Hurricane Wind, Wave, and Surge Computations Deficiencies and Research Needs

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10th IWWHF-CHS
November 11-16, 2007

Motivation

- USACE/FEMA have intensively focused on improving the definition of hurricane induced wind, wave, and surge conditions in the past 2 years
- Develop multi-process, multi-scale coupled modeling system allowing the interaction of tides, riverine flow, wind, atmospheric pressure and waves in order to determine wave conditions and still water levels
- Merge high resolution computational models with high resolution topographic, bathymetric, surface condition and raised feature definitions
- Do not use case specific parameter tuning of sub-grid scale processes in order to improve fit to observed data
  - *Improve the resolution and the physics*
- Many questions have arisen in terms of how we can best improve our hurricane wave and surge predictions

The Way Ahead

- Better resolution leads to better physics (meter scale)
- More efficient and accurate numerical engines allow higher *localized* resolution and therefore better physics
- Better physics for meteorology
- Better physics for waves and circulation
  - Momentum fluxes
  - Bottom friction and dissipation
  - Hydrologic rainfall/runoff coupling
  - 3D effects
  - Sediment morphology
- Better data collection, validation, and archiving

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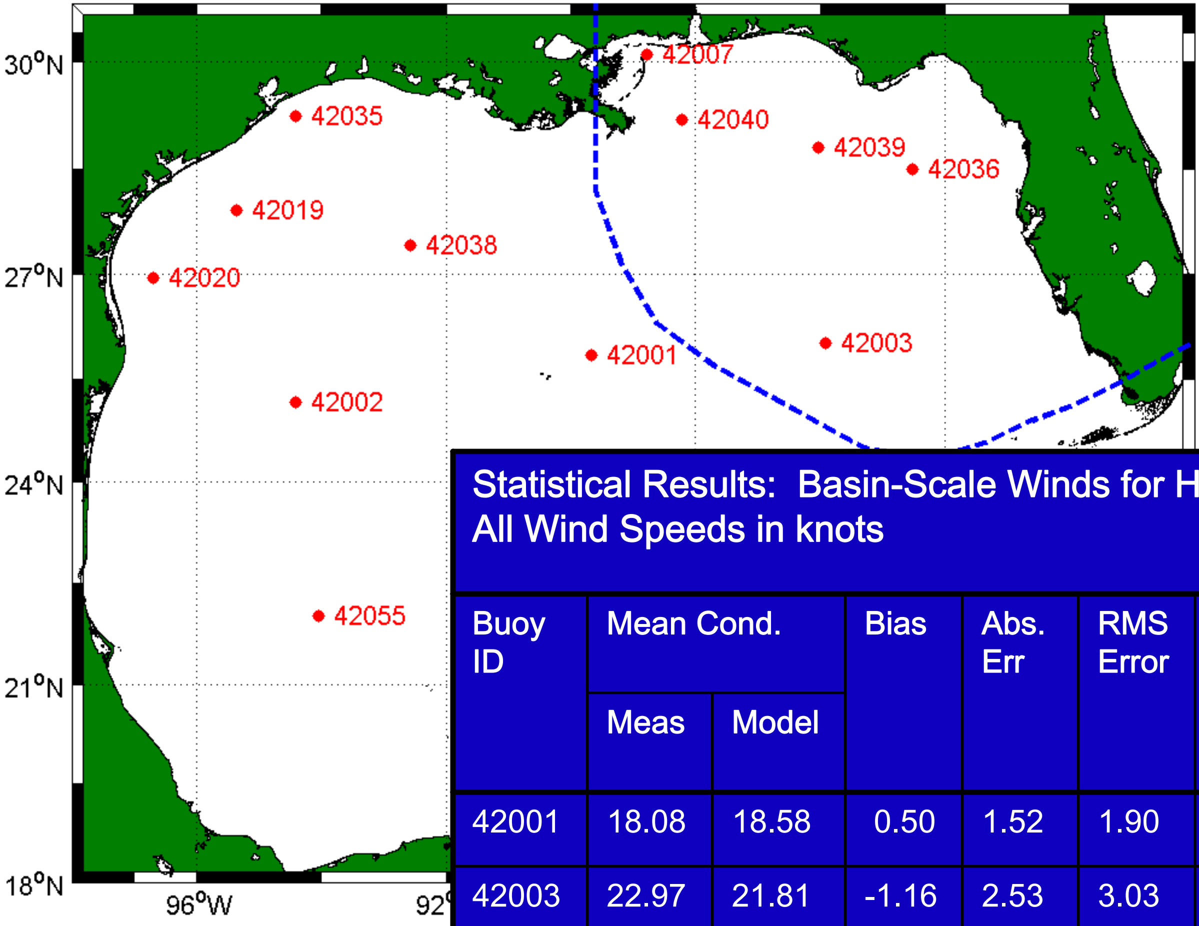
- J. Atkinson, L. Zevenbergen; Ayres Associates
- H. Roberts, Arcadis
- W. de Jong, Royal Haskoning
- C. Bender; Taylor Engineering
- V. Cardone, A. Cox; Oceanweather Inc.

Methods - Winds

- H*WIND/IOKA kinematic wind computations
  - Observational data rich
  - Validated against NDBC Buoys

H*Wind/IOKA Product vs Wind Measurements



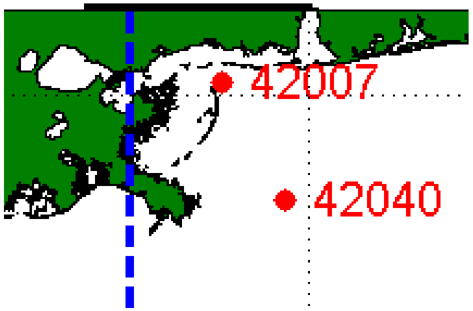
Statistical Results: Basin-Scale Winds for Hurricane Katrina
All Wind Speeds in knots

Buoy ID	Mean Cond.		Bias	Abs. Err	RMS Error	Scat Indx	Linear Regression Estimators				No. Obs
	Meas	Model					Corr r	Sys b	Slope	Intercp.	
42001	18.08	18.58	0.50	1.52	1.90	10	0.99	1.03	1.03	0.04	82
42003	22.97	21.81	-1.16	2.53	3.03	13	0.99	0.92	0.82	3.05	42
42007	15.92	15.49	-0.43	2.60	3.42	21	0.92	0.98	0.93	0.62	57
42036	21.36	21.01	-0.35	1.32	1.73	8	0.95	0.98	0.89	1.92	83
42038	12.97	13.41	0.44	1.94	2.35	18	0.95	1.01	0.90	1.71	82
42039	21.71	22.32	0.61	1.94	2.58	12	0.95	1.01	0.87	3.38	84
42040	20.74	21.62	0.87	2.06	2.72	13	0.98	1.01	0.93	2.27	84
42055	9.43	10.48	1.05	2.92	3.48	37	0.64	1.05	0.44	6.36	84

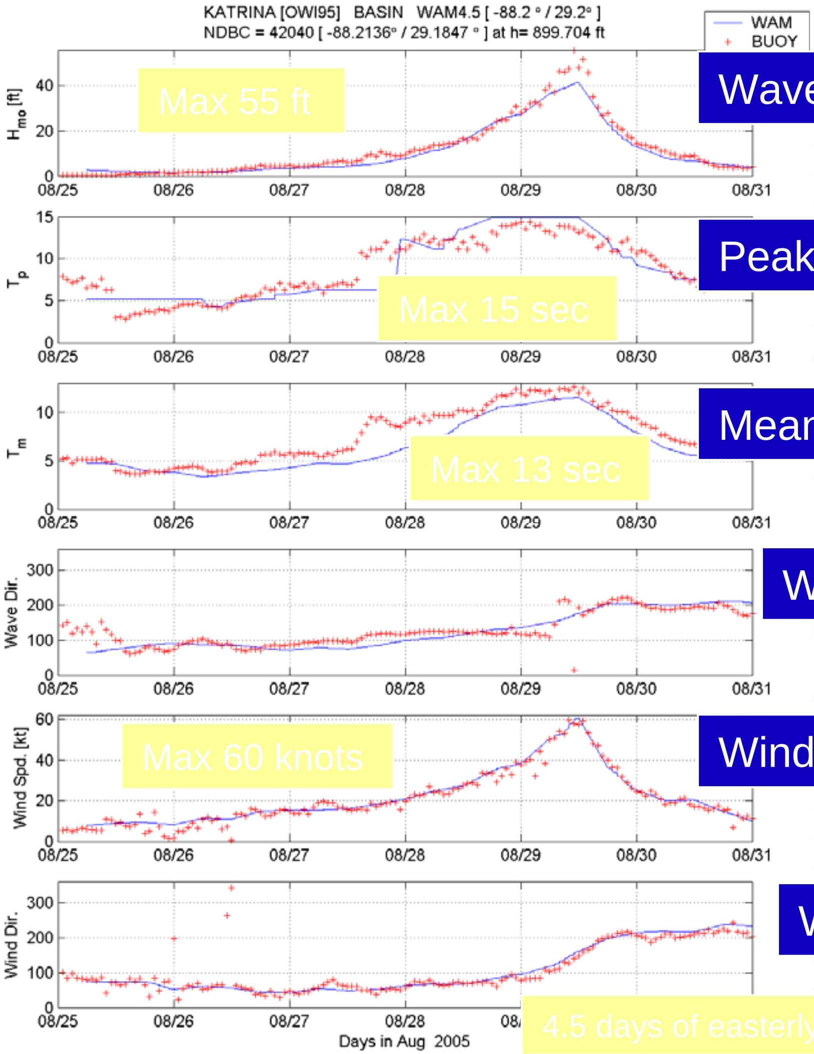
Methods - Waves

- WAM/STWAVE Wave Computations
  - Based on nested basin/local domains
  - High coastal resolution (200 m) models
  - Over 3.34 million cells (STWAVE)
  - Processes
    - Best winds (HRD H*WIND – OWI IOKA) / pressure
    - Elevations and Currents from Tides, Surge, Rivers
  - Topography
    - Lidar
  - Surface
    - NLCD/GAP wind boundary layer directional adjustment
    - NLCD/GAP based Manning n

WAM Model Computations and Measurements – SE Louisiana



Buoy 42040



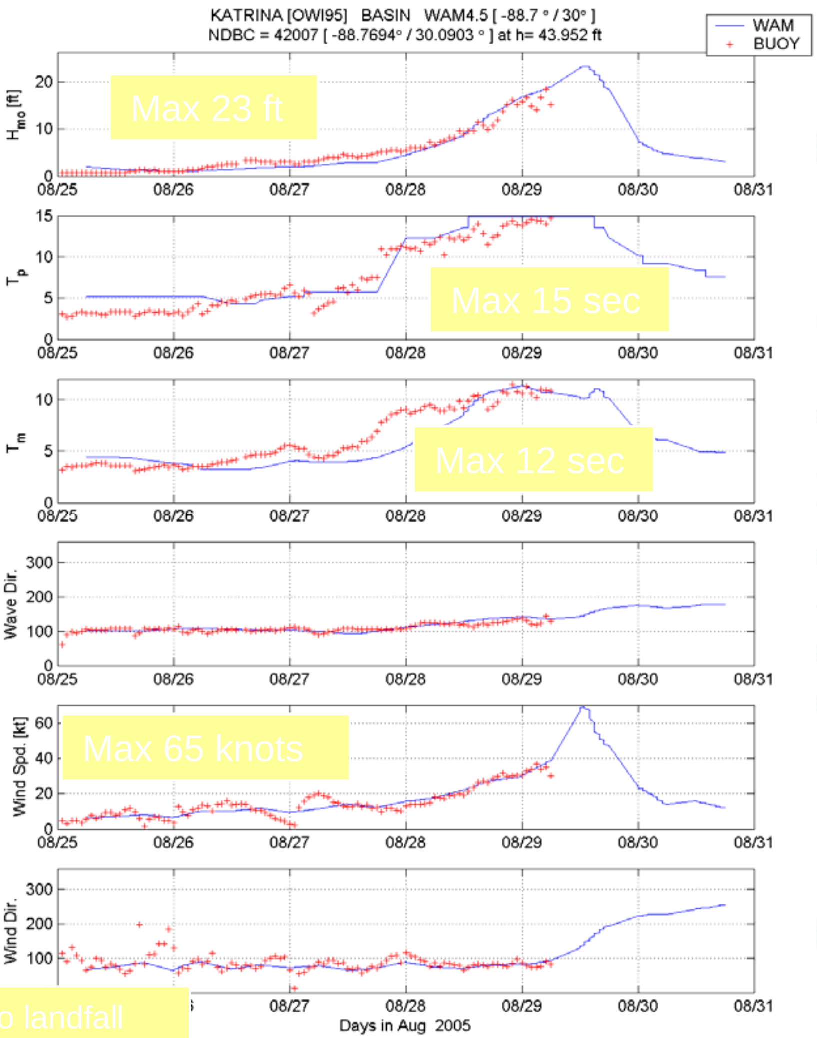
Max 55 ft

Max 15 sec

Max 13 sec

Max 60 knots

Buoy 42007



Max 23 ft

Max 15 sec

Max 12 sec

Max 65 knots

Wave Height

Peak Period

Mean Period

Wave Dir

Wind Speed

Wind Dir

4.5 days of easterly winds prior to landfall

Models - Circulation

- ADCIRC Surge Computations
  - Based on large domain – high resolution (30 to 60 m) model
  - Over 2.1 million nodes – 1 second time step
  - Processes
    - Best winds (HRD H*WIND – OWI IOKA) / pressure
    - Riverine flows
    - Tides
    - Wave radiation stress gradient coupling
  - Topography
    - Lidar
  - Surface
    - NLCD/GAP wind boundary layer directional adjustment
    - NLCD/GAP based Manning n

SL15 Tidal Validation

- Compare SL15 to NOAA error and NOAA to NOAA error
- Normalized Root Mean Square Constituent Amplitude Errors

Constituent	SL15 Computed to NOAA Measured/Analyzed Errors	Estimated NOAA Measured/Analyzed Data Errors
K_1	0.135	0.062
O_1	0.125	0.065
Q_1	0.146	0.104
M_2	0.119	0.041
S_2	0.211	0.050
N_2	0.249	0.101
K_2	0.275	0.134

SL15 Tidal Validation

- Compare SL15 to NOAA error and NOAA to NOAA error
- Average Absolute Constituent Phase Errors

Constituent	SL15 Computed to NOAA Measured/Analyzed Errors	Estimated NOAA Measured/Analyzed Data Errors
K_1	7.62	5.81
O_1	11.84	9.38
Q_1	10.32	6.37
M_2	18.64	16.64
S_2	24.19	11.75
N_2	22.46	18.37
K_2	60.16	11.06

SL15 Surge Validation Katrina and Rita

Storm	HWM Data Set	Slope	R	Average Error (ft)	Standard Deviation (ft)	HWM Error Estimate (ft)	Model Standard Deviation (ft)
Katrina	USACE IPET	1.01	0.97	0.08	1.53	0.60	1.41
Katrina	FEMA URS	1.04	0.97	0.61	1.42	0.63	1.34
Rita	FEMA	0.98	0.86	-0.03	1.32	0.60	1.19
Rita	FEMA w/o Vermilion	1.05	0.93	0.44	1.11	0.48	0.91

The Way Ahead - Resolution

- Better resolution leads to better physics (meter scale)
  - Higher resolution in rivers, channels, gulleys and critical conveyances
  - Better dissipation
  - Better meteorology, waves and circulation
  - Breaking of waves against structures
  - Finer detail in representation of surface roughness

The Way Ahead - Algorithms

- More efficient and accurate numerical engines allow higher *localized* resolution and therefore better physics
  - Better targeted resolution using *h-p* adaptive DG unstructured grid solutions (especially for wave transformation zones)
  - DG solutions are very accurate for advection dominated long-wave propagation problems
  - DG solutions are HIGHLY parallelizable (1000’s to 10000’s of processors) and are ideally suited for the next generation of Peta-scale Super-computers

The Way Ahead - Algorithms

- Large domains with deep ocean boundaries to avoid instabilities and inaccuracies at ocean boundaries
  - Mismatches between the interior physics and ocean boundary specification ALWAYS leads to robustness problems for good algorithms with physical damping
- Second and higher order accuracy algorithms should be implemented
  - Low order accurate schemes have truncation terms that look like large dissipation terms when the grid is coarse relative to the physical spatial gradients
  - This eliminates any hope of defining physics based sub-grid scale process closure coefficients

The Way Ahead - Winds

- Better Atmospheric Forcing
    - Stabilize wind and pressure analysis methods; both kinematic and dynamic
    - Understand the approach to coast issues using coupled 3D NWP/ocean models
    - Rescue and homogenize historical meteorological data
    - Build a library of 20th century storms using re-analysis

The Way Ahead – More Physics

- More Physics – Waves and Circulation
  - Improvements in vertical leveling and Lidar
  - Air – Sea interaction: Wind drag should be wind wave (steepness, direction, period, age) dependent
  - Improved representation of surface roughness to better account for actual biomass and sub-grid scale features (link this in with Lidar)
  - Modified bottom stress due to wave-current interaction
  - Larger regional coupling into wave radiation stresses
  - Hydrologic rainfall models should be coupled in
  - 3D effects should be evaluated
  - Coupled sediment transport models should allow morphology to evolve

The Way Ahead – Momentum Flux

- Air – Sea interaction
  - Wave and surge models should apply same surface stresses/drag laws
  - What is the drag coefficient upper limit and at what wind speed
    - 0.0035 is used while deep water data indicates 0.002
  - How can white capping be explicitly incorporated into air-sea momentum transfer
  - Momentum transfer in highly viscous “muddy” waters
  - Formulate momentum transfer in terms of wave conditions

The Way Ahead – Wave / Current

- Wave / current interaction
  - Wave effects on bottom stress for circulation model and current effects on bottom stress for wave model
  - Highly nonlinear waves – cause set down instead of set up – need to validate theory of Dean and Bender
  - Wave interaction with surge – tight coupling is critical where wave setup is large percentage of set up
  - Check assumption of linear theory for wave radiation stress which works fairly well on beaches due to canceling of errors; how much are we missing due to the nonlinearity
  - Pass wave radiation stress and compute wave radiation stress gradient in the model using them
  - Apply integrated wave radiation stress gradients onto current model nodes
  - Efficient dynamic interpolators in parallel world between wave and current modules

The Way Ahead - Waves

- Wave model improvements
  - Growth and rapidly turning winds – wind input, dissipation and nonlinear wave-wave interaction formulations (DIA->TSA)
  - Wave growth on swell
  - Wind effects on breaking
  - Wave nonlinearity in shallow water
    - Efficient calculation of low frequency energy transfers (efficient parametric Boussinesq solver)
    - Low-frequency energy critical for run up and overtopping

The Way Ahead – Bottom Friction

- Improved representation of bottom surface roughness to better account for actual biomass
  - Vegetation density, height, type
  - Seasonal changes
- Link roughness data with Lidar observations
- Feedback of water level and velocity into roughness
  - Water level to vegetation height ratio
  - Linear drag laws for very slow flows
  - Vegetation bending at high flows

- Vegetation impact on wave radiation stress
  - Emergent vs. submerged – theory suggests reduction by 2/3

The Way Ahead – Hydrologic Coupling

- Hydrologic rainfall routing models should be coupled into circulation models
  - Important for steep topography
  - Important for polders
  - Basin scale
  - Ditch scale
- Wave and surge into and in polders should be computed directly

The Way Ahead – 3D and Data

- 3D effects should be evaluated
  - Return flow produces stress in same direction as wind and therefore enhances the set up
- Data collection
  - Maintain a robust in-situ array of wind measurements
  - Deployable nearshore and marsh wave measurements
  - More survivable and dense network of deployable hydrographs in inland areas
- Validation
  - Continued, systematic validation of modeling components and model system

Acknowledgments

- U.S. Army Engineer Research and Development Center
- U.S. Army Corps of Engineers, New Orleans District
- U.S. Army Corps of Engineers, IPET
- Office of Naval Research
- National Science Foundation
- Morphos
- Federal Emergency Management Agency