Overview of the Advanced Circulation (ADCIRC) Coastal Ocean Modeling Framework

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ADCIRC Development Group (www.adcirc.org)

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- C.D., UT Austin
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- Chris Massey, ERDC

Major contributors: Arcadis, Inc.; Naval Research Laboratory, Stennis; U.S. Army Corps of Engineers ERDC and New Orleans District office.
ADCIRC design philosophy

- Accurately define the physical system
- Include all of the physical processes
- Numerically resolve the flow
- Ensure accuracy of the solution to the PDE’s
ADCIRC design criteria

• High grid resolution to define and capture
  Local topography and bathymetry
  Local roughness
  Critical hydraulic conveyances
  Structures and raised features that impede or focus flow
  Wind wave transformation scales

• Accurate numerical algorithms that
  Are not numerically dissipative
  Are phase accurate
  Accommodate high spatial gradients
  Are robust for high velocity flows
ADCIRC design criteria

- Fully integrate all important processes into the model
  - Accurate winds
  - Accurate momentum transfer to the water column
  - Riverine flows
  - Tides
  - Short wind waves
- Validation
Overview of the modeling system

- ADCIRC - Circulation model
- SWAN - Wind wave model (TU Delft)
- Various Wind inputs (NOAA, Whirlwinds, OWI, NHC forecasts, NCEP forecasts)

- Finite element discretizations on unstructured meshes
- Scalable parallel implementation
Models: ADCIRC: ADvanced CIRCulation

- Solves the Generalized Wave Continuity Equation (GWCE):

\[
\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{J}_x}{\partial x} + \frac{\partial \tilde{J}_y}{\partial y} - UH \frac{\partial \tau_0}{\partial x} - VH \frac{\partial \tau_0}{\partial y} = 0
\]

where:

\[
\tilde{J}_x = -Q_x \frac{\partial U}{\partial x} - Q_y \frac{\partial U}{\partial y} + fQ_y \frac{\partial \zeta}{\partial x} - gH \frac{\partial}{\partial x} \left[ \frac{p_s}{g \rho_0} - \alpha \eta \right] + \frac{\tau_{sx} + \tau_{bx}}{\rho_0} + (M_x - D_x) + U \frac{\partial \zeta}{\partial t} + \tau_0 Q_x - gH \frac{\partial \zeta}{\partial x}
\]

\[
\tilde{J}_y = -Q_x \frac{\partial V}{\partial x} - Q_y \frac{\partial V}{\partial y} - fQ_x \frac{\partial \zeta}{\partial y} - gH \frac{\partial}{\partial y} \left[ \frac{p_s}{g \rho_0} - \alpha \eta \right] + \frac{\tau_{sy} + \tau_{by}}{\rho_0} + (M_y - D_y) + V \frac{\partial \zeta}{\partial t} + \tau_0 Q_y - gH \frac{\partial \zeta}{\partial y}
\]

- Solves the vertically-integrated momentum equations:

\[
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV = -g \frac{\partial}{\partial x} \left[ \zeta + \frac{p_s}{g \rho_0} - \alpha \eta \right] + \frac{\tau_{sx} + \tau_{bx}}{\rho_0 H} + \frac{M_x - D_x}{H}
\]

\[
\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU = -g \frac{\partial}{\partial y} \left[ \zeta + \frac{p_s}{g \rho_0} - \alpha \eta \right] + \frac{\tau_{sy} + \tau_{by}}{\rho_0 H} + \frac{M_y - D_y}{H}
\]
Models: SWAN: Simulating Waves Nearshore

- Solves the action balance equation:

\[
\frac{\partial N}{\partial t} + \nabla \cdot \left[ \left( \tilde{c}_g + \bar{U} \right) N \right] + \frac{\partial c_{\theta} N}{\partial \theta} + \frac{\partial c_{\sigma} N}{\partial \sigma} = \frac{S_{tot}}{\sigma}
\]

- Computes significant wave heights and returns wave radiation stresses to ADCIRC
Spatial Discretization: the FEM method

- Both ADCIRC and SWAN are discretized using a continuous Galerkin method on unstructured triangular elements.

- All unknowns are approximated at the vertices of triangles.
Applications of ADCIRC

- Tidal data base for U.S. East Coast and Gulf of Mexico
- Hindcasts of major Gulf and East Coast Hurricanes
- Water levels for all *levee designs* in Southern Louisiana are based on models developed by our team
- Water levels for the **FEMA DFIRMS** (Digital Flood Insurance Rate Maps) for Louisiana, Texas, Mississippi, Florida, Georgia, South Carolina and North Carolina are based on ADCIRC models (our team developed the TX and LA models)
- ADCIRC is used as a *hurricane forecasting* tool by an LSU-UNC-UT team to provide emergency response information for the States of Louisiana and Texas
- Used to study DH oil spill
Western North Atlantic ADCIRC Model
Western North Atlantic—finite element mesh
Zoom: Southern Louisiana and Mississippi
**Bottom Friction**

- Surface roughness is based on USGS NLCD and GAP land cover/use data
- Standard Manning n values are assigned
<table>
<thead>
<tr>
<th>Color Key</th>
<th>RGB Value</th>
<th>Class Number and Name</th>
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<tr>
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<tr>
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<td>Orchard/Vineyard</td>
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<tr>
<td>71</td>
<td>Grassland</td>
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<td>Row Crops</td>
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<tr>
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<td>Small Grains</td>
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<td>Fallow</td>
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<tr>
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<td>Recreational Grass</td>
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<tr>
<td>95</td>
<td>Cypress Forest</td>
<td>0.120</td>
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Wind stress

• Improvements in winds by incorporating directional land roughness to adjust the overland/near-shore wind boundary layer

• Incorporation of canopies where winds are zeroed due to loss of momentum propagating through the canopy.

• Dynamic wind drag coefficient variation between land and sea values as region becomes inundated.
<table>
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<th>NLCD Class</th>
<th>Description</th>
<th>$Z_{0\text{-land}}$</th>
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<tr>
<td>51</td>
<td>Shrub Land</td>
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<td>61</td>
<td>Orchard/Vineyard</td>
<td>0.270</td>
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<td>Grassland</td>
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<td>Pasture</td>
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<tr>
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<td>Row Crops</td>
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<td>83</td>
<td>Small Grains</td>
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<td>Fallow</td>
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<tr>
<td>85</td>
<td>Recreational Grass</td>
<td>0.050</td>
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<tr>
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<td>Woody Wetland</td>
<td>0.550</td>
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<td>92</td>
<td>Herbaceous Wetland</td>
<td>0.110</td>
</tr>
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<td>95</td>
<td>Cypress Forest</td>
<td>0.550</td>
</tr>
</tbody>
</table>
ADCIRC Texas Model

txr2007 Grid and Bathymetry Region7
Upper Texas Coast Model Resolution
**Storm Surge Simulations**

**Hindcasting:** Studying historical hurricanes

- Evaluate inundation risk in coastal areas
- High impact – low probability events in an evolving system
- Critical to design of protection and mitigation systems in order to reduce that risk
  - Structures may in fact adversely impact components of the system and increase the risk of flooding

**Forecasting:** As storms approach land, estimate maximum surge and extent of inundation for emergency management. Must be done in “real-time”
2005 Hurricane Season

Katrina: 08/28 – 08/29

Rita: 09/22 – 09/24

http://cimss.ssec.wisc.edu/
2005 Hurricane Season: Rita: Inundation of Cameron Parish

21 September 2005

26 September 2005

NASA
Katrina: Water Levels: 2005/08/29
Katrina: High-Water Marks
Hindcast Study of Hurricane Ike

r09 c8+tides Water Surface Elevations + Winds
Ike surge contours (m) and wind vectors (m/s)
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r09 c8+tides Water Surface Elevations + Winds

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

- 12 hrs

- 43.31 days

- 43 m/s

- 5 m

- 4 m

- 3 m

- 2 m

- 1 m

- 0 m

- -1 m
Ike surge contours (m) and wind vectors (m/s)
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r09 c8+tides Water Surface Elevations + Winds

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

+ 1 hrs
Ike surge contours (m) and wind vectors (m/s)
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Ike surge contours (m) and wind vectors (m/s)

r09 c8+tides Water Surface Elevations + Winds

- 6 hrs

+ 6 hrs
Ike surge contours (m) and wind vectors (m/s)
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r09 c8+tides Water Surface Elevations + Winds

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

r09 c8+tides Water Surface Elevations + Winds

44.52 days

43 m/s

+ 17 hrs
Ike surge contours (m) and wind vectors (m/s)
$y = 0.98446 \times x$

$R^2 = 0.908339$
Ike significant wave height contours (m) and wind vectors (m/s)

- 48 hrs
Ike significant wave height contours (m) and wind vectors (m/s)
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r09 c8+tides Sig. Wave Heights

- 11 hrs
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Ike significant wave height contours (m) and wind vectors (m/s)
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LANDFALL = 0 hrs
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Ike significant wave height contours (m) and wind vectors (m/s)
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Ike significant wave height contours (m) and wind vectors (m/s)

+ 13 hrs
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Ike significant wave height contours (m) and wind vectors (m/s)
Ike significant wave height contours (m) and wind vectors (m/s)
Ike significant wave height contours (m) and wind vectors (m/s)
Ike significant wave height contours (m) and wind vectors (m/s)
Validation: High-Water Marks

- **Katrina (2005)**: $y = 1.00734x$, $R^2 = 0.933238$
- **Rita (2005)**: $y = 1.08678x$, $R^2 = 0.791692$
- **Gustav (2008)**: $y = 0.950467x$, $R^2 = 0.800035$
- **Ike (2008)**: $y = 0.984483x$, $R^2 = 0.908745$
Uncertainty in Forecasts
- Projected landfall location shifted from Florida to Louisiana
- Slow-moving storm caused extensive flooding of southeast Louisiana
Applications: Hurricane Forecasting: Isaac (2012)

ADCIRC Surge Guidance System (ASGS)

Runs continuously during hurricane season:
- Uses wind forecasts every 6hr from NHC to force SWAN+ADCIRC
- Portable to any unstructured mesh:
  - UT Austin - Texas floodplain from west Louisiana to Mexico border
  - LSU - entire Louisiana floodplain with focus on New Orleans
  - UNC Chapel Hill - floodplains of the Carolinas

Surge guidance to emergency managers during Isaac (2012):
- LSU and UNC Chapel Hill provided Web-based guidance:
  (http://cera.cct.lsu.edu/cgi-cera-ng/cera-ng.cgi)
- UT Austin also provided ASGS forecasts:
  - TX State Operations Center
  - NWS Fort Worth
  - NWS Miami
Applications : Hurricane Forecasting : Isaac

Evolution of Surge Forecasts

Maximum surge on EC95 mesh at 6hr intervals:

- Advisory 14 : About 105hr before projected landfall at Destin FL
- Advisory 38 : About 39hr after actual landfall at Mississippi River
Deepwater Horizon Oil Spill

Deepwater Horizon was a 9-year-old, mobile offshore drilling unit
Located 66km from the Louisiana coastline, in 1500m of water
Platform was engulfed on 20 April by an explosion of methane gas; structure burned for more than 24hr before sinking on 22 April
Explosion killed 11 workers and injured 17
Oil spill flow rates:
- Estimated to have begun at a rate of 9900 m³ d⁻¹
- Diminished over time to a final rate of 8400 m³ d⁻¹ on 15 July 2010
Emergency responders relied on satellite and aerial imagery
Nearshore Oil Transport: Motivation

Satellite imagery can only show current location of the slick
- Where will the oil move?
- What happens if a hurricane approaches?
Forecasts of oil transport need to be accurate and fast
- Provide results to NOAA and other spill modelers
- Provide results to emergency managers in real time (http://adcirc.org/oilspill)
Nearshore Oil Transport: Challenges

Spreading

Evaporation

Dissolution

OIL PARTICLES rise to the water's surface and spread

Sedimentation
Nearshore Oil Transport : Lagrangian Particles

Particle positions are tracked through the unstructured mesh:

\[
\bar{x}_p(t + \Delta t) = \bar{x}_p(t) + \bar{u}(\bar{x}_p, t)\Delta t + \bar{D}
\]

- where the dispersion uses a stochastic perturbation (Proctor et al., 1994):

\[
\bar{D} = (2R - 1) \sqrt{c\bar{E}_v} \Delta t
\]

- and where the velocities are a linear combination of currents and winds:

\[
\bar{u}(\bar{x}_p, t) = F_c \bar{u}_c(\bar{x}_p, t) + F_w \bar{u}_w(\bar{x}_p, t)
\]

Using hybrid OpenMP/MPI, 11M particles can be tracked on a 10M-element mesh in about **5.5 min/day** using 256 cores on TACC Ranger.
Nearshore Oil Transport: Flow Chart

Winds
Provided by NCEP (http://www.ncep.noaa.gov/) from WRF-NMM (http://nomads.ncdc.noaa.gov/), downloaded and converted to our format.

Currents
Waves from SWAN (http://swanmodel.sourceforge.net/) and circulation from ADCIRC (http://www.adcirc.org/), with currents provided hourly to the tracking model.

Initial Conditions
NESDIS (http://www.nesdis.noaa.gov/) provided slick extents, which were digitized and provided to the tracking model.

Oil Transport
Lagrangian tracking of conservative particles, with advection forced by winds and currents and dispersion via stochastic perturbations.

Emergency Managers
Animations posted online (http://adcirc.org/oilspill/).
Validation: Mid-June

Examples of available imagery during 13-23 June 2010:

- NESDIS consolidated observations from a suite of satellite sensors
Satellite Observations  Predicted Particle Locations
Satellite Observations  Predicted Particle Locations
Satellite Observations  Predicted Particle Locations
2010 / 06 / 16 / 1555 UTC ( + 72 hr / + 3.0 d )

Satellite Observations

Predicted Particle Locations
Satellite Observations  Predicted Particle Locations
Satellite Observations  Predicted Particle Locations
Satellite Observations

Predicted Particle Locations
Satellite Observations  Predicted Particle Locations
Satellite Observations

Predicted Particle Locations
Satellite Observations  Predicted Particle Locations
Overlap of our predictions to observations:

- **Solid brown** - Total areas of observed oil in satellite imagery
- **Solid red** - Total areas of predicted locations of Lagrangian particles
- **Dashed red** - Overlap between predictions and observations

After one week of simulation, overlap is about 60 percent
- Good qualitative and quantitative match to observations
Conclusions

ADCIRC model is a verified and validated tool for modeling coastal hydrodynamics, hurricane storm surges and oil spills. This is a great example of how basic algorithmic research can be transitioned into operational models.

ADCIRC forecast system runs successfully in real-time

Good match to overall movement of oil spill

Some small-scale features are modeled successfully

Oil spill validation is difficult due to lack of accurate data.
Open Questions

3D baroclinic, deep-water to near-shore to inland coupling (ADCIRC coupled to HYCOM, see Casey Dietrich’s talk tomorrow)

3D Oil transport, biogradation, weathering, etc. (Lagrangian vs. Eulerian methods; collaboration with Juan Restrepo and Shankar V.)