Coupled, Unstructured Grid, Wave and Circulation Models: Validation and Resolution Requirements

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ADvanced CIRCulation (ADCIRC):
- Developed by Westerink, Luettich, Dawson and many others
- Continuous-Galerkin, finite-element, shallow-water model
- Solves for water levels and currents at a range of scales
  - From rivers and tides to wind-driven storm surge
  - Resolution can vary from 20-30km to 30-50m
- Solves the GWCE for water levels
- Solves the vertically-integrated momentum equations for currents
Example: Louisiana Storm Surge Modeling
Example: Louisiana Storm Surge Modeling
‘Loose’ Coupling

‘Loose’ Coupling:
• Unstructured shallow-water model to structured wave model
• Models coupled through input files
  • Water levels and currents passed to wave model
  • Wave-driven forces passed to shallow-water model

ADCIRC Coupled to Wave Models:
• Basin/region scale: WAM, WaveWatch III
• Nearshore: STWAVE, SWAN
‘Loose’ Coupling

Example: Louisiana Storm Surge Modeling
‘Loose’ Coupling

Example: Louisiana Storm Surge Modeling

Nearshore STWAVE Model

Special Output Locations Hurricane KATRINA on 30-sec WAM CY4.5 Grid
‘Loose’ Coupling

It Works!

- Maximum significant wave heights in Hurricane Katrina
‘Loose’ Coupling

It Works!

- Maximum wave-driven forces in Hurricane Katrina
‘Loose’ Coupling

It Works!

• Effect of waves on water levels in Hurricane Katrina
Disadvantages of ‘Loose’ Coupling

1. Iteration:
   - Models coupled through input files
   - Water levels and currents passed to wave model
   - Wave-driven forces passed to shallow-water model
   - Process can be automated, but is still inefficient

\[ \zeta, u, v \]

\[ F_x, F_y \]
Disadvantages of ‘Loose’ Coupling

2. Interpolation:
   - Wave and circulation models run on different grids
     - Wave models on structured meshes
     - ADCIRC on unstructured, finite element mesh
   - Results must be interpolated onto each mesh
Disadvantages of ‘Loose’ Coupling

3. Resolution in wave breaking zones:
   • Circulation model has no knowledge of wave breaking
   • Must over-resolve these zones
‘Tight’ Coupling

Advantages:
- ADCIRC and wave model run on the same mesh
  - No nesting of meshes
  - No overlapping of meshes
- ADCIRC and wave model run on the same core
  - No interpolation
  - No global message passing
- Optimization of code
  - No iteration of models
  - No overhead for coupling modeling framework
  - Utilize shared memory on multi-core processors
- Optimization of physics
  - No need for directionality in waves model
  - Dynamic $h$- and $p$-adaptivity
‘Tight’ Coupling

Introducing … UnSWAN+ADCIRC

• ADCIRC coupled to Simulating WAves Near-shore (SWAN)
• SWAN:
  • Developed at Delft University
  • Non-phase-resolving, wave energy propagation model

Progress:

• SWAN converted to unstructured meshes (UnSWAN)
• UnSWAN implemented in parallel (PUnSWAN)
• ADCIRC and PUnSWAN compiled into PAdcSwan
  • Pass node-based information between models
  • Run on same local mesh
  • Leapfrog through time
Shared Local Meshes:
• Example of Mesh Decomposition on 1014 Cores
Passing Information:

- **ADCIRC to UnSWAN:**
  - Water levels, currents, and wind speeds
- **UnSWAN to ADCIRC:**
  - Wave-driven forces:

\[
F_x = - \frac{\partial S_{xx}}{\partial x} - \frac{\partial S_{xy}}{\partial y} \quad \text{and} \quad F_y = - \frac{\partial S_{xy}}{\partial x} - \frac{\partial S_{yy}}{\partial y}
\]

where the wave radiation stresses are:

\[
S_{xx} = \rho g \int \int \left( \left( n \cos \theta \cos \theta + n - \frac{1}{2} \right) \sigma N \right) d\sigma d\theta
\]

\[
S_{xy} = \rho g \int \int \left( n \sin \theta \cos \theta \sigma N \right) d\sigma d\theta
\]

\[
S_{yy} = \rho g \int \int \left( \left( n \sin \theta \sin \theta + n - \frac{1}{2} \right) \sigma N \right) d\sigma d\theta
\]
UnSWAN+ADCIRC

Schematic of Coupling:

- ADCIRC is run for 600 seconds ($\Delta t = 1$ sec)
- Water levels ($\zeta$) and currents ($u,v$) are passed to Swan
- UnSWAN is run for 600 seconds ($\Delta t = 600$ sec)
- Radiation stresses ($S_{xx}$, $S_{xy}$, $S_{yy}$) and wave-driven forces ($F_x$, $F_y$) are computed; forces are passed to ADCIRC
- Repeat

- UnSWAN and ADCIRC are always extrapolating in time
Hurricane Katrina

Katrina at 2005/08/29/1000Z

- Wind speed contours (m/s) and vectors (m/s)
Hurricane Katrina

Katrina at 2005/08/29/1000Z
• Significant wave height contours (m) and wind vectors (m/s)
Hurricane Katrina

Katrina at 2005/08/29/1000Z

- Peak wave period contours (s) and wind vectors (m/s)
Hurricane Katrina

Katrina at 2005/08/29/1000Z

- Wave-driven force contours (m²/s²) and wind vectors (m/s)
Hurricane Katrina

Katrina at 2005/08/29/1000Z

- Water level contours (m) and wind vectors (m/s)
Hurricane Katrina

Katrina at 2005/08/29/1000Z

- Wave set-up contours (m) and wind vectors (m/s)
Hurricane Katrina

Validation of SWAN in deep water

Significant wave heights (m) at MDIC buoys
Hurricane Katrina

Validation of SWAN in deep water

PEAK WAVE PERIODS (T(P)) AT NDBC BUOYS

USNCCM 10 – 15-19 JULY 2009 – 26
Hurricane Katrina

Computational Performance

- Timings on TACC Ranger
Conclusions

Implementation:
• ADCIRC and SWAN have been coupled so that they:
  • Run on the same processor
  • Run on the same local mesh
• The coupled model is efficient and scalable

Validation:
• Performed for Katrina (shown) and Rita (not shown)
• The coupled model performs surprisingly well, especially in deep water
• More resolution is needed in the Gulf of Mexico

Future Work
• Next generation of meshes
• Next generation of storms