Storm Surge/Inundation Modeling
State of the Science

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Primary Applications of Storm Surge Modeling

**Historical - what gets wet, how deep**
- Scenarios - understanding/communication (non real time)
- FIRMS - flood insurance (non real time)
- Hurricane Protection System Design (non real time)
- Evacuation (2-5 days b.l.)

**Recent - when, how long, consequences**
- Hurricane related infrastructure operations (0-2 days b.l.)
- Infrastructure damage/repair (1 day b.l. - 1 day a.l.)
- Contaminant transport (1 day b.l. - ? days a.l.)
- Search and rescue (0-? days a.l.)
- Post storm federal aid (0-? days a.l.)
- Erosion (beaches/barrier islands/wetlands) (non real time)
- Planning (non real time)

**Different time constraints, accuracy expectations**
= Different physics, models
Goal of Storm Surge Modeling Research

Understand/evaluate/prioritize physics for storm surge model applications

• Why use a simple model when a complicated model will do?
• Do we really need to include *that* (process/feature/resolution) in the model?
• What errors should we expect given the physics that are included in a particular storm surge model?
• Can we extrapolate parameterizations developed for less energetic flows to the extreme conditions of a hurricane?
• How tightly coupled do multi-process models need to be?
• How do we keep what we don’t know from biting us?
Basic Issues in Storm Surge Modeling

Wind stress, atmospheric pressure driven
local & remote

Topography & Bathymetry

Important water column physical processes
horizontal - basin/storm to local scales
vertical - momentum transport, 2D/3D waves
land effects
tides
precipitation/runoff
Wind Stress, Atmospheric Pressure

IT’S THE WINDS STUPID!!!
(Vince Cardone, Ocean Weather Inc.)

Observation Based
H*Wind - M. Powel, HRD - best near eye, no pressure field, can blend with Large Scale Winds (LSW)

Dynamical Meteorological Models
NAM, GFDL, HWRF - improving track skill, no improvement in intensity & size skill, resolution?

Parametric/PBL - OWI, ARA
uses 2D momentum eqs. in Planetary Boundary Layer + storm parameters, can blend with LSW

Parametric/Analytical - Holland, SLOSH
uses steady analytical eqs. for wind/pressure field + storm parameters, can blend with LSW
Wind Stress, Atmospheric Pressure

**Historical Analysis**

*Parametric or H*Wind* typically used, helpful to add far field

**Design, DFIRM, Planning - statistically based hurricanes**

*Joint Probability Method & variants - Parametric* wind models using statistical distributions of storm parameters

**Forecasting**

*Dynamical models* - sufficient skill, timely, easily ensembled?

*Parametric* wind models using NHC best track/forecast storm parameters + selected perturbations

Important to identify & separate error (bias) in meteorological model from that in storm surge model!
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Topography and Bathymetry

IT’S THE BATHY/TOPO STUPID!!!

A Geospatial Framework for the Coastal Zone National Needs for Coastal Mapping and Charting - NRC 2004

- Seemless national onshore/offshore topography/bathymetry
- Accurate, up to date, resolves datums - R.L.
- Feature files - R.L.
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  waves
  land effects
  tides
  precipitation/runoff
Horizontal Scales

Large domains are necessary to represent hurricanes and basin scale response without *ad hoc* boundary conditions.

Katrina
Aug 28/29, 2005
Horizontal Scales

The three R’s of Storm Surge Modeling

“Resolution, Resolution, Resolution”

- Local topography and bathymetry
- Critical hydraulic conveyances
- Structures and raised features that impede or focus flow
- Local roughness
- Effects of breaking short waves

Often don’t have a good idea of how much is enough in overland flooding situations
Southeastern Louisiana
Unstructured Grid
Greater New Orleans
Greater New Orleans
Lake Pontchartrain & Greater New Orleans
Sub-Grid Scale Features
Sub-Grid Scale Features

**Broad Crested Weirs**

- Critical Flow
  \[ Q_n = -\frac{2}{3} \mu_c \xi_1 \left[ \frac{2}{3} g \xi_1 \right]^{1/2} \]

- Sub-critical Flow
  \[ Q_n = -\mu_s \xi_2 \left[ 2 g (\xi_1 - \xi_2) \right]^{1/2} \]

**Culvert/submerged openings**
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Important water column physical processes
  horizontal - basin/storm to local scales
  vertical - momentum transport, 2D/3D
  waves
  land effects
  tides
  precipitation/runoff
Vertical Processes

1.) Surface momentum transfer/stress - (parameterized as a wind speed dependent surface drag coefficient)

\[ \frac{\tau_s}{\rho_a} = C_{da} \frac{W_{10}}{|W_{10}|} \]

\[ C_{da} = (0.75 + 0.67 |W_{10}|) \times 10^{-3} \]  \hspace{1cm} \text{(Garrett 1977)}

\[ C_{da} \leq C_{da \ max} \]  \hspace{1cm} \text{extreme/hurricane conditions}

\( C_{da} \) will be influenced by \( W_{10} \) averaging time

Should we explicitly including waves?
Vertical Processes

2.) Bottom momentum transfer/stress - (parameterized via a bottom drag coefficient) - 2 Dimensional Model

\[ \frac{\tau_b}{\rho_w} = C_{db} \frac{U}{|U|} \quad U = \text{depth-averaged velocity} \]

\[ C_{db} = 0.0025 - 0.003 \quad \text{typical for coastal modeling} \]

\[ C_{db} = gn^2/(H)^{1/3} \quad n - \text{Manning’s } n \text{ from hydraulics} \]

\[ n \text{ compiled for different “land covers”} \]

- \( U \) - representative of conditions near bottom?
- Maps of submerged/marine bottom types & \( n \) values?
- Include wave & sediment movement effects?
- How well does Manning’s \( n \) work under extreme conditions, submerged vs non submerged vegetation, structures?
Vertical Processes

2.) Bottom momentum transfer/stress - (parameterized via a bottom drag coefficient) - 3 Dimensional Model

\[ \tau_b/\rho_w = C_{db} u_b/|u_b| \quad u_b=\text{near bottom velocity} \]

\[ C_{db} = 0.005 - 0.010 \quad \text{typical for coastal modeling} \]

\[ C_{db} = f(z_{ob}) \]

\[ z_{ob} - \text{effective bottom roughness} \]

\[ z_{ob} \sim \text{actual bottom roughness}/30 \]

Maps of submerged/marine bottom types & \( z_{ob} \) values?

Include wave & sediment movement effects on \( z_{ob} \)?

Incorporate effects of objects that penetrate into the water column (e.g., vegetation) via additional drag terms distributed in water column?
3.) Water column momentum transfer/turbulence/velocity structure

2 Dimensional Model at Steady State

\[ \tau_s \]

\[ \tau_b \propto U = 0 \]

\[ (\partial \eta / \partial x)_{2d} \]

\[ U = 0 \]
Vertical Processes

3.) Water column momentum transfer/turbulence/velocity structure

3 Dimensional Model at Steady State

2D - 3D surge difference depends on the difference in bottom stress which depends on the development of the velocity profile

\[
\tau_s \quad \frac{\partial \eta}{\partial x} \mid_{3d}\n\]

\[
\tau_b \propto U = 0 \quad \frac{\partial \eta}{\partial x} \mid_{2d}\n\]
Vertical Processes

3.) Water column momentum transfer/turbulence/velocity structure

Development of the velocity profile depends on

- closeness to steady state conditions
- bathymetric variations that allow mostly horizontal return flow
- strength of the vertical momentum transfer - i.e., water column turbulence
Vertical Processes

3.) Water column momentum transfer/turbulence/velocity structure

50 km channel
depth = 40m - 1m
wind = 50 m/s
steady state

$E_z = 0.1 \& 1 \, \text{m}^2/\text{s}$
Vertical Processes

3.) Water column momentum transfer/turbulence/velocity structure

50 km channel
depth = 40m - 1m
wind = 50 m/s
steady state

\[ E_z = 0.1 \text{ & } 1 \text{ m}^2/\text{s} \]

\[ E_z = \text{MY 2.5} \]
Vertical Processes

3.) Water column momentum transfer/turbulence/velocity structure

50 km channel
depth = 40m - 1m
wind = 50 m/s
steady state

$E_z = 0.1 \& 1 \text{ m}^2/\text{s}$
$E_z = MY 2.5$

How valid are common turbulence parameterizations for extreme/hurricane conditions?
Basic Issues in Storm Surge Modeling

**Wind stress, atmospheric pressure driven**
- local & remote

**Topography & Bathymetry**

**Important water column physical processes**
- horizontal - basin/storm to local scales
- vertical - momentum transport, 2D/3D
- waves
- land effects
- tides
- precipitation/runoff
Waves

1.) Surface momentum transfer/stress - implicit in drag coefficient or explicitly include waves?

2.) Bottom momentum transfer/stress - explicitly include waves?

3.) Water column momentum transfer/turbulence - breaking waves inject turbulence into water column
   - $z_{os} \approx 1.3H_s$
   - Wave breaking surface layer may intersect/erode b.b.l.
   - Turbulence parameterization for extreme conditions?
Waves

4.) Radiation stress gradient forcing of surge

\[ R_x = \frac{1}{\rho_o} [\partial S_{xx}/\partial x + \partial S_{xy}/\partial y] \]
\[ R_y = \frac{1}{\rho_o} [\partial S_{yx}/\partial x + \partial S_{yy}/\partial y] \]

On steep slopes, waves become the dominant surge generator. This includes local scale near levees. Examples: reefed islands and many rocky coastlines. About 30% of total surge during Hurricane Opal in Panama City.

Upper and lower limits of typical wave model contributions to total surge.

2D Model: Enhanced surface stress

3D Model: Can be distributed through water column
Wave Radiation Stress Gradients - Hurricane Katrina
Wave Radiation Surge Contribution - Hurricane Katrina
Maximum Surge Elevations - Hurricane Katrina
Waves

5.) Wave mass flux?
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tides
precipitation/runoff
Land Effects - Flooding/Drying

**Wetting:** based on pressure gradient flow > minimum velocity and adequate water depth at all nodes
- \( \text{Vel} > \text{Vel}_{\text{min}} \sim 2 \text{ cm/s} \)
- \( \text{H} > 1.2 \text{ H}_{\text{min}} \)

**Drying:** based on water depth falling below minimum depth
- \( \text{H} < \text{H}_{\text{min}} \sim 10 \text{ cm} \)

Rather ad hoc

Inundation may be grid size dependent

Significant erosion (e.g., dune erosion) may have a major effect on inundation
Land Effects - Bottom Friction

Water Column

- Bottom/water column friction related to land type/vegetation
- 2D use simple engineering Manning’s n approach
  \[ C_{db} = gn^2/(H)^{1/3} \]
- n from land cover
Land Effects - Winds

**Water Surface**

- In significant canopies, wind speed at water surface $\approx 0$
- Emergent features/vegetation create roughness that affects the wind boundary layer
- Wind boundary layer will respond to land cover roughness in upwind direction
- Modify $W_{10}$ to account for this roughness
Land Effects - Eastern North Carolina
Land Effects - Satellite Image
Land Effects - USGS NLCD

National Land Cover Dataset Classification System Legend

<table>
<thead>
<tr>
<th>Color Key</th>
<th>RGB Value</th>
<th>Class Number and Name</th>
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<td>61 - Orchards/Vineyards</td>
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<td>144, 192, 217</td>
<td>92 - Emergent Herbaceous Wetlands</td>
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## Land Effects - Conversions

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<td>Developed - Open Space</td>
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<td>Developed - Low Intensity</td>
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<td>Developed - Medium Intensity</td>
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<td>Barren Land (Rock/Sand/Clay)</td>
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<td>Unconsolidated Shore</td>
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<td>Evergreen Forest</td>
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<td>Dwarf Scrub</td>
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<td>Shrub/Scrub</td>
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<td>Grassland/Herbaceous</td>
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<td>Sedge/Herbaceous</td>
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<td>Lichens</td>
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<td>91</td>
<td>Palustrine Forested Wetland</td>
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<td>Palustrine Scrub/Shrub Wetland</td>
<td>0.048</td>
<td>0.120</td>
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<tr>
<td>93</td>
<td>Estuarine Forested Wetland</td>
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<td>Emergent Herbaceous Wetlands</td>
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<td>Palustrine Emergent Wetland (Persistent)</td>
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<td>97</td>
<td>Estuarine Emergent Wetland</td>
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<td>99</td>
<td>Estuarine Aquatic Bed</td>
<td>0.015</td>
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</table>
Land Effects – Manning’s n
Land Effects - Canopy Coefficient

\[ w_{10} = w_{10} \]

\[ w_{10} = 0 \]
Land Effects: $z_{0\text{land}}$ N Wind
Land Effects: $z_{0\text{land}}$ E Wind
Land Effects: $z_{0\text{land}}$ S Wind
Land Effects: $z_{0\text{land}}$ W Wind
Land Effects on Maximum Wind Speed

Hurricane Ophelia 2005

No Land Effects

With Land Effects
Land Effects on Maximum Elevation

Hurricane Ophelia 2005

No land effects

Wind reduction + Mannings n
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local & remote

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precipitation/runoff
Other Relevant Forcing/Processes

**Tides**
- Inundation is clearly affected by tidal phase
- Water column turbulence & bottom stress will depend on combined surge, tide & wave effects

**Precipitation/runoff**
- Importance depends on storm characteristics (precip vs wind)
- Particularly significant in coastal areas with flat coastal plain
- Lagged in time ~1-3 days from coastal surge
- Ongoing activities to couple precip, hydrologic & coastal models - e.g., NOAA CI-FLOW (not simply river BC’s)
Conclusions

Remaining need to understand/evaluate/prioritize physics for storm surge/inundation model applications

Different storm surge applications may favor different models/model implementations

It’s the winds stupid! - It’s the topo/bathy stupid!

Predictive storm surge calculations require horizontal resolution from storm/basin scales to local scales.

3D models may give higher surge than 2D models -

- vertical physics and drag parameterizations strongly influence the size of this difference.
- Inherent differences in 2D & 3D drag parameterizations make it difficult to compare.
Conclusions

Waves strongly influence vertical physics
• Coupled wave - surge models, but to what extent?
• Requires comparable wave and surge model resolutions to capture radiation stress effects.

Uncertainty in model parameterizations associated with turbulence and drag for both 2D & 3D models. Considerable uncertainty for extreme conditions.

Land cover can have a significant effect on wind and inland surge propagation. Wind roughness adjustment length scale?

Surge and inundation are sensitive to tides.

Precipitation and hydrologic runoff may also be critical contributors to flooding associated with hurricanes.
Representative Surge Model Performance

2D ADCIRC - SL15 grid (2.3 million nodes)
H*Wind + Large Scale Winds by Ocean Weather Inc
Garrett drag law with $C_{da\ max} = 0.0035$
wave radiation stress
objective land effects

Hurricane Katrina - skill vs high water marks:

<table>
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<tr>
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<th>avg absolute error</th>
<th>std dev</th>
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<tr>
<td>USACE (206):</td>
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<td>0.43 m</td>
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<tr>
<td>URS (193):</td>
<td>0.26 m</td>
<td>0.37 m</td>
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</tbody>
</table>

Hurricane Rita - skill vs high water marks:

URS (60): 0.20 m 0.35 m