time series observations are not widely available due to the cost of installing and maintaining gauge sites. Additionally, many gauges subject to the strong storms are destroyed, eliminating data from severe events.

In order to expand the suite of data available to characterize the impact of the storm, many times a post-event survey of peak storm tide levels is undertaken. These surveys collect High Water Marks (HWMs) which are generally water or debris lines on structures or similar features that represent the peak storm tide. However, these observations often include not only the storm tide but also wave run-up, flooding from precipitation, and other local variability. Therefore confidence is increased by collecting a HWM from a building interior and by ensuring consistency with marks in close proximity. Still, their values may vary by 20 percent or more against nearby marks (Jelesnianski *et al.*, 1984; Harper *et al.*, 2001b), and one study has found that only 15 percent of marks were high quality indicators of peak storm tide (Ebersole *et al.*, 2007).

Once a storm surge model has been developed for a particular geographical region and a hindcast has been made of a historical storm which has good observations of the storm tide, a skill assessment of the model can be performed. This is necessary to validate the model for use. The correlation between the modeled and observed peak surge can be calculated to evaluate model skill. State-of-the-art storm surge model simulations have been found to produce mean error measures of one half of a meter and less (Westerink *et al.*, 2008).

3. Storm Surge Systems

The storm surge community continues to develop and apply systems for a variety of purposes. These include providing local high resolution predictions, improving modeling skill, examining location-specific environmental and management issues, and more. Descriptions of some prominent storm surge modeling systems are provided in section 3.1 below to illustrate the types of efforts underway.

3.1. *Models in Use*

There is a wide range of storm surge modeling systems in use for predicting the impact of tropical cyclones, covering a range of numerical methods, model domains, forcing and boundary conditions, and purposes. However, in the US there are two primary surge models: the Sea, Lake, and Overland Surges for Hurricanes (SLOSH) model and the Advanced Circulation (ADCIRC) model. While sometimes used for similar tasks, they are quite different in approach, have different strengths and weaknesses, and each is likely more well-suited for a particular application. Of course, there are many other models in use, and a survey of some notable approaches is provided.

3.1.1. *SLOSH*

The SLOSH storm surge model was developed by the US NWS (Jarvinen and Lawrence, 1985; Jelesnianski *et al.*, 1992). It is based on a linearized form of the governing SWE; the advective terms in the equations are discarded. The SLOSH model is a FD model that employs an orthogonal curvilinear grid. SLOSH grids for all vulnerable areas of the US coast have been constructed by the NWS for use in emergency management (http://www.weather.gov/tdl/marine/Basin.htm). The structure of a SLOSH grid results in fine resolution near the pole of the grid (which is placed near the area of interest) and larger elements at its outer boundary. These grids are limited in domain size and have their open ocean boundaries located on the shelf. SLOSH has the capability to simulate wetting and drying as well as parameterize sub-grid scale features such as 1-D channel flow with contractions and expansions, vertical obstructions to flow with overtopping (levees, roads, and banks that include cuts) and increased friction drag in heavily vegetated areas. However, it is not able to account for inflow, rainfall, or tides.

The SLOSH model contains an internal parametric tropical cyclone wind model used for forcing both forecast and hypothetical storm simulations. The tropical cyclone track, central pressure deficit, and radius of maximum winds are used as input to create wind and pressure fields which are interpolated onto the grid. A wind drag coefficient that is constant with respect to wind speed is applied, although it changes according to vegetation over land.

SLOSH has an extensive history of use by the U.S. National Weather Service (NWS) over nearly four decades. An extensive skill assessment found peak surge errors to be less than 0.6 m for nearly 80 percent of evaluations (Jarvinen and Lawrence, 1985). However, while it is a capable model, it does have limitations. First, at present it cannot provide astronomical tide forcing or river inflow. Second, it is a linearized model subject to error in locations where advection is important, such as in the vicinity of tidal inlets and similar constrictions. Finally, a SLOSH grid is generally limited in size to the coastal shelf surrounding the study area. Two issues arise from this limited domain strategy. First, the use of a structured grid limits the capability to provide localized refinement. While SLOSH grids do have increased refinement at their center, it is not always possible to resolve additional features that may be elsewhere (e.g., an inlet along the coastline that is away from the center of the grid). Conversely, the semi-annular structure of the grid also leads to over-resolution in regions outside of the area of interest (e.g., inland beyond the floodplain). Second, the shelf-based, regional nature of a SLOSH domain limits accurate specification of boundary conditions during storm surge events because of lack of knowledge of set-up at the open boundary, and prevents dynamic coupling to larger basins.

In the US, flood-prone areas are usually determined by using the SLOSH model and input parameters from thousands of hypothetical hurricanes. These model runs are used to create atlases of potential surge, which guides emergency managers in creating evacuation plans (Jarvinen and Lawrence, 1985). The US NWS's National Hurricane Center (NHC) also runs SLOSH for prediction of storm surge from potentially land-falling tropical cyclones. The storm's parameters (track, size, and intensity) are provided by the official hurricane forecast. These forecasts are distributed in real time to the forecast and emergency management community as Geographic Information System (GIS) products. They begin when a storm is within 24 hours of landfall due to the limitations of storm forecast accuracy; therefore they are only used to augment the pre-computed atlases of surge potential, which is the basis for emergency management activities. A probabilistic component based on the official NHC track forecast has been developed which forecasts the likelihood of surge as a function of the historical range of track error; see http://www.weather.gov/mdl/psurge/.

3.1.2. *ADCIRC*

The ADCIRC model was originally developed for the US Army Corps of Engineers for high resolution coastal ocean modeling (Luettich *et al.*, 1992). It has since been used by federal agencies, academic researchers, and private companies for a wide range of modeling applications, include storm surge, basin-scale tidal modeling, and tidal inlet circulation studies. ADCIRC solves the SWE discretized in space using the FE method, which allows for highly flexible, unstructured grids. All non-linear terms have been retained in these equations. ADCIRC can be run either as a 2-D depth-integrated (2DDI) model or as a 3-D model. In either case, elevation is obtained from the solution of the depth-integrated continuity equation in Generalized Wave-Continuity Equation (GWCE) form. The GWCE is implemented to prevent generation of spurious oscillations; however, it replaces the continuity equation with its time derivative, meaning continuity is not satisfied and mass balance errors exist. Velocity is obtained from the solution of either the 2DDI or 3D momentum equations. ADCIRC requires input of wind and pressure fields to consider the effect of storm surge. These wind and pressure fields are developed by meteorological models independent of ADCIRC. For further description of the model implementation see the ADCIRC theory report (Luettich and Westerink, 2004).

In order to accurately simulate storm surge, several features have been included within ADCIRC. It can model the wetting and drying of inundated areas, it can represent subgrid scale obstructions to flow as weirs, and it can apply the transfer of momentum from breaking wind waves as surface radiation stresses. Most importantly, its unstructured grid methodology allows for very high refinement of coastal regions (successfully modeled at scales less than 50 meters). These highly refined coastal regions are built into basin scale domains by smoothly varying element size. With the high resolution of inundation regions and the small time steps required by the semi-explicit solution scheme comes high computational cost, however. The model can be run on a single processor, but most often is run in parallel on high performance computing systems with hundreds of processors using the Message Passing Interface (MPI).

ADCIRC is presently in wide use in the US by federal agencies for storm surge modeling. Following 2005's Hurricane Katrina, the US Army Corps of Engineers partnered with other federal agencies, academic, and private institutions to extend an existing ADCIRC storm surge application for Southern Louisiana (Westerink *et al.*, 2008). The extension of the model built for studying the hurricane protection system for Louisiana was to conduct an extremely large and highly refined forensic study of Katrina's disastrous storm surge. As part of the Interagency Performance Evaluation Task Force (https://ipet.wes.army.mil/), this project applies very high resolutions of 50 to 100 m across coastal Louisiana and Mississippi, resulting in grids exceeding one million nodes. This model was adopted by FEMA to produce flood insurance rate maps for the Gulf Coast. Furthermore, both NOAA and the US Navy have been applying ADCIRC as a storm surge model for specific research and development projects.

3.1.3. *Survey of Other Approaches*

In addition to the two predominant storm surge models in the US (SLOSH and ADCIRC), a number of other modeling systems have been developed and applied worldwide. A few of the predominant systems are presented here as an overview in order to illustrate how storm surge simulations are being improved and the range of issues being addressed.

One of the predominant FD coastal ocean models is the Princeton Ocean Model (POM; Blumberg and Mellor, 1987). POM is a 3-D, fully nonlinear hydrodynamic model that has been in development and use by a wide range of user over the past three decades. It has been applied for use in tropical storm surge modeling in North Carolina (Xie *et al.*, 2003; Peng *et al.*, 2004, and Pietrefesa *et al.*, 2007). In this application it has been coupled with meteorological (wind, pressure, and precipitation), wave, and river discharge models in order to provide a comprehensive description of a storm's impacts.

Another well-developed FD model that has been applied to storm surge is the Curvilinear-grid Hydrodynamics model in 3D (CH3D; Sheng, 1986; Sheng and Alymov, 2002). It is a parallelized model capable of running large grids using MPI on high performance computing systems. CH3D uses a structured curvilinear grid and has been applied on domains with resolution reaching less than 20 meters. It is a fully nonlinear model that has been coupled with wave models and has been coupled with larger scale circulation models. Various wind models have been used to provide input.

In Australia, the FD MMUSURGE model developed at James Cook University has been widely applied along the north-eastern coastline and especially optimized for the complex Great Barrier Reef environment using subgrid boundary controls (e.g., Bode and Mason, 1994; Bode *et al.*, 1997; Harper *et al.*, 2001b (Appendix D), Harper *et al.*, 2007). Also, the commercially available TUFLOW hydrodynamic model (www.tuflow.com) is well suited to linked 2D and 1D applications and has been successfully used for many storm surge modeling studies.

Another FD SWE model has been developed in Australia for tropical storm surge modeling. The Global Environmental Modeling Systems 2D Coastal Ocean Model (GCOM2D; McInnes *et al.*, 2002) solves for depth-averaged flow and includes overland flooding and runoff as well as wave setup effects through coupling to atmospheric and wave models. In applications, the researchers have employed a coarse (1 km) far-field model and coupled that to a finely resolved (100 m) local model using a nested grid strategy.

The Chesapeake Inundation Prediction System (CIPS) focuses on the forecast needs of emergency managers and first responders (Stamey *et al.*, 2007). CIPS is a combined surge-tide-river discharge flood prediction system for the Potomac River near Washington, DC. It applies the mass-conserving unstructured model ELCIRC (Eulerian-Lagrangian Circulation; Zhang *et al.*, 2004), which is based upon a low order finite volume technique. While the domain is of limited extent (the Potomac River), it is highly resolved and includes inland regions at scales of 50 to 100 meters. CIPS combines the storm surge model with a high resolution (4 km) atmospheric prediction system and river discharge forecasts from NOAA in order to provide a comprehensive characterization of the flooding threat for a coastal riverine system. Model output is provided in GIS formats that allow for mapping and visualization applications in conjunction with other datasets.

Two additional FV coastal ocean models have been used for tropical cyclone surge modeling applications. The fully nonlinear 3-D model FVCOM has been applied to storm surge simulations in Florida (Weisberg and Zheng 2006). This modeling application demonstrates a mass-conserving 3-D simulation on an unstructured grid extending past the continental shelf.

Several projects have focused on approaches that leverage models available in the community. The Southeastern Universities Research Association's Coastal Ocean Observing and Prediction (SCOOP) project is a community approach employing Grid computing techniques that leverage resources over a wide range of locales (Bogden *et al.*, 2007). By combining a suite of models available in the community (including ADCIRC, ELCIRC, CH3D, and wave models) the system is not tied to one model but rather is an infrastructure for enabling model predictions. It does this by providing streamlined access to model inputs and outputs over a high speed network in standardized formats. Similarly, a project funded by the National Oceanographic Partnership Program (NOPP) combines readily available models for surge (ADCIRC), waves (the Wave Analysis Model (WAM)), and tropical cyclones (NOAA's real-time analysis system H*WIND and Oceanweather's Interactive Objective Kinetic Analysis (IOKA)) for simulations of events (Graber *et al.*, 2006). By constructing an ensemble of forecast tracks this networked system of models is used as a probabilistic forecast tool.

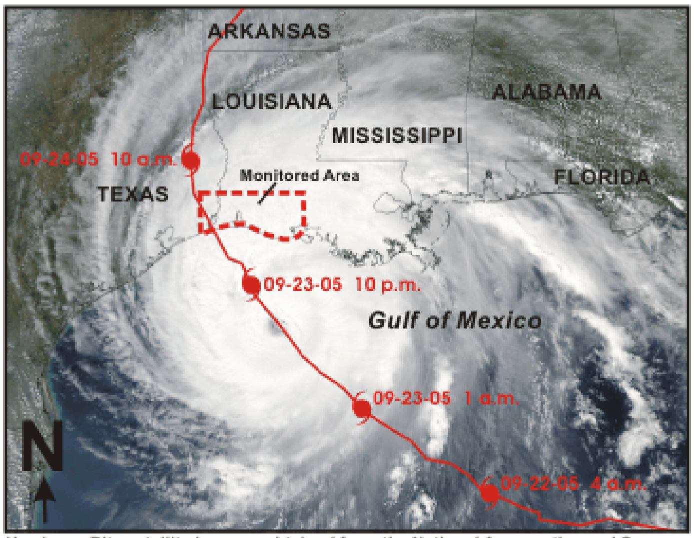
Finally, commercial hydrodynamic modeling systems by the Danish Hydraulic Institute (DHI) and Deltares (Delft Hydraulics) are widely used in storm surge risk assessment studies around the world. For example, DHI's MIKE 21 model has a FV version that has been used to simulate storm surges for the coast of Bangladesh (Paudyal, 2002).

3.2. *Storm Surge Measurements*

3.2.1. *Storm Surge Measurement on Land*

Storm surge height typically is based on high water marks (see section 2.1.6) or eye-witness accounts. This type of information can be useful, and combined with information such as debris piles, and structural and vegetation damage can provide estimates of the inland extent of the storm surge. These somewhat qualitative records, however, do not provide information about the timing of the surge and can be subject to major errors. In 2005, the US Geological Survey (USGS) initiated a program to collect more detailed storm surge information. The program consists of deploying a network of unvented pressure transducers in advance of cyclone landfall along the predicted path of the storm. Some transducers are positioned well above the expected storm surge height so that barometric pressure can be measured and used to correct the measurements from the unvented transducers used to measure water-surface elevation. These transducers then record the timing, spatial extent, and magnitude of storm surge over the affected region. The first deployment was along the coasts of southwest Louisiana and southeast Texas, USA (Fig. 4) in anticipation of the landfall of Hurricane Rita in September 2005 (Fig. 5). Subsequent deployments were made along the east coast of Hurricane Eduardo, but storm surge was minimal during that event.

A total of 34 storm surge sites were deployed for Hurricane Rita. Sensor locations ranged from a few meters from the coast to about 50 km inland. An additional 13 sensors were deployed to measure barometric pressure. Data were recorded at 30-second intervals and are available from McGee *et al.* (2006b). This unique network provides some of the most comprehensive storm surge data yet available. Time-series of storm surge elevations are available for the almost 2-day period when the coast was inundated, and maps showing inundation at 3-hour intervals have been prepared



Hurricane Rita satellite imagery obtained from the National Aeronautics and Space Administration (NASA), 2006

Figure 4. Path of Hurricane Rita, September 22–24, 2005; satellite imagery obtained from National Aeronautics and Space Administration (2006); from McGee *et al.*, 2006a.

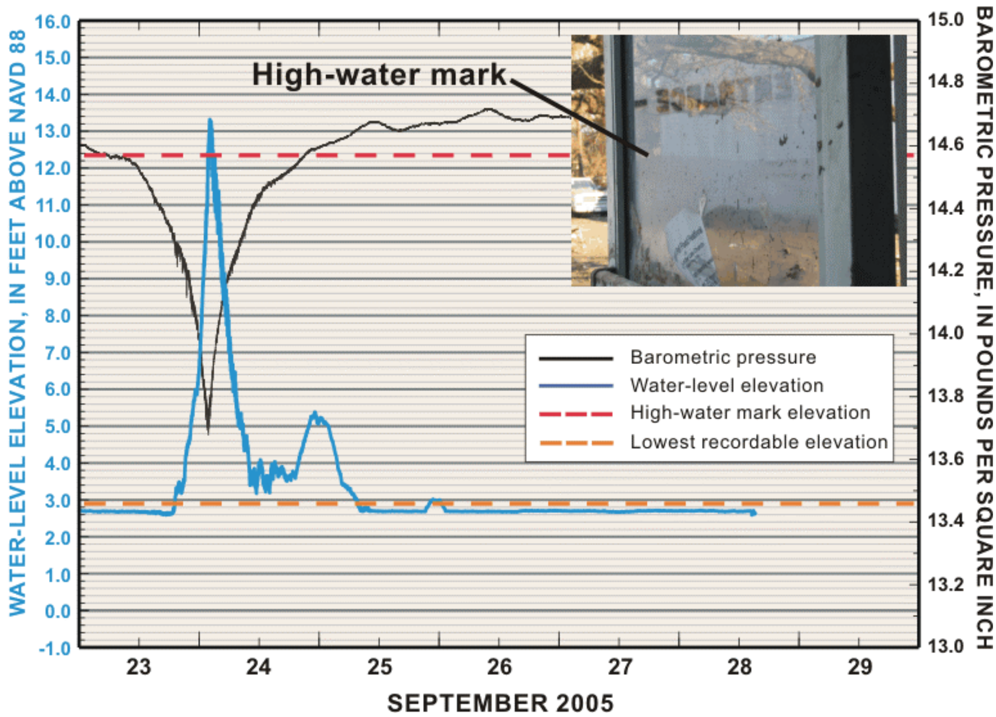


Figure 5. Example of Hurricane Rita storm surge data, along with a well-established high-water mark (from McGee *et al.*, 2006b).

(Berenbrock and Mason, 2008). One key finding from the data network was that high-water marks may underestimate storm surge heights by as much as 0.5 m, perhaps because the high-water marks are established as water is retreating to the ocean rather than during the initial surge.

3.2.2. *Remote Sensing Techniques*

For more than a decade, radar technology on board orbital satellites have been utilized to track, measure and monitor the ocean surface, including the wind, waves, and eyes of damaging hurricanes. Satellite altimeters provide indirect measures of ocean surface currents through monitoring sea level anomalies. The currents are then interpreted to generate a topographic map of the sea surface, which relates to wave height and direction. Ocean surface wave measurements were made from airborne Scanning Radar Altimeter (SRA) in tropical cyclones in 1998. At this time, wave heights, wave variations and direction of motion around the tropical cyclones were measured and provided near real-time estimates of wave height and storm surge at landfall (http://www.aoml.noaa.gov/hrd/hrd_sub/milestones.html).

Researchers from both the hydrodynamic and the remote sensing communities should work closely to have remotely sensed derived data not only for wave characteristics as an input into coupled model systems but also in support of determination for storm surge. The remotely sensed data can be used to fill gaps in the absence of sufficient in-situ data while hydrodynamic models outputs could be used to validate remotely sensed derived storm surge products. The new satellites missions, such as the Advanced Land Observing Satellite (ALOS), Sentinels, and the RADARSAT, in addition to their primary missions, are designed to address ocean tidal characteristics based on some of the concerns from researches (Johannessen *et al.*, 2006).

4. Storm Surge System Applications

A properly implemented, well-validated storm surge model can be used to simulate surge from historical, predicted, or hypothetical tropical cyclones. Each application has value in a different context, and the constraints of an individual project can define which modeling approach will be the most appropriate.

4.1. *Review and Status of Storm Surge Modeling Applications in the US*

4.1.1. *Forecasts*

It is common for predictions of a tropical cyclone to be made in order to provide information needed to implement emergency management measures such as evacuations. These predictions can be combined with hydrodynamic models to forecast storm surge. However, tropical cyclone storm surge is very sensitive to the bathymetry and topography of the ultimate landfall location. Equally important are the internal characteristics of the storms themselves — especially intensity and structure. Regardless of the model(s) chosen for calculating storm surge, their operational use presently is limited by the quality of the meteorological input. Better meteorological forecasts will result in better storm surge calculations. For example, cyclone landfall accuracy better than 20 miles at 36 to 48 hours in advance, along with intensity forecasts to within 10 mb central pressure deficit are needed to provide accurately useful storm surge calculations for evacuation purposes. Therefore, the most promising avenue for operational storm surge calculations useful for evacuations lies in improvements in meteorology.

Many national meteorological service agencies have implemented operational surge prediction systems for vulnerable regions. These model implementations provide guidance to forecasters and emergency managers about possible flooding conditions. For example, when a hurricane is threatening the US coast, NOAA's National Hurricane Center initiates storm surge predictions based upon forecast advisories it provides (Glahn *et al.*, in preparation). The following information is used to drive a parametric tropical cyclone wind model: (1) storm track to characterize location and forward speed, (2) radius of maximum winds to define the storm's size, and (3) the central pressure deficit, which defines the storm's intensity.

However, considering the importance of the tropical cyclone wind field in producing an accurate surge simulation, these storm surge forecasts are only valuable if the tropical cyclone prediction is accurate. The error in track prediction leads to a wide variation in distribution of wind speeds and thus possible surge predictions depending on where a storm makes landfall (Ginis, 1995). Similarly a tropical cyclone forecast of landfall 24 hours in advance has an error in track location that exceeds 113 km two-thirds of the time (National Hurricane Center, 2007). Considering a typical storm forward speed of 25 km/h, the time of landfall has an uncertainty of 4.5 h. Astronomical tidal conditions cannot be accurately predicted for landfall because of this uncertainty in timing. This makes it difficult to sequence surge simulations with astronomical tide forcing (Jelesnianski *et al.*, 1992). Therefore, it is difficult to combine surge and astronomical tide predictions in a forecast simulation. Instead, the tide level can be added linearly to the peak surge prediction once more confidence in land-falling time is gained; this approach is taken by US National Hurricane Center forecasts (Jelesniaski *et al.*, 1992). Finally, predictions of tropical cyclone intensity can be less reliable than track predictions, also enhancing surge forecast errors.

Emergency managers and first-responders still find forecasts of storm surge valuable, despite the uncertainty. One strategy under development for dealing with the inherent errors in tropical cyclone predictions is to implement a probabilistic forecast of surge based upon an ensemble of simulations (e.g., Graber *et al.*, 2006). A suite of possible tracks can be constructed based upon knowledge of the range of tropical cyclone prediction errors. These hypothetical tracks can vary the location, speed, size, and intensity of the predicted storm. This suite of possible storm conditions can then be fed into a storm surge model which produces the corresponding suite of results. From this output the distribution of risk can be inferred along the coast. One difficulty in this approach is that now instead of needing sufficient resources to complete one surge simulation; computational requirements increase several-fold so that all runs can be finished in a timely manner. However, an Australian forecasting system has implemented a hybrid approach that uses dynamic models to inform parametric probabilistic models that allow for variation of a wide variety of variables, such as track, size, and intensity (Systems Engineering Australia, 2005; Harper *et al.*, 2007). This method provides rapid computation and is well suited to regions where more sophisticated dynamical modeling is either unaffordable, impractical or the lack of accurate data (atmospheric, bathymetric or topographic) provides little improvement. Another challenge is communicating information about the resulting distribution of risk in a manner that can be easily understood and acted upon by emergency managers.

4.1.2. *Planning and Management*

Although forecasts of potential surge heights may be valuable in real time, emergency management plans such as evacuation routes must be in place well before the storm approaches in order to be effective. Therefore, characterization of the vulnerability from future storms is needed to guide these types of planning and management activities.

By generating a suite of possible tropical cyclone parameters that could affect a region, an atlas of possible storm surges can be produced from a storm surge model to guide planning. By varying important parameters such as track, size, and intensity, a complete set of hypothetical storms can be created. The output from simulations of these storms can then be compiled into useful tools that describe the distribution of risk across a region. In the US, NOAA produces maps of maximum surges generated by a specific class of tropical cyclones (e.g., Category 3 storms approaching from the south) for a specific impact zone. This map is called the Maximum Envelope of Waters (MEOW). A set of maps can then be referred to when developing evacuation plans or when a storm of similar characteristics is approaching land. For more detailed discussion of the implementation of this methodology, see Jelesnianski *et al.*, (1992).

While an atlas of possible storm surges is a useful planning tool for emergency management, it does not provide information about the probability of surge for each region. By combining a suite of potential storm conditions with statistical information about the likelihood of occurrence for these events, an understanding of flooding risk can be determined for coastal regions. This information can then be used to define insurance rates and building codes. In the US, the Federal Emergency Management Agency (FEMA) applies storm surge models to construct flood insurance rate maps according to the recurrence interval of potential tropical cyclones (Massey *et al.*, 2007).

4.1.3. *Coastal Engineering*

Storm surge simulations are needed for engineering design projects to predict the impacts of future storms. One significant example is in the design of hurricane protection systems, which need to simulate not only the potential surge height but also how it will be changed by proposed design projects. Along the US Gulf Coast many design projects are underway to restore barrier islands, dunes, and beaches as well as improve levee systems in order to reduce storm surge impacts in highly populated regions (e.g., see http://lacpr.usace.army.mil/). Considering the detail involved in designing these public works, it is common for very high resolution models to be utilized. Similarly, building standards are generally defined by the risk that exists from natural hazards within local areas. By computing the surge risk from a stochastically chosen set of storms, the potential likelihood of surge occurrence can guide implementation of building standards.

4.2. *Review of Recent Developments in Predicting the Storm Surges in the Bay of Bengal and Arabian Sea*

Storm surges are extremely serious hazards along the east coast of India, Bangladesh, Myanmar, and Sri Lanka. Although Sri Lanka is affected only occasionally by storm surge, tropical cyclones of November 1964, November 1978 and November 1992 caused extensive loss of life and property damage in the region. Storm surges affecting Myanmar appear to be much less intense than those occurring in India and Bangladesh. Notable storm surges, which have affected Myanmar, occurred during May 1967, 1968, 1970, 1975, 1982, 1992, 1994, and 2008. Of these, Nargis 2008 was the worst cyclone. Nargis generated storm surge in excess of 4 m near Ayeyarwady deltaic region. The entire deltaic coast of Myanmar was flooded with surges ranging from 1.5–4.5 m.

Of all the countries surrounding the Bay of Bengal, Bangladesh suffers most from storm surges. The main factors contributing to disastrous surges in Bangladesh are: (a) shallow coastal water, (b) geographical convergence of the bay, (c) large astronomical tides, (d) densely-populated lowlying islands, (e) favorable cyclone track, and (f) innumerable number of inlets including those in the world's largest river system (Ganga-Brahmaputra-Meghna). Detailed reviews of the problem of storm surges in the Bay of Bengal are given by Ali (1979), Rao (1982), Roy (1984), Murty (1984), Murty *et al.* (1986), Das (1994a,b), Dube *et al.* (1997, 1999, 2000a, 2006, 2009), Rao *et al.* (1997), Chittibabu (1999), and Gönnert *et al.* (2001),

Although storm surges are less frequent in the Arabian Sea than in the Bay of Bengal, major destructive surges occasionally have occurred along the Gujarat Coast of India and Pakistan. Storm surge only infrequently affects the Gulf of Oman, but there have been some cases when storm surge caused destruction along the coasts of Oman. The most recent example was the super cyclonic storm Gonu that struck Oman and caused about $4 billion in damages and 49 deaths (JTWC, 2007).

4.2.1. *Real Time Storm Surge Predictions System for the Bay of Bengal and the Arabian Sea*

In India, the study of numerical storm surge prediction was pioneered by Das (1972). Subsequently several workers attempted the prediction of storm surges in the Bay of Bengal (Das *et al.*, 1974; Ghosh, 1977; Johna and Ali, 1980; Johns *et al.*, 1981; Murty and Henry, 1983; Dube *et al.*, 1985a; etc.). Dube *et al.* (1994), Dube and Gaur (1995) and Chittibabu *et al.* (2000) developed a real-time storm surge prediction system for the coastal regions of India. Real-time storm surge prediction systems have also been developed for Bangladesh, Myanmar, Pakistan, Sri Lanka, and Oman (Dube *et al.*, 2004; Jain *et al.*, 2006 a, b; Rao *et al.*, 1994; and Chittibabu *et al.*, 2002).

The national meteorological and national hydrological services of many countries surrounding the North Indian Ocean have achieved some success in providing storm surge warnings and implementing improved models through cooperative and coordinated sharing of responsibilities. Much of this work is done within the framework and overall guidance and supervision of the Tropical Cyclone Programme (TCP) of the World Meteorological Organization (WMO). The TCP of WMO supported technology transfer to run and operationalize storm surge models for Bangladesh, Myanmar, Oman, Pakistan, and Sri Lanka from the Indian Institute of Technology (IIT)-Delhi/Kharagpur.

The forecasting system developed at IIT Delhi is based on the vertically-integrated numerical storm surge models that were developed by the group (Johns *et al.*, 1981, 1983; Das *et al.*, 1983; Dube *et al.*, 1985a,b). The model is fully nonlinear and is forced by wind stress and uses a quadratic bottom friction formulation. The nonlinear advection terms in the model were found to have a significant effect on the simulations, especially in the shallow coastal waters of the head Bay of Bengal. Therefore, although the numerical solution of these terms affects the computational speed of the model, the nonlinear terms must be included in the operational model in order to provide the best forecasts. The details of the model and the numerical solution procedure are described in Das *et al.* (1983) and Dube *et al.* (1985b).

Surface winds associated with a tropical cyclone are derived from a dynamic storm model of Jelesnianski and Taylor (1973). The only meteorological inputs required for the model are the positions of the cyclone, pressure drop and radii of maximum winds at any fixed interval of time, and the model can be run in a few minutes on a PC in an operational office. The system is operated via a terminal menu and the output consists of the peak sea surface elevations and currents. One of the significant features of this storm surge prediction system is that the meteorological input needed for surge prediction can be periodically updated with the latest observations and forecasts of national weather services. The model has extensively been tested with severe cyclonic storms.

4.2.2. *Location-Specific Models*

The evolution of storm surges near the coast is known to be very sensitive to the coastal geometry and offshore bathymetry at the location of the landfall of the cyclone. As a result, operational models should include these factors as accurately as possible. This means that in addition to the large-scale storm surge prediction models, operational offices should also use high-resolution location-specific models for accurate prediction of the surges. Based on this need for location-specific models, Chittibabu (1999), Chittibabu *et al.* (2000, 2002); Dube *et al.* (2000b, 2000c; 2004) and Jain *et al.* (2006a, b) have developed location specific high-resolution models for the Andhra, Orissa, Tamil Nadu, and Gujarat coasts of India, and for Bangladesh, Pakistan, Myanmar, Oman and Sri Lanka, following an approach similar to that of Dube *et al.* (1994). An important feature of each of these location-specific models is that they use accurate and highly-detailed bathymetry for the offshore waters. A simple wetting -drying scheme also has been included in the models in order to avoid the exposure of land near the coast to strong negative surges. The reliability of these models has been tested using data from several severe cyclones, which struck the coastal regions of the countries in the Bay of Bengal and the Arabian Sea. The following sections describe results of selected numerical experiments carried out using location-specific models to simulate the surges.

4.2.2.1. Myanmar: Mala cyclone (May 2006)

Peak storm surge of about 4 m was reported for the May 2006 Mala cyclone on the Myanmar deltaic coast near Gwa by the Department of Meteorology and Hydrology, Yangon. The simulated surge contours (Fig. 6) show a maximum surge of 3.6 m to the right of the landfall point near Gwa, and the peak surge at Pathein is about 2 m. The coast from Ye to Moulmein also was affected by surges of 1 to 2 m.

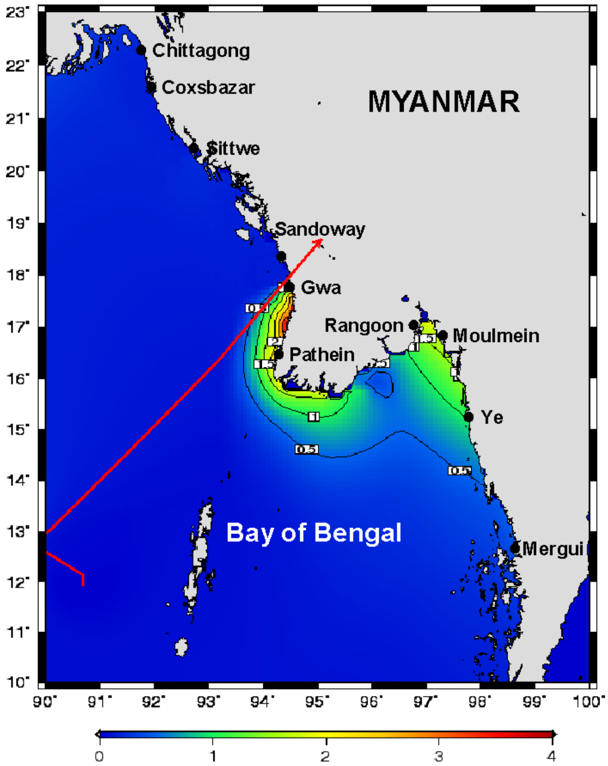


Figure 6. Simulated peak surge envelope for the May 2006 Mala cyclone (after Dube *et al.*, 2009).

4.2.2.2. Sri Lanka: Rameswaram cyclone (December 1964)

The December 1964 Rameswaram cyclone was one of the most severe storms to have affected Sri Lanka and the southern Indian peninsula. The simulated maximum surge of about 5.4 m occurred near Tondi (Fig. 7). Heavy inland flooding in the region, with an estimated peak elevation of about 5 m was reported by Rao and Mazumdar (1966), which is in good agreement with the simulations. It can also be seen from the figure that the coastal region to the north of Mannar Island along the west coast of Sri Lanka was flooded with a surge of more than 4 m.

4.2.2.3. Oman: Gonu cyclone (June 2007)

Simulations for the June 2007 Gonu cyclone were made using a pressure drop of 98 hPa and radius of maximum wind of 40 km (Fig. 8). A maximum surge of 2.6 m was simulated to have occurred near the eastern tip of Oman, which is where the storm was nearest the shore. Peak surges of about 2.6 m and 2.5 m were simulated at Sur and Nazwa Fins, respectively. The peak surge value at Muscat was around 2 m. About 100 km of the coast in northeastern Oman was flooded with surges of about 1 m. The computed maximum surge value of 2.6 m is comparable with the estimated range of surge heights.

4.3. *Review of Recent Developments in Predicting Storm Surge in Australia*

Australia has an extensive tropical coastline that is regularly impacted by severe tropical cyclones (TCs) and, in spite of its sparsely settled population, has recorded significant storm tide impacts dating from the late 1800s.

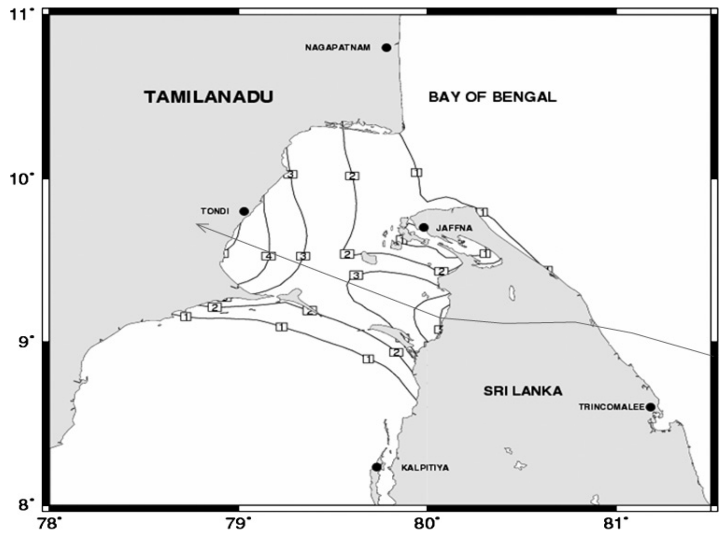


Figure 7. Simulated peak surge envelope associated with the December 1964 Rameswaram cyclone (after Dube *et al.*, 2009).

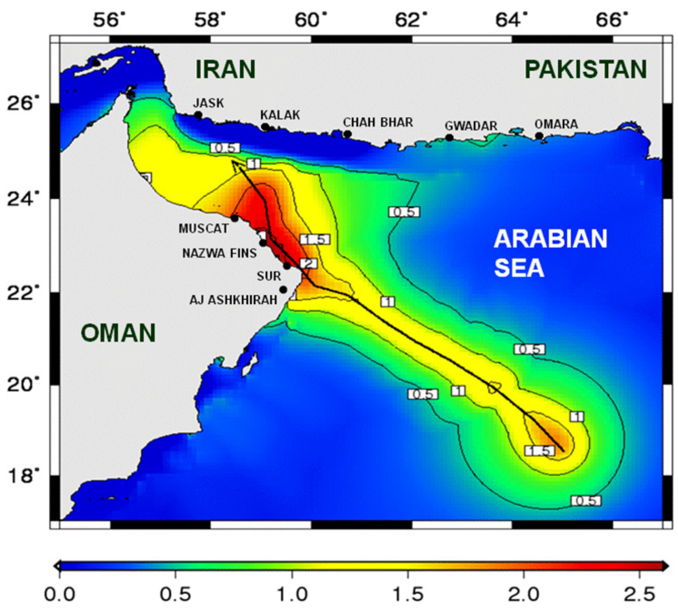


Figure 8. Simulated peak surge envelope associated with June 2007 Gonu Cyclone (after Dube *et al.*, 2009).

Accordingly there has been a history of development of storm surge modeling, risk assessment and associated atmospheric modeling capabilities since the availability of significant computational power in the 1970s. This work has focused on the east coast of Queensland (Harper, 1999) where TCs occur along a settled and rapidly developing coastal margin, much of which is bounded by the Great Barrier Reef (GBR). The most intense TCs in Australia are observed in the northwest of Western Australia, although the population there is relatively sparse and storm tide studies have been typically limited to specific towns or industrial facilities. This brief summary follows Harper *et al.* (2007).

4.3.1. *Queensland Climate Change Study (QCCS)*

This refers to a number of investigations undertaken over the period 2000 to 2004 that were funded primarily through Government enhanced-greenhouse research allocations. The initial work (Harper, 2001b) was conducted by Systems Engineering Australia (SEA) in association with the James Cook University Marine Modeling Unit (JCU-MMU) and others. This initial reference sets out recommended methodologies for storm tide studies that would also be capable of addressing climate change (enhanced-greenhouse) issues within the context of tropical cyclones. Importantly, a holistic approach was advocated for identifying the physical forcing mechanisms, ocean responses, vulnerabilities and impacts that would lead to informed decision making and the long term mitigation of storm tide threats. Subsequent studies conducted principally by JCU-MMU provided updated TC-induced surge plus tide updates for selected east coast sites, all with and without allowance for predicted enhanced-greenhouse effects by 2050. This work was done using the JCU-MMU storm surge, wave, and TC wind field models that had been extensively calibrated over many years. The extent of the numerical 'A' and 'B' modeling domains is shown in Fig. 9, covering some 3500 km of coastline and completely enclosing the Great Barrier Reef at spatial resolutions of 13.9 km and 2.78 km respectively. A further 20 'C' model domains were nested within the 'B' domains at 0.55 km resolution. A series of demonstration hindcasts of significant historical storms indicated that peak surge levels were likely reproducible within 5% of measured values provided that adequate meteorological and bathymetric data was available. An example of one such event, Severe Tropical Cyclone *Althea* in 1971, is shown in Fig. 10.

4.3.2. *Local Coastal Inundation Studies*

In addition to the State-wide QCCS described above, coastal Local Government regions in Queensland have been active in assessing storm tide risks for the purposes of updating local planning levels in response to enhanced-Greenhouse and for emergency response. Local

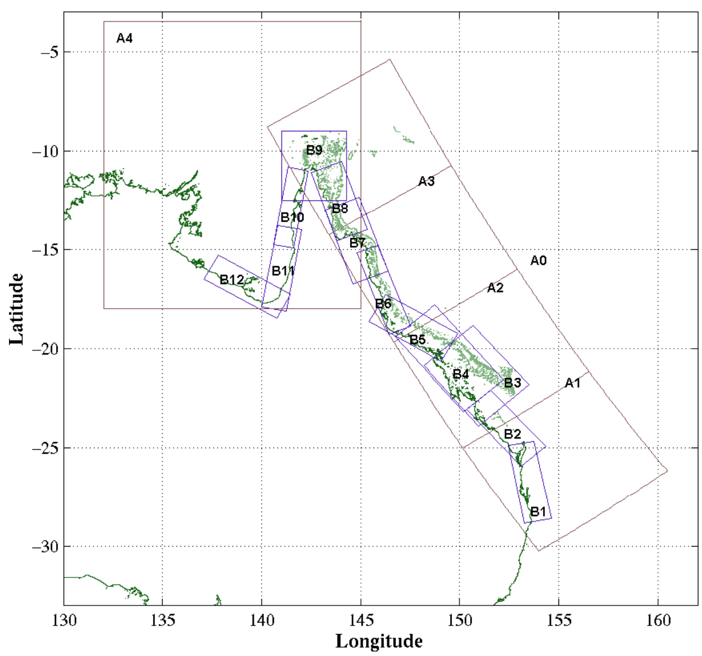


Figure 9. Queensland climate change 'A' and 'B' numerical domains (after Harper *et al.*, 2001b).

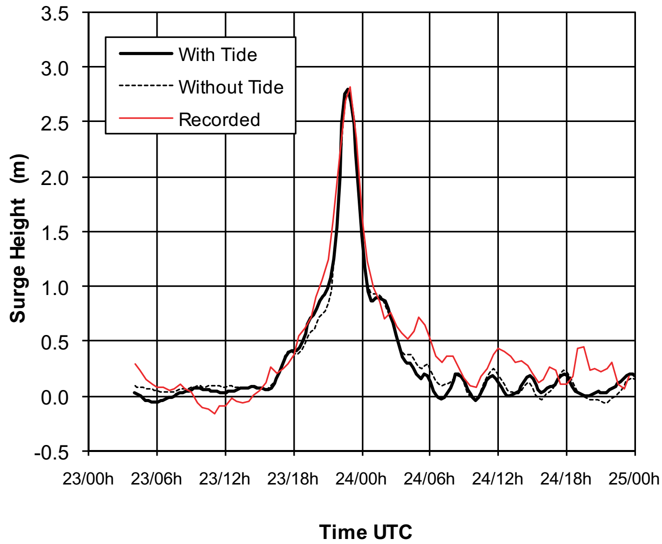


Figure 10. Measured and modeled surge component at Townsville Harbour for *Althea* (1971) (after Harper *et al.*, 2001b).

inundation studies are typically conducted at spatial resolutions of 50 m or finer, depending on the available topographic data and the need for representation (e.g., Fryar *et al.*, 2004). Many such studies have adopted a methodology similar to that described as the "hybrid" approach recommended in Harper (2001b). To achieve this, a parametric storm tide model (surge and wave) is developed based on comprehensive hydrodynamic model parameter response mapping of the study region. The parametric model then provides an economical kernel for Monte Carlo simulation and a flexible test bed for sensitivity testing of a range of model assumptions, El Niño Southern Oscillation (ENSO) or climate change influences. Water level persistence and joint probabilities of surge, tide, wave height and period are also available from these types of studies.

4.3.3. *Coral Atoll and Reef Environments*

Coral atoll and fringing reef environments can present with significantly different vulnerabilities from the typical continental margin environments described previously and require consideration of concurrent non-linear tide, surge and wave interactions. The principal threat of inundation in such low lying environments is due to extreme water levels on the outer reefs due to the combined effects of the pressure deficit component of a storm surge acting coincidentally with a high tidal level and high wave setup, caused by wave breaking on the outer reefs and reef entrances. Breaking wave setup can be expected to be the dominant water level controller with magnitudes as high as several meters. Wind-stress induced storm surge setup is small because of the surrounding deep ocean environment but potentially more significant in some parts of shallow lagoons.

Because of the complex non-linear interactions of storm surge, tide and breaking wave setup, a statistical simulation methodology is again advisable and a combination of parametric surge, wave and wave setup models have been used successfully within a Monte Carlo driven TC climatology (e.g., Harper *et al.*, 2001a). The method has been validated against historical events and delivers sequences of time-varying water level components that would be generated during a severe tropical cyclone event, with breaking wave setup on the outer reef flats and local wind stress influencing the shallow lagoon regions. Both these effects are critically modulated in a non-linear fashion by the stage of the tide.

4.3.4. *Storm Tide Warning Systems*

One of the aims of the QCCS was to develop self-consistent methodologies for both mitigation/planning and forecast/warning applications that could be efficiently developed and deployed to provide coverage over large sections of coastline. The proposed "hybrid" approach, a combination of detailed deterministic hydrodynamic modeling and derived parametric models, satisfied these criteria by providing a self-consistent framework for long term climatology modeling and short term warning needs. This method differs from the static Maximum Envelope of Waters (MEOW) approach in that it provides a rapid response tool that can incorporate tidal variation and storm parameter uncertainty.

Based on these recommendations, the Bureau of Meteorology (BoM) in Queensland subsequently adopted this approach in developing a parametric surge model for the east coast that would augment their existing access to real time hydrodynamic modeling. This provided a significant benefit in operational flexibility and also in training of forecasters, who could quickly examine and test a range of forecast scenarios. Importantly, this approach recognizes that the greatest uncertainty in the storm tide forecast relates to the variability of the forecast meteorological parameters. This is especially relevant to the vast majority of tropical cyclone forecast centers around the world that do not have aerial reconnaissance capability, where the Dvorak satellite image interpretation method is the primary intensity forecast tool. Even with the rapid development of advanced atmospheric models this situation is unlikely to change significantly within the next few decades.

The Northern Territory BoM engaged SEA in 2005 to provide a turnkey parametric storm tide forecasting system that incorporates tidal prediction, storm surge, waves and wave setup for the entire northern Australian coast from the Gulf of Carpentaria west to the Kimberley region in Western Australia. Figure 11 shows the area that was comprehensively modeled using seven along-coast domains, each of about 400 km extent, to provide the basis for the necessary

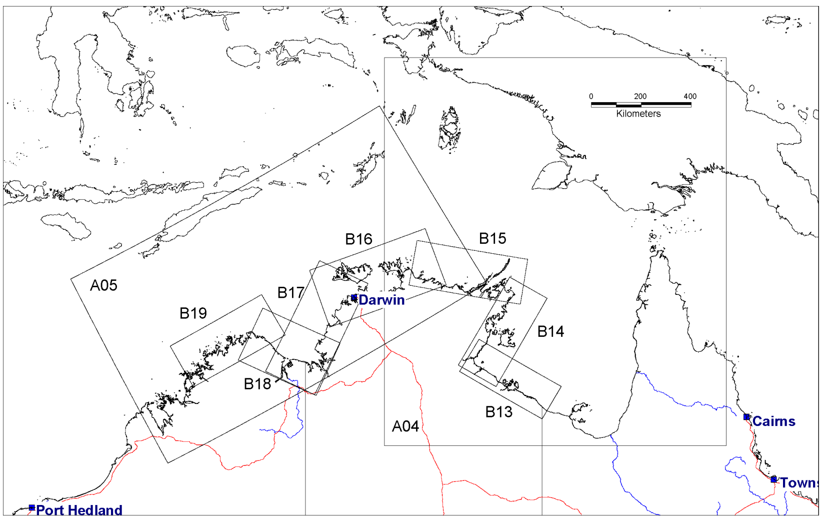


Figure 11. Extent of the Northern Territory storm tide warning modeling system (after Harper *et al.*, 2007).

parametric models. Approximately 25,000 individual TCs were modeled as part of this development and storm tide predictions are available for over 1,000 named localities. However, the resulting parametric prediction model SEAtide can generate more than 100 probabilistic storm tide forecasts within one minute on a typical desktop computer.

5. Future Development

Extensive storm surge modeling applications have been made with existing modeling systems. These efforts have been extremely valuable in reducing the damages caused by extreme tropical cyclones by provided emergency managers with reliable planning tools. However, there are many issues where future development is needed to further decrease the potential for loss. A brief discussion follows, including some of the main issues that are outstanding or under development by the research community.

5.1. *Improved Hurricane Forecasts*

The most important factor affecting the accuracy of a storm surge model is the forcing; that is, the ability of a tropical cyclone model to construct realistic wind and pressure fields. Since the most significant improvement in storm surge forecasting depends on improvements in predicting tropical cyclones, particularly for track and intensity, surge simulations are critically dependent on the accuracy of these storm characteristics. Without confidence in tropical cyclone forecasts, storm surge models have limited use for prediction.

5.2. *High Quality Bathymetry and Topography*

The most significant factor affecting model skill besides meteorological forcing is the accurate description of geographic features in the model grid. These errors can be minimized by careful grid construction and inclusion of sub-grid scale features in the model, but this depends upon the quality of the geographic data. Coordinated collection of high-resolution topographic and bathymetric data, especially LiDAR datasets, is needed to accurately model coastal inundation. Furthermore, vertical datum transformations are essential for combining coastal geospatial data. Elevations that are referenced to inconsistent vertical datums can cause artificial discontinuities in model grids, especially at the coast. Therefore, the capability to transform coastal elevations to a common datum is crucial for developing the geospatial infrastructure for the coastal zone. Finally, the creation of seamless elevation datasets (such as Digital Elevation Models) for storm surge model development would enable accurate grid construction.

5.3. *Air-Sea Interaction*

The interaction between the wind, sea surface and water column is not well understood, particularly at hurricane wind speeds. What is required is an accurate description of the physics of momentum transfer from wind to waves to water column. However, data used to parameterize wind drag coefficient relationships is difficult to collect and is nearly non-existent from tropical cyclones. Research indicates that the assumption of a linear increase in surface stress may not apply at hurricane strength winds (Powell *et al.*, 2003). Furthermore, wind drag laws are developed under the assumption of open marine conditions, but increased roughness is likely to exceed these conditions in nearshore and overland conditions. Surface waves also affect air-sea interaction; this is especially true as waves break and inundation occurs, since roughness increases and becomes more localized. Further research is needed to characterize air-sea interaction under tropical cyclone conditions.

5.4. *Observations of Surge*

There is a shortage of comprehensive data available to evaluate storm surge simulations.

Observations of water levels during hurricanes are not extensive. Gauges are not widespread and are often destroyed during severe events. Post-storm HWM surveys are unreliable because of the difficulty in collecting accurate data and are not done for all storms. Therefore, there is an important need for expanded and coordinated collection of water level data from tropical cyclone systems. A network of gauges that are hardened to survive strong storms and collect data throughout is needed. Furthermore, this permanent network should be augmented by a suite of temporary pressure gauges installed in the path of a storm, as done in the US for Hurricane Rita in 2005 (McGee *et al.*, 2006b). Third, post-storm collection of HWMs should be systematically completed and archived. Fourth, all water level observations need to be accurately tied to a geodetic network so that a common vertical datum can be used for both model output and observations.

5.5. *Communication of Uncertainty*

There is inherent uncertainty in tropical cyclone forecasting and corresponding predictions of surge. However, users of such products need estimates of this uncertainty in order to guide decision-making processes. Development of probability distributions of storm forecasts will be increasingly required, created by an ensemble of simulations whose results need to be combined in a fashion that communicates risk appropriately.

5.6. *Improved Model Accuracy and Efficiency*

Although there is a large number of storm surge models available in the community, there are still outstanding needs to improve model accuracy by including additional physics and increasing resolution. For example, surge water levels are affected not only by wind and pressure fields, but also by tides, waves, river inflow, precipitation, and erosion, factors that few if any models comprehensively consider. Conversely, it is important that the high-resolution models being implemented run quickly in order to satisfy the large suites of runs required for probabilistic forecasts, creation of storm surge atlases, and calculation of historical flooding probability.

5.7. *Wave Modeling*

One of the predominant effects of a tropical cyclone is the large wind waves generated by the storm, which affect the storm surge in a number of ways. While research and development is ongoing into coupling surge and wave models (see section 2.3.3), many systems are lacking a full description of the physics that occurs. A wind wave model will provide wave radiation stresses which drive wave-current interaction and increase storm surge height. Furthermore, wave-current interaction modifies the bottom friction stresses in shallow areas, increasing the bottom friction as the wave height increases. Finally, the wave model describes the conditions of the sea state as the hurricane travels from offshore to land, enabling improved description of the drag coefficient based upon sea state.

5.8. *River Forecasting*

There are important interactions between rivers and the coastal environment during tropical cyclones. While the flooding caused by rainfall generally occurs after the surge conditions have passed, the occurrence of multiple storms in succession requires the accurate knowledge of river inflow and water levels to accurately model surge throughout an estuarine system. Inclusion of river inflow and precipitation can address these issues.

5.9. *Coastal Geomorphology*

Future focus is needed on study of geomorphological changes that can occur during surge events, as these can be important in defining the volume of water that passes over an eroding barrier island, for example. The present state of sediment transport models is generally not sufficiently development to consider these conditions. Sediment transport models are needed that accurately predict the time rate of change of the coast, and especially dune systems, under the effects of waves and surge from a tropical cyclone.

5.10. *Decision-Support Tools*

Increased utilization of surge model output can be made by providing it in GIS formats and combining it with other data layers. This leads to easily utilized maps and visualizations, and enables incorporation of socioeconomic and demographic data with model output. This enables decision makers to evaluate risks in a more thorough manner.

5.11. *Community Approach*

Improvements in storm surge modeling benefit both the public and private sector. When there are advancements in the knowledge and prediction of storm surge impacts, appropriate mitigation steps can be taken to minimize losses. A community approach to model development that shares the funding burden as well as the benefits of research and development advances all interests. A community approach is one where both resources and developments are shared across all model users, whether government, academic, or private. It allows all members of the community to benefit from the advancements that are made so that the state of the technology is continually moving forward. This strategy enhances both research and applications by allowing researchers to focus on making scientific improvements without having to recreate the larger set of technology needed to support such work, and facilitating operational application of developments which improve skill and further the use and value of a model. Therefore, a community approach streamlines the research to operations pathway by sharing common technology. It also promotes uniformity of techniques which enhances reliability, and it provides the best leverage of limited funding. Open sharing of data, tools, models, and approaches increases the value and reliability of the system as a whole. Leadership from the public sector is necessary to support a community approach as they are the major provider of storm surge mitigation strategies and they develop and implement relevant technical standards.

One major benefit of a community approach is a standardization of terminology that increases understanding of storm surge threat in the user community. It avoids confusion caused when federal agencies provide information described in a multitude of ways; uncertainty about differences in technical language has confused the public in the past.

A community approach does not mean that a single model is selected for use by the community. Different models will likely continue to be advantageous for specific applications. Rather, it establishes an infrastructure that enables developments to be shared across models. Tools such as standards and documentation will enable technology advancements to benefit the community at large.

Finally, an open, coordinated forum for a community approach to modeling can provide standards and regional test beds can be used for model comparisons which will guide future applications. This will enable the community to select an appropriate model implementation for specific applications.

6. Integrated Modeling in Coastal Areas

Generally, it takes a long time for riverine flooding to reach the coast, whereas storm surges are roughly coincident with landfall. However, high river flows occurring simultaneously with storm surge likely will have adverse impacts on coastal inundation. The discussion below will refer to coupling of river flow and coastal hydrodynamic models to address potential coastal inundation.

6.1. *Hydraulic and Storm Surge Model Coupling*

Most of the studies reviewed address models that forecast either storm surge or river flow, but few studies have described the coupling of both inland flood and storm surge models for forecasting purposes. Even though in most cases, surge and river flooding occur separately, with storm surge coming at time of land-fall and river flooding occurring later. There are situations when both effects might co-exist and setup a severe flooding situation. This was experienced in 1999, when Hurricane Floyd affected the East Coast of the United States. Not only Floyd's storm surge was affecting coastal areas of North Carolina but also torrential rainfall occurred in an area hit by Hurricane Dennis just weeks earlier. Rivers were already in flood by the time Floyd made land-fall. In the USA, coupled systems using 1-D models are operational for several coastal rivers and some of them were utilized in pilot projects for generation of inundation mapping in real-time. Reed and Stucky (2005) described the application of the NWS Dynamic Wave Operational Model (DWOPER) on the lower Ohio/Mississippi Rivers to the Gulf of Mexico. This model uses the Sea, Lake, and Overland Surges for Hurricanes (SLOSH) water level forecasts as the downstream boundary. Brown *et al.* (2007) recently described "the first attempt to model storm surge flooding of an urban area with 2-D hydraulic model and to explore the uncertainties associated with model predictions" for the Canvey Island, UK.

In order to accurately reproduce the passage of a flood wave through a river reach, the responses (water level, flow, velocity) are simulated using unsteady-state hydraulic models. Many hydraulic models are available to simulate water levels and river flow, but the local site characteristics might require specific model capabilities. Low-lying coastal estuaries are complex hydrodynamic systems that often require 2-D models for accurate simulation, and the 1-D approach may not be appropriate. Issues of computational grid resolution must sometimes be addressed during the coupling process. For example, if the downstream boundary of the 1-D hydraulic model includes multiple surge model computational cells, then averaging of surge elevation across the hydraulic model boundary may be required. Likewise, in the case of a 2-D depth-average hydraulic river model, the downstream boundary will likely include multiple river cells which must be linked with one or more surge model computational cells, again requiring some averaging or smoothing across the boundary. The Tar River example discussed below illustrates this issue.

The Tar River, North Carolina, USA, was modeled using the 1-D NWS hydraulic model called Flood Wave (FLDWAV) and coupled with a tidal model (Riverside Technology, Inc., 2006). The lower river reach of the Tar River is described as follows (p. 8):

> "The Tar River drains into the Pamlico Sound, which also receives flow from several other rivers in North Carolina. The Sound is protected by a series of barrier islands with a number of inlets through which tidal influences are transmitted and hydrologic inflows drain to the Atlantic Ocean. Tidal influences predominate in the determination of water levels in the Pamlico Sound and have a strong influence on stages in the Tar River as far upstream as Greenville under normal flow conditions and as far as Rock Springs under very low flow conditions."

This is an example in which the use of a 1-D hydraulic model might be inadequate for simulating conditions near the Sound; a 2-D model might be more appropriate for simulating flood and storm surge in the estuary. However, because of operational constraints it was modeled using a 1-D model.

Following selection of the hydraulic and tidal models, the general approach for simulating the coupled surge-inland flooding response of the river system includes: (i) selection of river-reach boundaries, type and location; (ii) collection of cross-section geometry to build the channel and flood plain geometry for the hydraulic model, and (iii) determination of local flows using data or previously-developed hydrologic models. The upstream boundary of the model reach is usually defined by a time-series of flow; the water-level time series for the downstream boundary will be provided by the surge model. This rather simplistic approach might become cumbersome when considering operational implementation. Data demand for research and model development is usually confined to historical data for calibration. Real-time operations require either observed or forecast information on rainfall, a forecast inflow hydrograph, and forecast surge elevations derived from a surge model driven by meteorological forecast.

Issues to be considered for the hydraulic/tidal coupling include:

1. The calibration period should be selected to ensure there is enough data for all the time series required by the model system. In addition, the period selected should include a wide range of river flows (low, medium and high flows) and minor, medium and major surge effects.
2. The forecast window for individual models (including the hydrologic and meteorological models) must be examined to define the window for the coupling system and to ensure that data from each model is available as needed by the dependent models.
3. The time interval for the system coupling must be selected based on the minimum allowed to describe the process while maintaining feasibility of model execution for forecasting purposes. For example, in the USA most of the operational models used to forecast river flow are performed for incremental periods between 1-hour and 6-hours. Storm surge models can produce output for time increments on the order of a few minutes. However, because the forecast system architecture might be too rigid and because of operational limitations for execution of the hydraulic models, the coupling is performed in hourly increments.
4. Consistency of reference datums is essential for the accuracy of results. This includes vertical and horizontal datums for cross sections, water levels, and tide gages.
5. Consistency of boundary conditions must be maintained for situations in which multiple river computational cells (2-D hydraulic model) coincide with a single surge model cell. Multiple iterations between the hydraulic and estuarine models might be required.
6. Continuous execution of the coupled system ensures that the models are initialized correctly, but this might not be possible for a situation in which a surge model is not run continuously and no downstream real-time tidal data are available.

A coupled system for St. Johns River, Florida, USA has been in operation since 2001 (Fig. 12). The US NWS Southeast River Forecast Center (SERFC) is currently forecasting water levels in the lower end of the St. Johns River near Jacksonville using the NWS hydraulic model FLDWAV. The model is executed for a 300-mile reach; the upstream boundary (flow hydrograph) as well as the local inflows from tributaries is derived from the hydrological model Sacramento Soil Moisture Accounting. The downstream boundary selected is the tide gage located at Mayport at the mouth of the river near Jacksonville, Florida. A forecast window of 5 days is used.

The time series for the water level at the downstream boundary are composed of the observed water level up to the forecast time. For the forecast period, the astronomical tide forecast provided by the National Ocean Service (NOS) is combined with the output from the

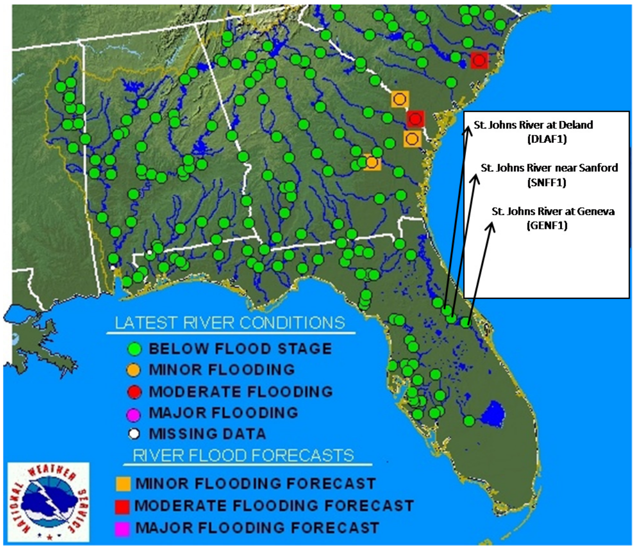


Figure 12. St. Johns River, Florida, USA. The river flows from South to North.

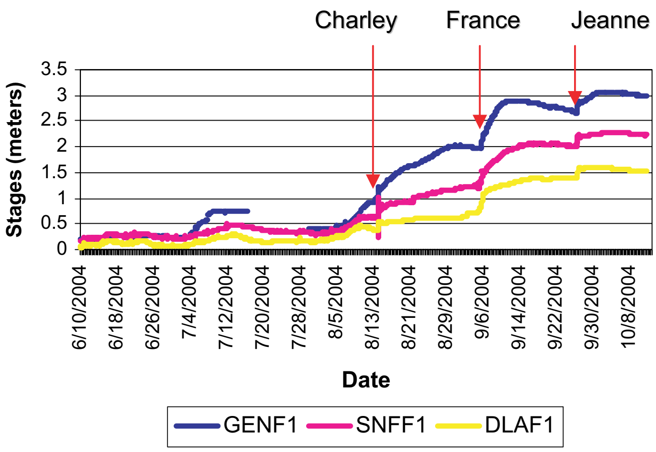


Figure 13. Water levels in St. Johns River during 2004 hurricane season (Charley in August, Frances and Jeanne in September).

Sea, Lake and Overland Surges from Hurricanes (SLOSH) model. The NWS developed blending techniques to correct the downstream water level once observed data becomes available

The 2004 hurricane season provided insight on the performance of the hydraulic model. Three hurricanes affected this area: Charley, Frances, and Jeanne (Fig. 13). Rainfall produced by these systems affected the water levels in the St. Johns River. Water levels were low at the beginning of August, and the rainfall associated with Hurricane Charley produced a significant rise, but it wasn't until the passage of Hurricane Frances that the rises reached flood stage and remained above flood stage until the beginning of November 2004.

During the operational performance of the system, the wind acting on the river reach was observed to greatly influence the propagation of the surge and forecasts of water levels. The jump in water levels due to wind effect (Fig. 13) was more noticeable at the station of Deland

(DLAF1) when Charley affected the area and the river was at low levels. The hydraulic model, used by the NWS at that time, (FLDWAV) had the capability to incorporate wind direction and magnitude as a single value for the whole reach, but this is not practical for the entire 300-mile reach. As a result, wind effects on the river are not included in the coupled system. The NWS is in the process of incorporating this variable into the hydraulic modeling.

6.2. *Inundation Mapping*

Several countries are working on projects involving potential inundation mapping. In China, the production of flood maps has been in practice since 1986. Today all available Flood Hazard Mapping are being posted on the internet (WMO Draft Report, Typhoon Committee, Macao, Republic of China, 2006). A pilot project in the Philippines produced a preliminary flood hazard map of flood-prone areas in the San Juan River Basin. Flood maps were produced for Kuala Lumpur in Malaysia, as well as maps showing minimum, moderate, and severe flooding for the Gomback basin. Most of the mapping projects mentioned above involved steady-state models for the generation of static-map libraries of inundated areas at different water levels. Maps from these libraries are then called up for application based on water-level forecasts.

6.2.1. *Development in the USA*

Inundation maps are based on predictions of water levels along the river reach and the corresponding terrain information. The whole process to determine inundation mapping in coastal areas due to topical cyclones involves meteorological forecasting (storm tracking, intensity, and precipitation totals), oceanographic, estuarine, and riverine hydrodynamic modeling (including wave effects), watershed modeling of storm runoff, and spatial mapping of inundation (Fig. 14).

In addition to forecasts of surge timing and height, flood inundation maps are increasingly being requested by emergency managers and decision makers. Maps are needed not only of coastal storm surge, but also inland flooding resulting from high rainfall associated with cyclones. In the USA, since the NWS instituted a program to model tropical cyclone

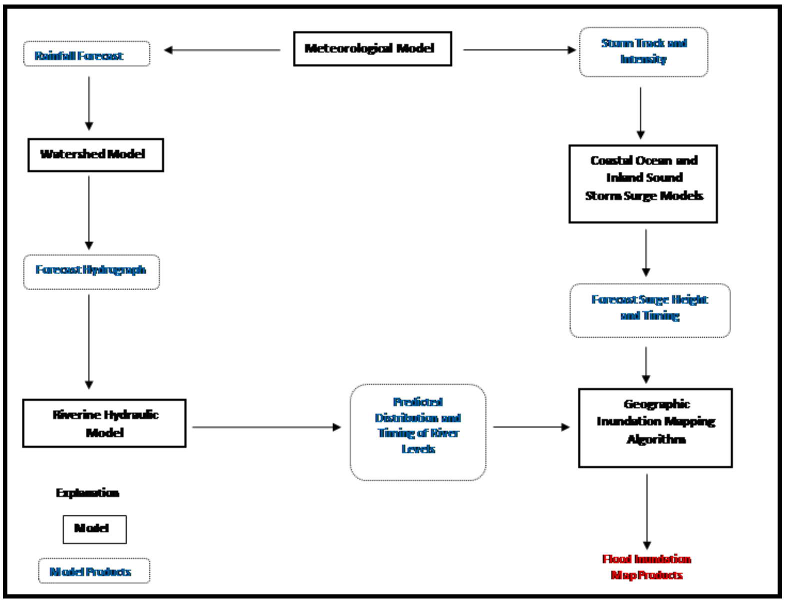


Figure 14. Suite of models required to simulate inundation from storm tides and upland flooding.

storm surge, more fatalities occur from inland flooding resulting from tropical cyclones than from storm surge (not including statistics from Hurricane Katrina), although this is not the case in all areas of the world. Flood inundation maps are useful in advance planning, as well as for response during events and for post-assessment after events.

In the USA, after Hurricane Floyd (1999) the State of North Carolina began a project to generate maps depicting inundated areas. This was the first NWS project involving the generation of inundation map libraries for a river reach (Fig. 15). The graph below is a representation of flood inundation for NWS flood categories. These maps are based on steady-state

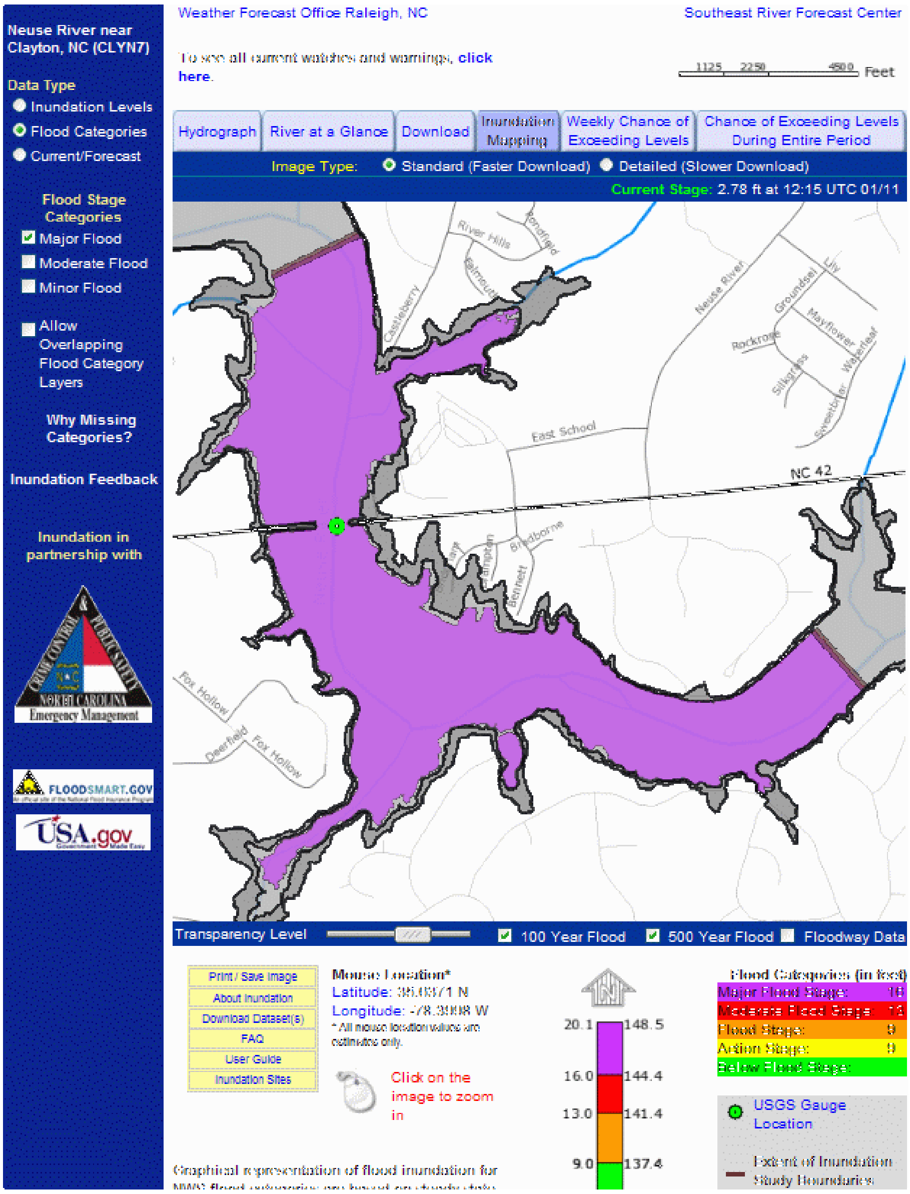


Figure 15. Inundation map for the Neuse River near Clayton, North Carolina, USA. (http://newweb.erh.noaa.gov/ahps2/inundation/inundation.php?wfo=rah&gage=clyn7)

hydraulic modeling of water surface elevations for incremented discharges.

The alternative to the use of the steady-flow assumption and development of inundation map libraries is to estimate inundated areas in real time during, or immediately prior to, a flood so that the particular characteristics of the rainfall and flood hydrograph are well represented in the hydraulic modeling. The limitation of this approach is that the models must be executed in real time for each event and that results must be distributed quickly to emergency management officials and all other interested parties. Moreover, there will be some uncertainty in the forecast flows for which the inundation modeling is to be conducted. A recent pilot project in the USA to test and evaluate dynamic mapping concluded that ongoing efforts in static mapping should be fully tested and evaluated before embracing implementation of operational, real-time (dynamic) inundation mapping (NWS, Office of Hydrologic Development, R-Time Report, 2007, in review).

Several approaches have been taken to develop inundation maps and include: (i) assuming that a storm surge of a given height will inundate or impact up to that height of the land contour, (ii) pre-generating a library of maps for a range of water levels (static maps), and (iii) generating inundation maps from real-time forecasts of water level (dynamic maps) based on unique features of a given event. Although dynamic mapping might seem the best option, implementation can be difficult and costly.

An example of static maps is presented by Bales *et al.*, 2007. He generated a set of water-surface profiles at 0.305 m (1 ft) increments for a reach of the Tar River. Based on the water-surface profile, a water-surface elevation was assigned to each cross section in the reach; the water surface was assumed to be level across the cross section, which is consistent with the 1-D modeling approach. Water-surface elevations between cross sections were estimated using a spline interpolation. Inundated areas were identified by subtracting the water-surface elevation in each grid cell from the land-surface elevation in the cell. An automated procedure was developed to identify all inundated cells that were hydraulically connected to the cell at the downstream-most gauge in the model domain. This process resulted in a set of inundation map libraries for each modeled reach. Inundation polygons were merged with a variety of other geospatial data to provide information for flood mitigation and emergency response.

At this time, the NWS does not use 2-D hydraulic models for operational purposes, so tests and pilot projects developed for dynamic maps have mainly focused on areas for which the 1-D approach is valid or can be approximated. However, in one of the pilot projects, St. Johns River, Florida there was an opportunity to test the coupling by using the 1-D hydraulic model to generate flow outputs which in turn were used as inputs for a 2-D estuarine model. The estuarine model was also used to forecast salinity and temperature.

Currently, the USA's strategy is to develop static maps for flood-prone areas and gradually develop hydrodynamic models for estuaries to provide real-time flood maps. The increased demand of probabilistic inundation maps by emergency managers is being recognized, but the need for developing operational procedures remains, including priorities for addressing mapping uncertainty.

6.2.2. *Case Study: Andhra Pradesh Coast of India*

Rao (1968) classified the Indian coastline into three categories based on combined storm surges and wind waves. According to this classification, the Andhra Coast of India from 14° N to 16.5° N falls in the B-category (2 to 5 m surge) with a short C-type belt ($>$ 5 m surge) near Nizampatnam bay. According to an analysis of historical records by Jayanthi (1999), the Andhra coast is high-risk prone with a small very high-risk prone zone near Nizampatnam Bay. The storm surges occurred that during 1977 and 1990 near Machilipatnam further support the vulnerability of Andhra coast for disastrous surges. In recent years, there has been considerable concern regarding the vulnerability of coasts due to cyclones and associated surges in view of projected global warming and sea level rise. In this section, we have undertaken as a case study the development of Disaster Management Plan (DMP) for cyclones and associated storm surges for mitigation in the nine coastal districts of the State of Andhra Pradesh (AP), India.

Based on historical cyclone data, through a simple statistical analysis, Delta P (atmospheric pressure deficit) was determined for cyclones making landfall on the AP coast, for return periods of 2, 5, 10, 25 and 50 years. The Storm Surge Model developed by IIT-Delhi was applied with the 50-year Delta P value for a set of synthetic tracks, which were developed by compositing actual tracks, ensuring that each coastal district was covered. The results of the computer simulations, calibrated with observed surge data for each region of the coast, provided maximum probable surge amplitudes at the mandal level, which is the geographical unit immediately below the district level, and is made up of several villages and maybe towns.

A generally accepted procedure in determining the extent of land inundation by a storm surge is to assume that, a water level of 5-m at the coastline would have an impact up to the 5-m land contour, a 10-m water level would impact up to the 10-m contour, and so on. This is a standard approach when very detailed orographic information is not available and might somewhat over-estimate the extent of inundation, but is an acceptable approach for coastal zone storm mitigation planning purposes.

In summary, the approach for determination of the Physical Vulnerability (PV) is as follows:

(a) A database of Tropical Cyclone (TC) generated Storm Surges (SS) impacting the AP Coast was drawn from the India Meteorological Department (IMD) and from several other national and international sources.
(b) Because of climate change, projections into the future were limited to 50 years all the available cyclone tracks for AP were synthesized into composite tracks to cover each of the coastal districts of AP.
(c) Making use of the projected pressure drop, the IIT-Delhi Storm Surge Model was applied using the synthetic tracks to determine the maximum possible storm surge amplitude (during a 50 year period) at various locations along the AP Coast.
(d) The Total Water Level Envelope (TWLE) was determined by superimposing the tidal amplitudes and wind wave setup on the surge amplitudes.
(e) These water levels were then projected onto the coastal land using onshore topography data to demarcate the horizontal extent of inundation.
(f) This conservative approach may slightly over-estimate the extent of inundation, but is desirable for Hazard Mitigation and for Coastal Zone Management, and is widely used around the world.
(g) Maps of regions subjected to possible wind damage from cyclones also were prepared.

6.2.2.1. Physical Vulnerability (PV) Maps for the Coastal Districts

Inundation by storm surge and regions subjected to wind damage were mapped for the districts of Prakasham (Fig. 16) and Guntur (Fig. 17) of coastal AP. The PV maps were prepared for four scenarios: (a) frequent (10-percent

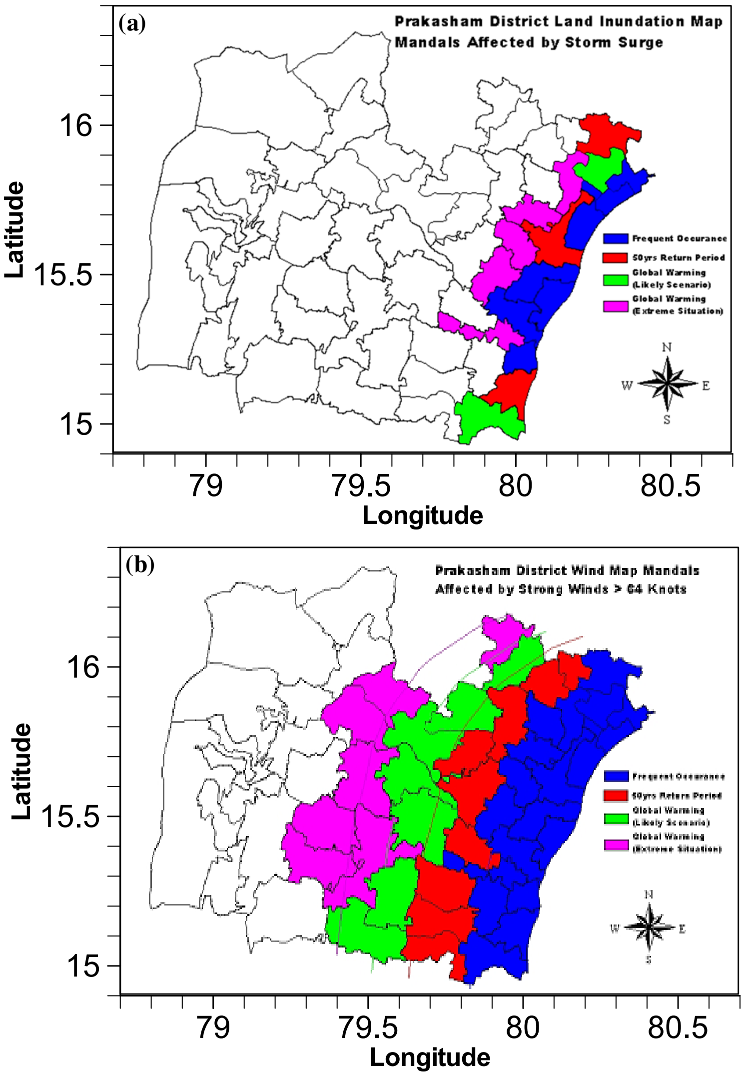


Figure 16. (a) Land inundation map affected by storm surge, (b) regions affected by cyclonic winds for Prakasham District, Andhra Pradesh, India (after Dube *et al.*, 2009).

annual recurrence interval), (b) infrequent (2-percent annual recurrence interval), (c) a future climate scenario resulting in an intensification of the pressure field by 5 percent, and (d) a more extreme case of intensification of 7 percent.

The three large rivers in AP, Godavari, Krishna and Pennar, are subject to storm surge penetration. The storm surge penetration into these rivers was determined by projecting the surge water levels into the rivers. It was assumed that for a river with many meanders, the

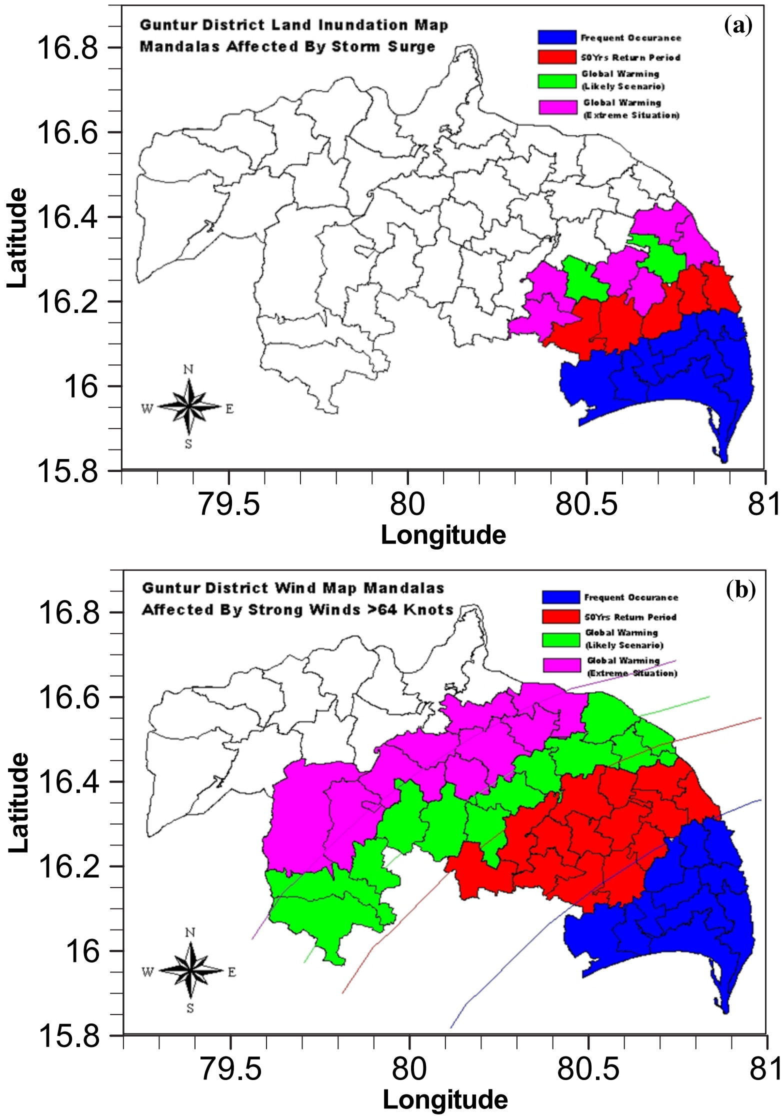


Figure 17. (a) Land inundation map affected by storm surge, (b) regions affected by cyclonic winds for Guntur District, Andhra Pradesh, India (after Dube *et al.*, 2009).

storm surge would penetrate 10 percent farther than on land. If the river had few meanders, the increased penetration was 15 percent. The 10–15 % numbers are arrived at based upon actual observations of storm surge penetration through these rivers (Murty, 1984). PV maps for storm surge penetration up the rivers were then prepared (Fig. 18).

6.2.2.2. Social Vulnerability (SV)

Social Vulnerability was developed for physically vulnerable mandals. By using available population and other data, along with the PV maps, overall cyclone vulnerability index maps were developed. Figure 19 shows the map for one of the districts of coastal Andhra Pradesh.

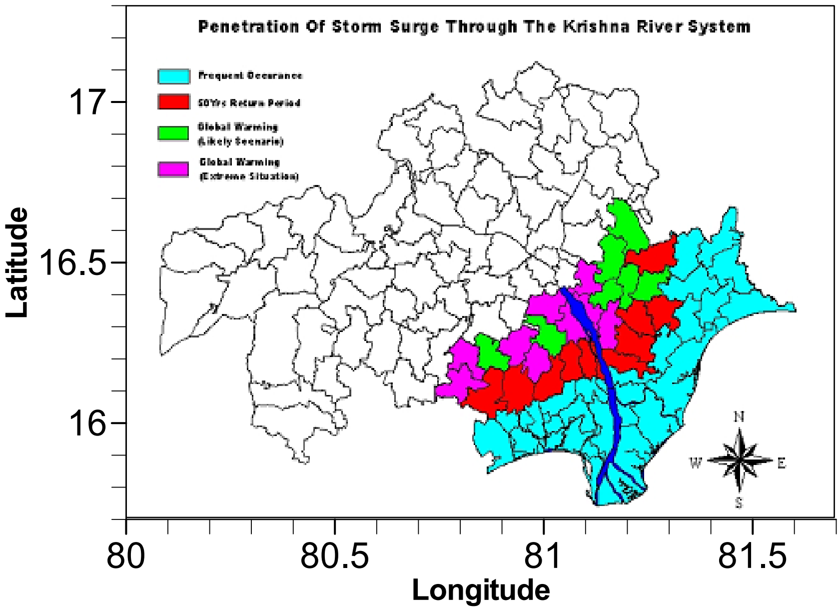


Figure 18. Storm surge penetration through the Krishna River System (after Dube *et al.*, 2009).

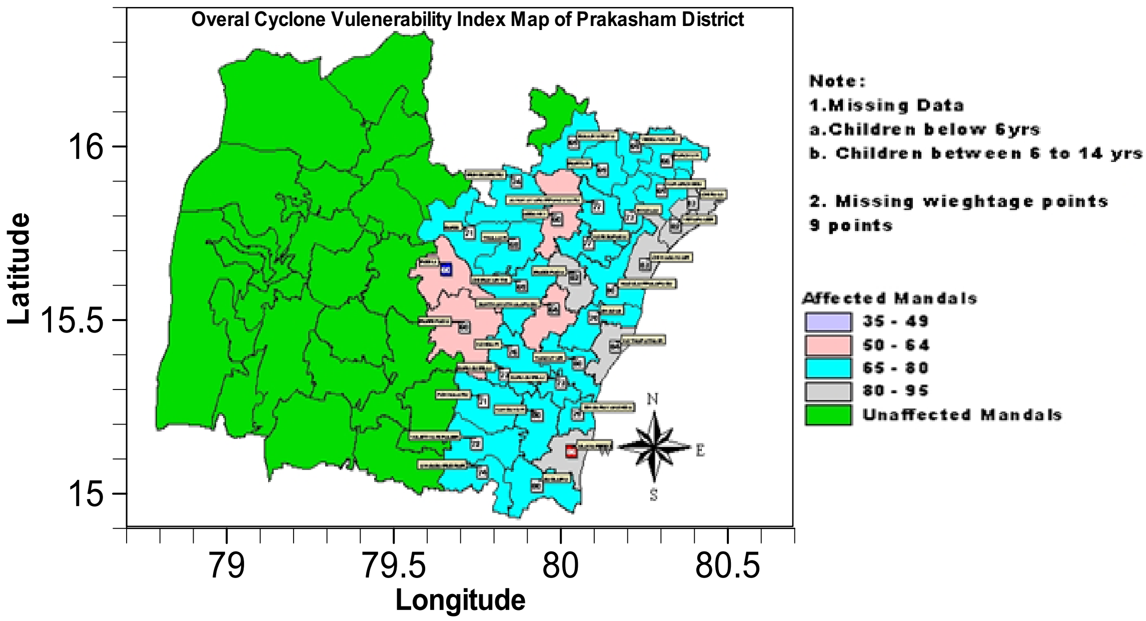


Figure 19. Overall Cyclone Vulnerability map for Prakasham District, Andhra Pradesh, India (after Dube *et al.*, 2009).

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