The Power of Storm Surge

A neighborhood in Long Beach, MS August 29, 2005
Why Model Storm Surge?

1) Storm surge impacts can be devastating to life and property
   A cubic yard of water weighs about 1,700 pounds.

2) Resulting damage affects infrastructure, economy, and environmental conditions.

Storm surge impacts in communities along the U.S. Gulf coast

Models are an economically feasible virtual laboratory to assist in coastal planning

Hal Needham and Barry D. Keim (2011).
STORM SURGE MODELING

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Universidad Técnica Federico Santa María,
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STORM SURGE MODELING

Outline

1) What is Storm surge?
2) Factors Contributing to Storm Surge
3) Simulation requirements
4) Operational Surge Models
5) ADCIRC – Katrina Example
6) Considerations
   a) domain size
   b) inundation algorithm
   c) bottom friction representation
   d) specification of GWCE weighting parameter
   e) surface roughness and wind drag
7) Drivers for accurate surge modeling
What is Storm Surge?

Abnormal sea level elevations (or depressions) caused by wind and atmospheric pressure

“Piling up of water at the coast”
What is Storm Surge?

• How it all piles up:
  – *low pressure system* (storm) generates wind
  – *wind* blows across the sea surface
  – *friction* between the wind and water pushes the water in the direction of the wind
  – *tides* caused by the gravity of the sun and moon contribute to the rise in ocean surface
  – the ocean starts to pile up along the coastline
  – *waves* form on top of the newly arisen sea
Coastal set-up due to alongshore wind -
Due rotation water moves at right angles to the wind stress,
Geostrophic balance results in < 1m of surge

Coastal set-up due to cross-shore wind -
largest contribution

1 mb decrease in P = 1 cm increase in surge

Components of Storm Surge
Factors Contributing to Storm Surge

- Wind – usually associated with a tropical storm or hurricane speed, direction, angle of approach to the coast
- Storm forward speed and size affects:
  - fetch – the distance over which the wind interacts with the surface of the ocean
  - time – the length of time wind blows over an area of the ocean

Strong wind + large fetch + long time + track perpendicular to the coast = Highest Surge
Factors Contributing to Storm Surge

- Low (air) storm pressure over the ocean
- Tides - phase of the tide dictates contribute to storm surge height
- Waves – additive to storm surge
- Slope and width of the continental shelf
  - in shallow water the sea surface slope required to balance the across shelf wind stress is inversely proportional to water depth. Hence wide, shallow shelves are prone to larger storm surges.
- Coastal geometry
  - by varying fetch and direction relative to a hurricane, embayment geometry is very important, as are the water depths and land elevations.
- Friction
  - presence of barrier islands, land cover with high surface roughness
What Storm Surge is Not

- Storm surge is not:
  - High tide
  - High waves
  - Swell - waves outside the fetch
  - Limited to the immediate coast – affects adjoining rivers and bays

Katrina Storm surge along the coast also forced adjoining waters in bays and bayous to rise. As a result residents as far as 10 miles inland were flooded. Some areas were flooded from the south (coastal ocean water) and from the north (overflowing bays and bayous).
Hurricane Storm Surge Simulation Requirements

- A high resolution, physics-based circulation model with flooding and drying capabilities.
- A high resolution water depth (bathymetry) and land (topography) elevation data set on which to overlay the model.
- Accurate (time and space) wind and pressure fields to drive the model.
- Land cover/land use data base for establishing bottom friction coefficients and wind drag modifications.
Operational Storm Surge Prediction

- Operational surge forecast models used today, e.g.
  - Extended Area Continental Shelf Model: fine grid (CS3X) – National Oceanography Center, England
  - Shallow Water Hydrodynamic Finite Element Model (SHYFEM), Institute of Marine Sciences - National Research Council (ISMAR), Italy
  In the U.S.:
  - SLOSH (Sea, Lake, and Overland Surges from Hurricanes), National Weather Service/National Hurricane Center
  - ADCIRC – (Advanced CIRCulation), Army Corps of Engineers, US Navy

Criteria for Success
- Accurate and flexible dynamical model
- Ability to meet operational time constraints
- Automated, rapid relocation
- Generation of meaningful operational products
- Quantification of forecast skill
Predictive Capability for Coastal Circulation

- High resolution (meters) currents, water levels, temperature, and salinity in littoral environments that include bays, estuaries, inter-tidal marshes and rivers

ADCIRC Model

- 3D coastal ocean dynamics
- Forcing from tides, wind, waves, buoyancy, and rivers
- Shoreline inundation/recession
- Utilizes unstructured grids (based on finite elements)
- MPI parallelization
ASGS : ADCIRC Surge Guidance System

**WINDS**: Forecasts from the NHC used to generate dynamic asymmetric hurricane vortex model based on Holland (1980).

**TIDES**: Tidal potential and harmonic constituents recomputed for each simulation.

**RIVER FLOW**: Rates obtained dynamically from the NSSL.

**UNSTRUCTURED COMPUTATIONAL MESH**

**ADCIRC**
Finite-element model solves continuity and momentum equations for *long waves* (tides, storm surge).

**SWAN**
Finite-difference model solves action balance equation; integrated solution represents *short waves* (wind-sea, swell).

**OUTPUT**: Water levels and significant wave heights provided to emergency managers as time series or in graphical format (including raster images, Google Earth KMZ files).
Forecast Modeling for Hurricane Issac, Aug. 2012

27 August 2200 CDT - Forecast issued about 24hr before initial landfall

Max Significant Wave Height

NDBC 42003:
Adv 20 - 4.07m
Adv 24 - 8.56m
Adv 28 - 6.43m
Actual - 5.18m

NDBC 42036:
Adv 20 - 7.11m
Adv 24 - 2.91m
Adv 28 - 4.39m
Actual - 4.57m

NDBC 42012:
Adv 20 - 4.50m
Adv 24 - 4.05m
Adv 28 - 3.72m
Actual - 5.78m
Hurricane Katrina Storm Surge and Inundation

- NOAA HRD Reanalysis Winds
- 28 Aug 1800 UTC – 31 Aug 0000 UTC
Hurricane Winds

NOAA HRD H*Wind Reanalysis


28 Aug 1800 UTC – 30 Aug 1000 UTC
Lagrangian interpolation to 15-minute intervals
Garratt surface wind drag parameterization
Resolution 225 m near the coast and inland

Finite Element Mesh

No. elements = 730,431
No. nodes = 375,479
Hindcast Description

- Tides forced at boundary from Grenoble FES99
- Tidal potential forced within the domain
- Wetting and drying
- Nonlinear hybrid bottom friction relation
- Constant frictional coefficient
- Time step of 1 sec
- 15 day ramp-up of forcing
- 3 days and 10 hrs simulated
  8/27 0000 UTC - 8/30 1000 UTC
- 128 processors NAVOCEANO IBM-P4
- ~1 CPU hour/ simulation day
Elevation (ft) on 28-August-2005 at 5:00:00 AM
Above Mean Sea level

x Storm Center
ADCIRC Computed Tides + Surge

Elevation (ft) on 29-August-2005 at 5:30:00 AM
Above Mean Sea level

Feet

[Map showing elevation with shades indicating feet above mean sea level]

x Storm Center
ADCIRC Computed Tides + Surge

Elevation (ft) on 29-August-2005 at 5:59:59 AM
Above Mean Sea level

Feet

<table>
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<tr>
<th>35</th>
<th>30</th>
<th>25</th>
<th>20</th>
<th>15</th>
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</tbody>
</table>
ADCIRC Computed Tides + Surge

Elevation (ft) on 29-August-2005 at 6:30:00 AM Above Mean Sea level

Feet

X Storm Center
ADCIRC Computed Tides + Surge

Elevation (ft) on 29-August-2005 at 7:29:59 AM
Above Mean Sea level

x Storm Center
ADCIRC Computed Tides + Surge

Elevation (ft) on 29-August-2005 at 8:30:00 AM
Above Mean Sea level

Feet
ADCIRC Computed Tides + Surge

Elevation (ft) on 29-August-2005 at 8:59:59 AM Above Mean Sea level

x Storm Center

Feet

-15
-10
-5
0
5
10
15
20
25
30
35

Latitude (deg)

Longitude (deg)
ADCIRC Computed Tides + Surge

Elevation (ft) on 29-August-2005 at 9:30:00 AM
Above Mean Sea Level

x Storm Center
ADCIRC Computed Tides + Surge

Elevation (ft) on 29-August-2005 at 10:29:59 AM
Above Mean Sea level

x Storm Center
ADCIRC Computed Tides + Surge

Elevation (ft) on 29-August-2005 at 11:00:00 AM
Above Mean Sea level

x Storm Center

Feet

-15
-10
-5
0
5
10
15
20
25
30
35
ADCIRC Computed Tides + Surge

Elevation (ft) on 29-August-2005 at 11:30:00 AM
Above Mean Sea level

Feet

x Storm Center
ADCIRC Computed Tides + Surge

Elevation (ft) on 29-August-2005 at 11:59:59 AM
Above Mean Sea level

x Storm Center
Comparison to USGS High Water Marks

Average error = 1.2 ft

LATITUDE (DEG)

30.6
30.4
30.2
30.0
30
-90.5
-90
-89.5
-89
-88.5
-88

HIGHT WATER MARK (FT)

Wet - 315
Dry - 143

OBSERVATION
MODEL

Average error = 1.2 ft

LATITUDE (DEG)

30.6
30.4
30.2
30.0
30
-90.5
-90
-89.5
-89
-88.5
-88

HIGHT WATER MARK (FT)

Wet - 315
Dry - 143

OBSERVATION
MODEL

Average error = 1.2 ft
Water Level Comparisons

Station ID: 8760922 -- Pilots Station East, Sw Pass, LA

Correlation: 0.7515
RMS: 0.6745
Water Level Comparisons

Correlation: 0.7606
RMS: 0.6969
Water Level Comparisons

Correlation: 0.8428
RMS: 0.7072
Current Comparisons

USM Buoy (Courtesy of Dr. Stephan Howden)
Hurricane Storm Surge Modeling

• The large domain strategy correctly captures
  – Basin to basin interactions
  – Basin to shelf dynamics
  – Shelf to adjacent coast/floodplain dynamics
  – Control structure and channel influence on flood propagation

• The large domain strategy significantly simplifies the specification of boundary conditions by selecting hydrodynamically simple boundaries

• Localize resolution in the unstructured grid to accurately resolve the physics
Use Large Domain Size

<table>
<thead>
<tr>
<th>Domain</th>
<th>Area (km²)</th>
<th>Max Depth (m)</th>
<th>Discretization</th>
<th>Grid Size (km)</th>
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<tbody>
<tr>
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<td>8.35x10⁶</td>
<td>7765</td>
<td>22711</td>
<td>41407</td>
</tr>
</tbody>
</table>
Use Large Domain Size

Florida Coast domain:
- Situated on shelf
- Small wrt storm size
- Large portions of cross-shelf boundaries

Gulf of Mexico domain:
- Captures peak surge
- Oscillatory behavior due to resonance of basin
- Sensitivity to boundary condition specification
ADCIRC Inundation Algorithm

Based on 1-D momentum balance between a pressure gradient and friction:

\[ gH \frac{\partial \eta}{\partial x} = \tau_b = C_D \nu \]

Classify elements as either wet (sufficient water elevation) or dry (removed from computation) – effectively turn in and off elements for wetting/drying.
ADCIRC Wetting/Drying Criteria

PHASE I

Loop Over All Wet Nodes (k)

- If $H_k \leq H_0$
  - Make Dry
  - Ensure $H_{absm} \leq H_k \leq H_0$
  - Absolute Min. water depth = 0.8 $H_0$

- False
  - Keep Wet
  - End

Leaves residual water between $H_{absm}$ and $H_0$

Results in asymmetric drying
ADCIRC Wetting/Drying Criteria

PHASE II

Dry elements with 2 wet nodes are considered for wetting

For wetting from one node to the next,

\[ H \geq 1.2H_0 \]

and

\[ v_{wet} \geq v_{min} \]

where

\[ v_{wet} = g \left( \frac{\Delta \eta}{\Delta x} \right) \frac{1}{\tau_{wet}} \]

A larger H for wetting than drying eliminates numerical oscillations in the wetting/drying

No directionality of flow is considered
1D Wetting/Drying on Gentle Slope

Applied Elevation Forcing

Issues:
- spatial asymmetry
- temporal asymmetry btw wetting and drying
- ponding

Solutions:
- appropriate grid spacing and parameter specifications
- gradient checking and smoothing
- elemental averaging
- moving towards DG flux-based approach
Hybrid Non-linear Bottom Friction

Bottom stress

Hybrid formulation

$\tau_b = C_D v$

$C_D = \max \left\{ C_D^{\min}, \left(1 + \frac{H_{\text{break}}}{H} \right)^{\frac{\gamma}{\theta}}, 10^{-4} \right\}$

Drag coefficient

Linear or quadratic drag coefficient

Depth-dependent drag

Depth for deep to shallow water switchover

Results in greater friction coefficient in shallow water

Typically $C_D^{\min} = 0.003$; $H_{\text{break}} = 2\text{m}$; $\theta = 10$; $\gamma = 1.33333$

Effect of mesh size for required $\Delta \eta = 0.1$

For a given $v_{\text{min}}$, a higher change in elevation is required for wetting at coarser resolution.
Specification of GWCE parameter, $\tau_0$

Weighting parameter for the Generalized Wave Continuity Equation (GWCE)

$\tau_0 = 0 \quad \longleftrightarrow \quad \tau_0 = 1$

pure wave equation
(greatest mass imbalance)

primitive continuity
formulation
(unstable solution)

Best results for a spatially and temporally variable, $\tau_0$

$$\tau_0 = \tau_{0\text{min}} + 1.5 \frac{C_d |v|}{H}$$

Within min and max limits $\tau_0$, typically 0.005 to 0.2
Surface Roughness and Wind Drag

To improve wind accuracy, apply wind reduction due to enhanced friction (roughness) over land.

Surface stress term
\[ \frac{\tau_{sx}}{\rho H} = \frac{C_d}{H} \frac{\rho}{\rho} \|W_{10}\| W_{10} \]

Standard drag coefficient

Full marine Wind speed at 10m

Reduce winds over land by applying a weighted roughness

\[ W_{land} = f_d \cdot W_{10} \]

where \( f_d = \left( \frac{z_{marine}}{z_0} \right)^{0.0706} \)

Ratio of marine roughness to land roughness

In areas where local vegetative canopy includes forested trees and thick shrubs, \( W_{land} = 0 \)

Account for wind direction through a directionally dependent roughness value

- Use land use information from land cover databases to assign land roughness values for each land cover type

Westerink et al. 2008
Surface Roughness and Wind Drag

Directional roughness length

North Wind

Southerly Wind

Forested canopy – no wind stress applied
What’s Next – Hydrodynamic-Hydrologic Model Coupling

Better river discharge estimates

Hydrology Model

Wind Model

Wave Model

Hydrodynamic Model

Total Water Levels

Significant Wave Heights

CI-FLOW
VanCooten et. al 2011, Bul Am. Met. Soc
Summary of Modeling Strategy

• Localized high resolution is critical to capture the physics of surge generation and propagation

• Large domains to capture the entire storm and its surge generation throughout the basin

• A physics based approach including tides, riverine flows, air-sea interaction and wave-current interaction
Primary Drivers for Accurate Surge Modeling

- Bathymetric and topographic variations
- Wind field
- Representation of the coastal boundary geometry
- Model resolution appropriate for bathy/topo scales and movement of inundation front
- Frictional characteristics of the region