Mathematical and Computational Issues in Coastal Modeling

Clint Dawson
The University of Texas at Austin
Institute for Computational Engineering and Sciences
Computational Hydraulics Group
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Coastal ocean applications

• Coastal inundation due to tropical storms and hurricanes
• Tsunamis
• Oil spills
• Dredging and harbors
• Coastal ecology
• Water quality
• Saltwater intrusion
• Coastal infrastructure
**NSF CMG Projects**

- **2006-2009:** Adaptive Numerical Methods for Shallow Water Circulation with Applications to Hurricane Storm Surge: C.D., Joannes J. Westerink, and Rick Luettich

- **2010-2013:** Simulation of Wave-Current Interaction Using Novel, Coupled Non-Phase and Phase Resolving Wave and Current Models: Joannes J. Westerink, Andrew Kennedy, Ethan Kubatko, C.D.
**Issues in Coastal Modeling**

- Multiscale domains: from deep ocean to coastal inlands
**Issues**

- Multiscale resolution: from deep ocean to coastal inlands
Multi-physics:

- 2D (depth-averaged) or 3D in space
- Hydrostatic or nonhydrostatic
- Baroclinic or barotropic
- Coupling with other models: wind, waves, sediment erosion/deposition, salinity and temperature transport...

2D SWE:

\[
\begin{align*}
\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(Hu) + \frac{\partial}{\partial y}(Hv) &= 0 \\
\frac{\partial}{\partial t}(Hu) + \frac{\partial}{\partial x}(Hu^2 + \frac{1}{2}g(H^2 - b^2)) + \frac{\partial}{\partial y}(Huv) &= g\zeta \frac{\partial b}{\partial x} + F_x \\
\frac{\partial}{\partial t}(Hv) + \frac{\partial}{\partial x}(Huv) + \frac{\partial}{\partial y}(Hv^2 + \frac{1}{2}g(H^2 - b^2)) &= g\zeta \frac{\partial b}{\partial y} + F_y
\end{align*}
\]
**Issues**

Discretization:

- Gridding: unstructured or structured, hybrid,….
- Appropriate approximating spaces: conforming or nonconforming, order of approximation, mass conservation, well-balanced property,…
- Time stepping: explicit, implicit, how to handle coupling, parallelism

\[
\int_{\Omega_e} \frac{\partial u_h}{\partial t} \cdot v d\Omega - \int_{\Omega_e} [\mathbf{F} \cdot \nabla v + G \nabla u_h \cdot v] d\Omega + \int_{\partial \Omega_e} \hat{\mathbf{F}} \cdot n v ds = \int_{\Omega_e} s \cdot v d\Omega
\]

\[
\frac{d}{dt} u_h = L_h(u_h)
\]
**Issues**

Other aspects of coastal models:

- Internal barriers: levees, roads, railways….
- Many subgrid scale parameterizations: friction, eddy viscosity,….
- Wetting and drying and free surfaces
**Issues**

Benchmarking, Verification and Validation: codes must go through rigorous V&V before being accepted by the community. We have substantial sources of data.
**Issues**

HPC Performance

SWAN+ADCIRC performance on Kraken, Ranger, and Lonestar
**Advanced Circulation (ADCIRC) Framework**

- Solves for 2D and 3D currents driven by wind, wind waves, tides, rivers, and density gradients
- Original algorithmic design criteria
  - Unstructured grids
  - Robust and second order
  - Highly scalable in parallel
- ADCIRC has evolved into a multi-algorithmic code (CMG funded work)
  - CG solution (ADCIRC-CG)
  - DG solution (ADCIRC-DG)
  - Coupled with SWAN to model waves: SWAN + ADCIRC
Collaborators: ADCIRC Development Group

- Joannes Westerink, University of Notre Dame
- Rick Luettich, University of North Carolina
- Randy Kolar, University of Oklahoma
- Ethan Kubatko, Ohio State University
- C.D., University of Texas at Austin
- Various collaborators at USACE New Orleans District, ERDC-Vicksburge, LSU, Arcadis, NOAA
Research Avenues

Improved algorithms which capture highly advective, multi-scale flows and are dynamically adaptive

• Discretizations: conforming and non-conforming

• h-p adaptivity

• Local time stepping

• Tightly coupled physics
**Research Avenues**

**Resolution** of subgrid-scale coastal features—vegetation, marshes, bridges, seawalls, streets, buildings

- Multi-scale coupling and upscaling of LES and RANS models to shallow water models
- Fluid-structure interactions

**Improved wave/current coupling**, including phase-resolving wave models

- Green-Naghdii models (current CMG project)
Research Avenues

Rainfall runoff dynamically coupled with surge

- Simple routing models vs. physics-based models
- Rainfall models tend to be very localized

Sediment erosion and deposition

- Very complex physics involved between suspended sediment and bed load.

Uncertainty quantification and data assimilation

- Ensemble and data assimilated models
CMG Application: Hurricane Ike

Hurricane Ike
2008 Sep 01 15:00 to 2008 Sep 15 03:00 UT

WIND SPEED
5 ≥ 156 MPH
4 ≥ 131 MPH
3 ≥ 111 MPH
2 ≥ 96 MPH
1 ≥ 74 MPH
> 30 MPH
> 0 MPH

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Hurricane Ike

- Third costliest hurricane to make landfall in the U.S.
- Strong Category 2 storm but produced large storm surge
- Produced 6-8 foot “forerunner” surge along upper TX coast 24 hours before landfall
- Similar characteristics to 1900 Galveston hurricane
Hurricane Ike “Forerunner” Study
Ike surge contours (m) and wind vectors (m/s)
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- 27 hrs
Ike surge contours (m) and wind vectors (m/s)

r09 c8+tides Water Surface Elevations + Winds

- 26 hrs
Ike surge contours (m) and wind vectors (m/s)
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- 21 hrs
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- 15 hrs
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- 7 hrs
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r09 c8+tides Water Surface Elevations + Winds

- 3 hrs
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+ 3 hrs
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r09 c8+tides Water Surface Elevations + Winds

+ 6 hrs
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Ike surge contours (m) and wind vectors (m/s)

+ 9 hrs
Ike surge contours (m) and wind vectors (m/s)

r09 c8+tides Water Surface Elevations + Winds

+10 hrs
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+ 16 hrs
Ike surge contours (m) and wind vectors (m/s)
Ike surge contours (m) and wind vectors (m/s)

+ 18 hrs
**Summary**

- CMG funded research allowed us to develop a state of the art storm surge model and to lay the groundwork for future development.

- The next steps will focus on **sustainability, resiliency and quantifying risk** in coastal environments.