

The US Navy coastal surge and inundation prediction system (CSIPS): Making forecasts easier

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Objective

- To develop a tool (GUI) for storm surge and inundation prediction which results in a minimization in man-hours and required operator knowledge for model set-up as well as result in optimal surge and inundation forecasts
 - GUI – Delft Dashboard with CSIPS toolbox
 - Optimal forecasts – Improved resolution and physics over current system



Coastal Surge and Inundation Prediction System (CSIPS)

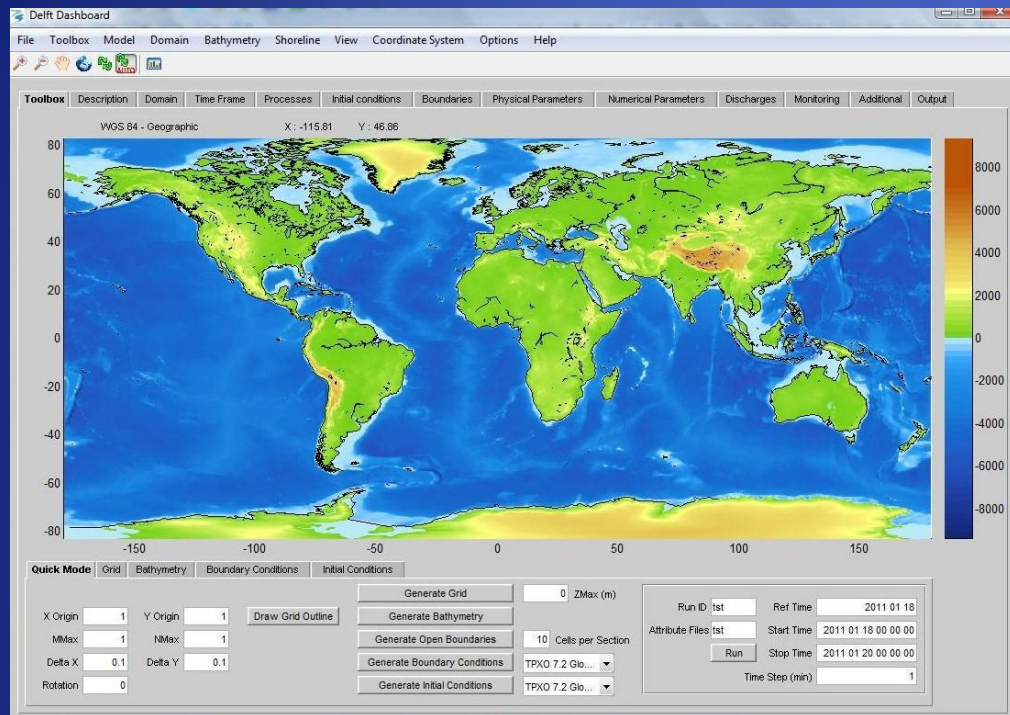
- Delft3D - integrated modeling suite, which simulates 2D and 3D flow, sediment transport and morphology, waves, water quality and ecology.
 - Delft3D – FLOW: Hydrodynamic module
 - Delft3D – WAVE : Wave module
- FLOW is dynamically coupled to WAVE by passing water level, currents, winds, and bed level to WAVE and in return gets radiation stresses for wave setup calculations
- Improved physics and resolution over currently used model – PC-Tides
 - Inclusion of wave coupling and large scale circulation



Delft Dashboard

Capabilities from Deltares

- GUI specific to Delft3D
- Select an area from the world map using the GUI – rectangular grid, size and resolution
- Interpolate bathymetry from dataset
- Specify type of boundary conditions (water level, Riemann, discharge etc)
- Specify type of forcing (Astronomic, time series etc)

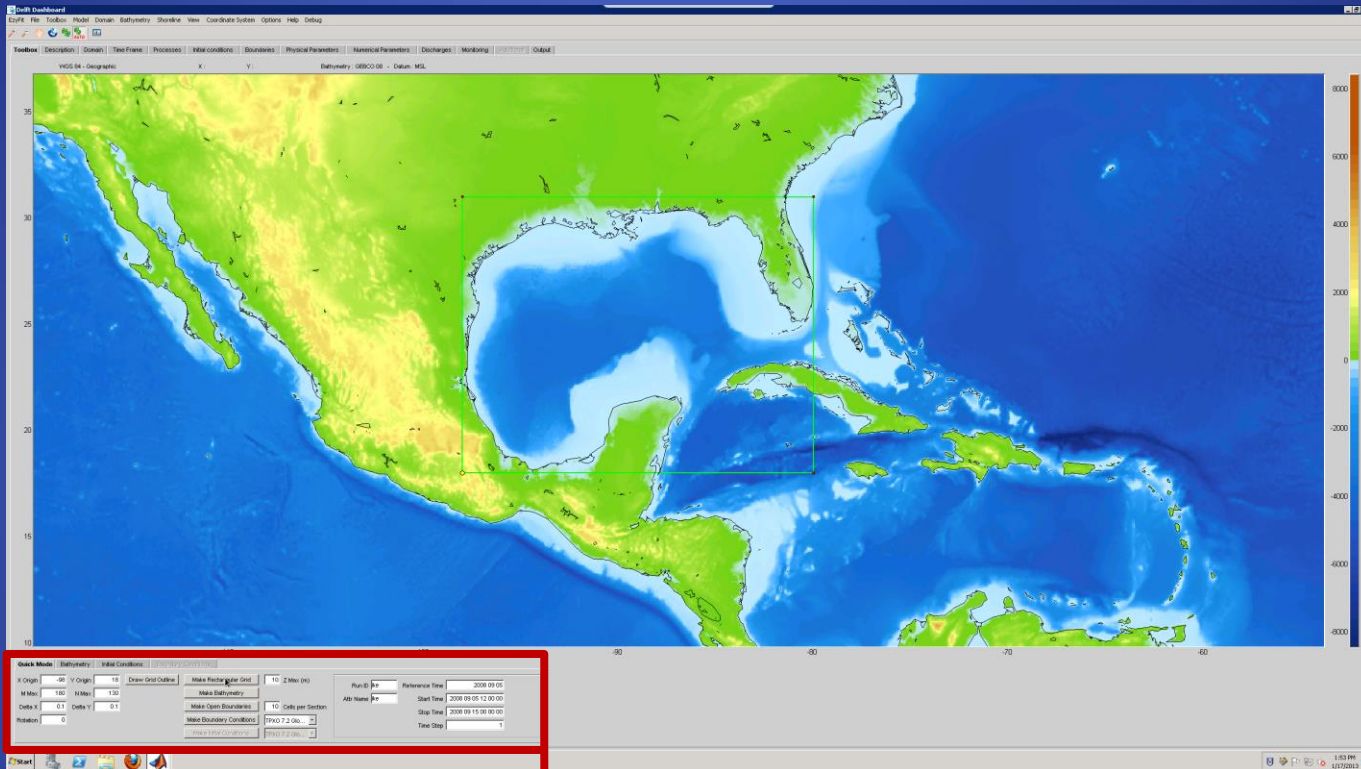


New capabilities from Deltares

- Extend GUI to include Delft3D-WAVE (delivered, under testing)
- Capability to set up nested domains (delivered, under testing)
- Extension of functionality with outer boundary forcing data from NCOM/HYCOM, COAMPS, WAVEWATCH III (delivered, under testing)



Delft Dashboard - Grid



Quick Mode | Bathymetry | Initial Conditions | Boundary Conditions

X Origin: -98 Y Origin: 18 Draw Grid Outline: ☐ Make Rectangular Grid: ☒ Z Max (m): 10
M Max: 180 N Max: 130 Make Bathymetry: ☐
Delta X: 0.1 Delta Y: 0.1 Make Open Boundaries: ☐ 10 Cells per Section
Rotation: 0 Make Boundary Conditions: ☐ TPXO 7.2 Glo...
Make Initial Conditions: ☐ TPXO 7.2 Glo...

Run ID: ke Reference Time: 2008 09 05
Attr Name: ke Start Time: 2008 09 05 12 00 00
Stop Time: 2008 09 15 00 00 00
Time Step: 1

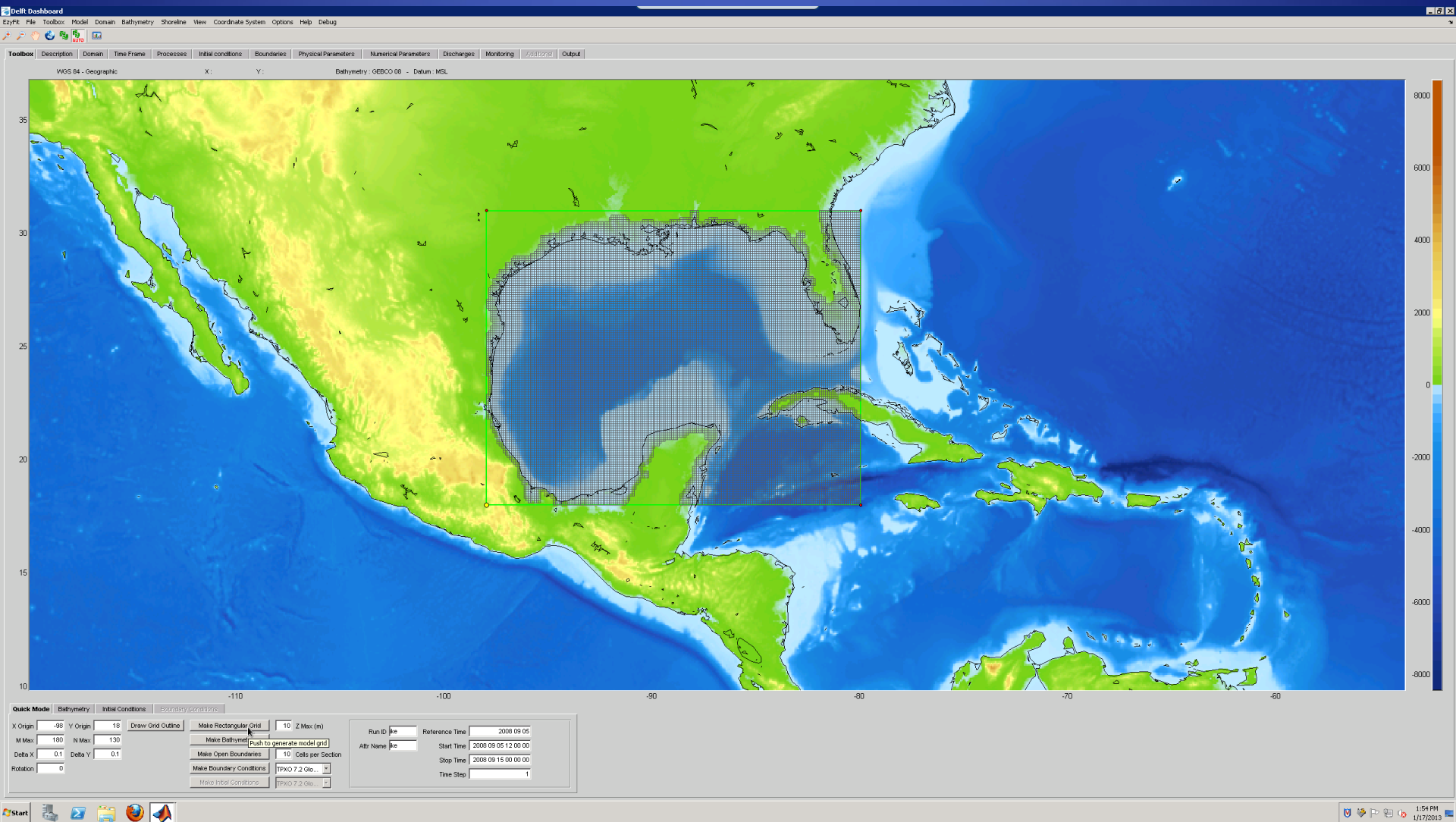
Quick Mode | Bathymetry | Initial Conditions | **Boundary Conditions**

X Origin: -98 Y Origin: 18 Draw Grid Outline: ☐ Make Rectangular Grid: ☒ Z Max (m): 10
M Max: 180 N Max: 130 Make Bathymetry: ☐
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Run ID: ke Reference Time: 2008 09 05
Attr Name: ke Start Time: 2008 09 05 12 00 00
Stop Time: 2008 09 15 00 00 00
Time Step: 1



Delft Dashboard - Grid





Delft Dashboard - Bathy

Quick Mode **Bathymetry** Initial Conditions Boundary Conditions

X Origin Y Origin Draw Grid Outline Z Max (m)

M Max N Max

Delta X Delta Y Cells per Section

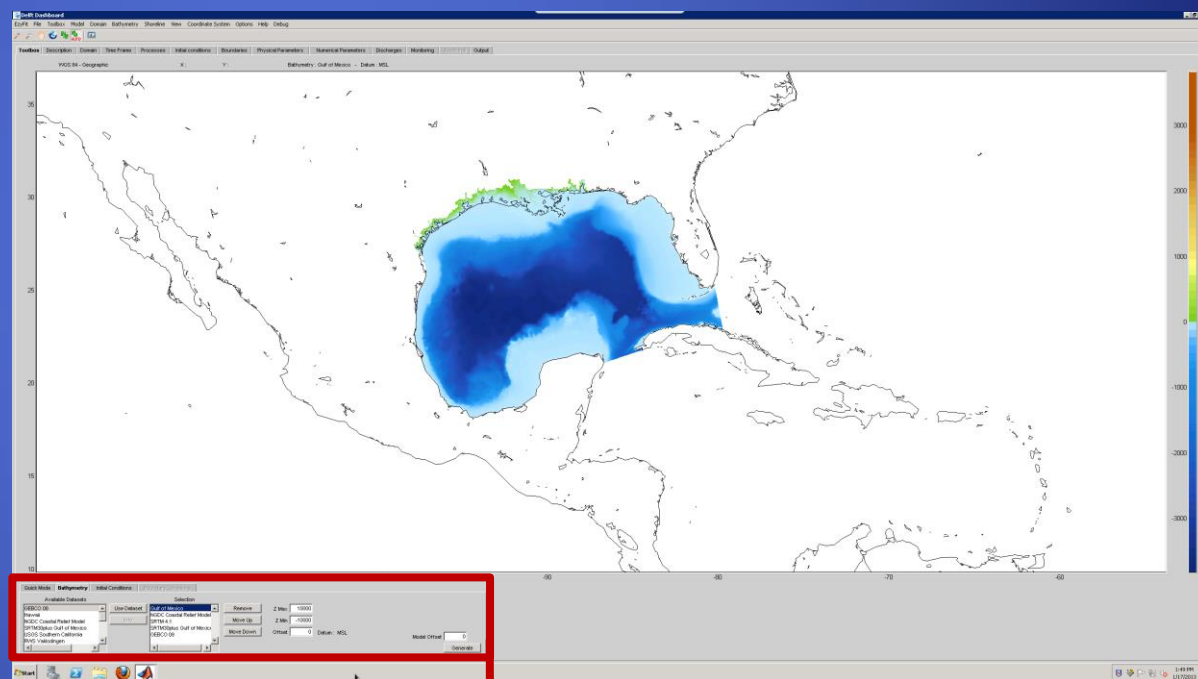
Rotation TPXO 7.2 Glo... TPXO 7.2 Glo...

Run ID Reference Time

Attr Name Start Time

Stop Time

Time Step



Quick Mode **Bathymetry** Initial Conditions Boundary Conditions

Available Datasets Selection

Available Datasets	Selection	Remove	Move Up	Move Down	Z Max	Z Min	Offset	Datum	Model Offset
GEBCO 08	Gulf of Mexico	Remove	Move Up	Move Down	10000	-10000	0	MSL	0
Hawaii	NGDC Coastal Relief Model								
NGDC Coastal Relief Model	SRTM 4.1								
SRTM30plus Gulf of Mexico	SRTM30plus Gulf of Mexico								
USGS Southern California	GEBCO 08								
RWS Vakkoddingen									

- SURA – Gulf of Mexico
- NGDC Coastal Relief Model
- SRTM 4.1 / 3.0
- GEBCO 08
- USGS California
- RWS Vakkoddingen
- EMODnet
- MarineScotland
- GeoScienceAustralia
- NCTR



Delft Dashboard – BC's

Quick Mode | Bathymetry | Initial Conditions | **Boundary Conditions**

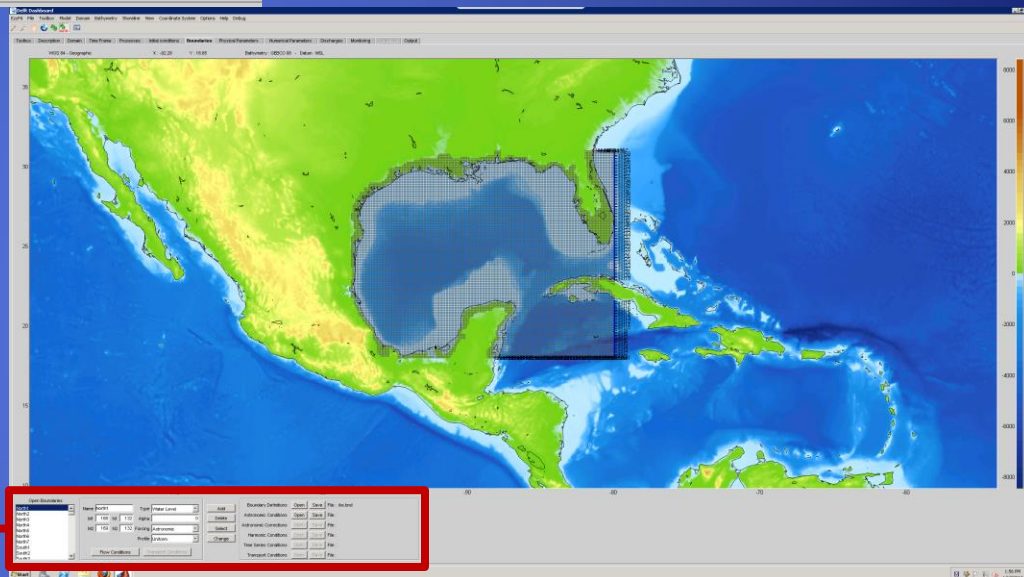
X Origin: -98 Y Origin: 18 Draw Grid Outline: ☐ Z Max (m): 10
M Max: 180 N Max: 130
Delta X: 0.1 Delta Y: 0.1
Rotation: 0

Make Rectangular Grid
Make Bathymetry
Make Open Boundaries
Make Boundary Conditions
Make Initial Conditions

Run ID: ike Reference Time: 2008 09 05
Attr Name: ike Start Time: 2008 09 05 12 00 00
Stop Time: 2008 09 15 00 00 00
Time Step: 1

TPXO 7.2 Glo...
TPXO 7.2 Glo...

- Oregon State University Global Model of Ocean Tides
 - TPXO 6.2
 - TPXO 7.2
- Mediterranean
- European Shelf



Open Boundaries

North1
North2
North3
North4
North5
North6
North7
South1
South2
South3

Name: North1 Type: Water Level
M1: 168 N1: 132 Alpha: 0
M2: 169 N2: 132 Forcing: Astronomic
Profile: Uniform

Flow Conditions Transport Conditions

Boundary Definitions Open Save File: ike.bnd
Astronomic Conditions Open Save File:
Astronomic Corrections Open Save File:
Harmonic Conditions Open Save File:
Time Series Conditions Open Save File:
Transport Conditions Open Save File:

Quick Mode | Bathymetry | Initial Conditions | **Boundary Conditions**

X Origin: -98 Y Origin: 18 Draw Grid Outline: ☐ Z Max (m): 10
M Max: 180 N Max: 130
Delta X: 0.1 Delta Y: 0.1
Rotation: 0

Make Rectangular Grid
Make Bathymetry
Make Open Boundaries
Make Boundary Conditions
Make Initial Conditions

TPXO 6.2 Global Inverse Tide Model
TPXO 7.2 Global Inverse Tide Model
Mediterranean
European Shelf 2008
TPXO 7.2 Glo...
TPXO 7.2 Glo...

Run ID: ike Reference Time: 2008 09 05
Attr Name: ike Start Time: 2008 09 05 12 00 00
Stop Time: 2008 09 15 00 00 00
Time Step: 1

Select tide database for boundary conditions

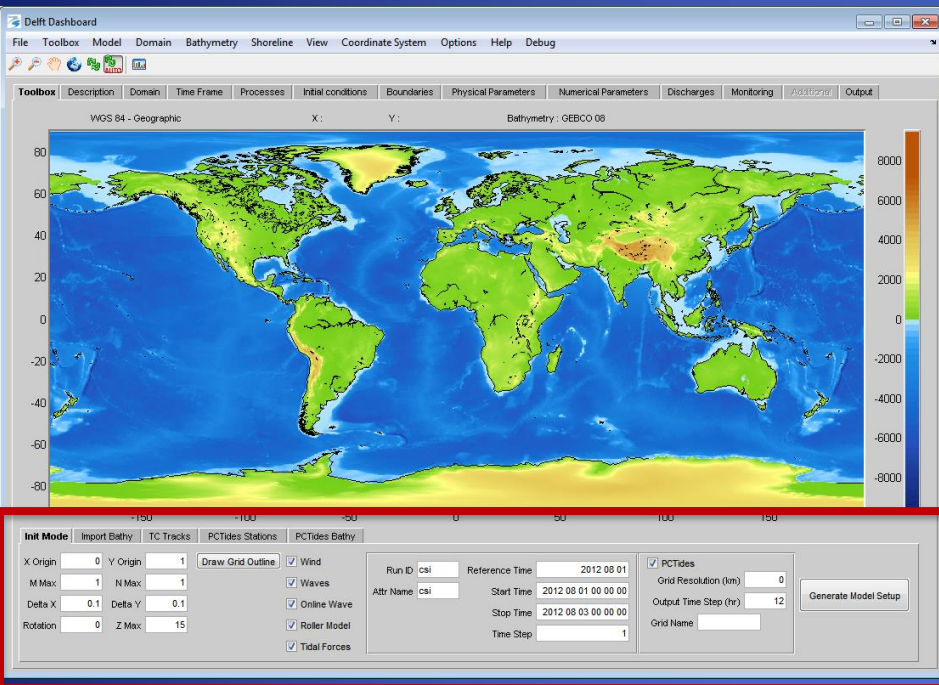


Delft Dashboard – Other Capabilities

- Observation Points / Monitoring
- Physical Parameters
- Numerical Parameters
- Processes
- Initial Conditions
- Discharge
- Output



Delft Dashboard – CSIPS



CSIPS TOOLBOX highlights

- Grid parameters: Size, resolution, orientation
 - Option: Draw box for creating grid
- Activate/deactivate processes
- Select forecast start and end time; time step for computations
- PCTides support
 - + Model currently used by NAVO
 - + Seamless transition (saves setup time and training time)
 - + Quick output O(mins)
 - Low resolution grids O(km)
 - No waves

Init Mode | Import Bathy | TC Tracks | PCTides Stations | PCTides Bathy

X Origin: 0 Y Origin: 1 Draw Grid Outline ☒ Wind

M Max: 1 N Max: 1 ☒ Waves

Delta X: 0.1 Delta Y: 0.1 ☒ Online Wave

Rotation: 0 Z Max: 15 ☒ Roller Model

☒ Tidal Forces

Run ID: csi Reference Time: 2012 08 01

Attr Name: csi Start Time: 2012 08 01 00 00 00

Stop Time: 2012 08 03 00 00 00

Time Step: 1

☒ PCTides

Grid Resolution (km): 0

Output Time Step (hr): 12

Grid Name:

Generate Model Setup



Delft Dashboard – CSIPS

Bathymetry/Topography

- Default: GEBCO 08
- Import feature: Can import xyz/yxz/arc files (standard NAVO format)
 - Convert to tiled netcdf for use in model generation
- Currently supported datums:
 - MSL, MLLW, MHW
 - Can specify offset

TC Tracks

- Full support (D3D, PCTides) for JTWC warning, NHC forecast/advisories, best track files
- Download TC track data on-demand or use locally archived files
 - Time, location checks to avoid mismatches w/model domains



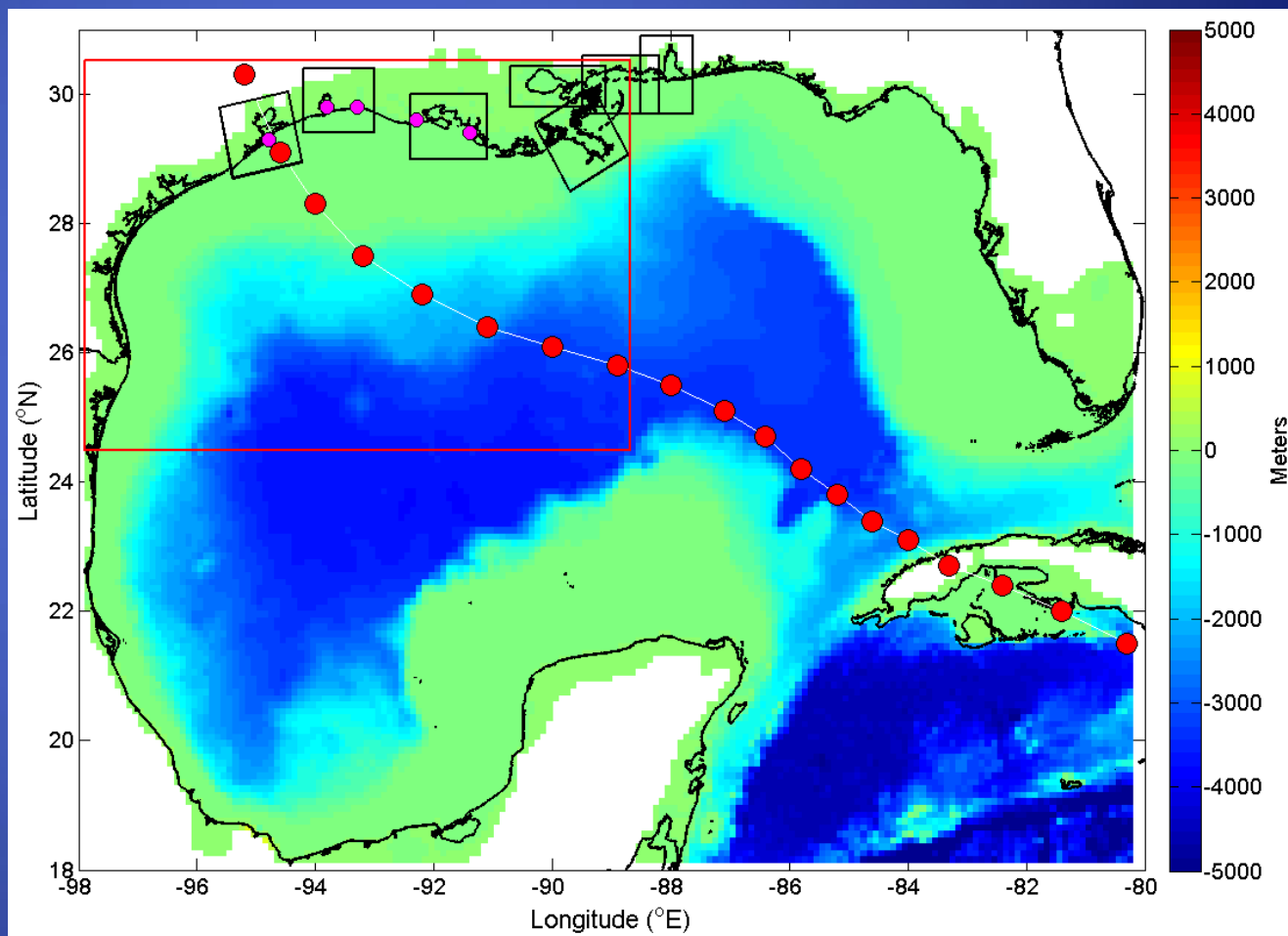
Hurricane Ike

- September 1 – 15, 2008
- Landfall:
 - September 13 0700 UTC
 - North end Galveston Island
 - Strong and large Category 2
 - Highest water mark 5.3 m (17.5 ft.) NAVD88
 - 3rd Costliest storm in US history



Domains

- Gulf of Mexico Domain
 - $0.1^\circ \times 0.1^\circ$
 - 179×129
 - 1 day runtime ~ 30 min @ $dt = 10$ min
- Nearshore Domain
 - $0.02^\circ \times 0.02^\circ$
 - 462×302
 - 1 day runtime ~ 60 min @ $dt = 5$ min
- Coastal Domains
 - $0.004^\circ \times 0.004^\circ$
 - Various sizes
 - 1 day runtime ~ 30 min @ $dt = 1$ min





Baseline Simulation Model Setup

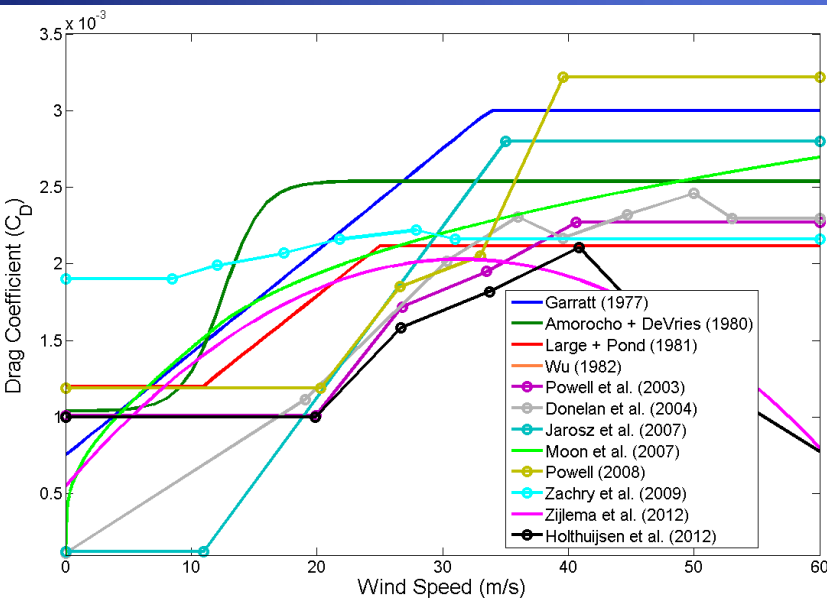
- Gulf of Mexico domain
- Bathymetry / Topography data:
 - SURA inundation testbed GoM dataset
 - NOAA NGDC Coastal Relief Model
 - SRTM topography data
 - GEBCO 08
- Riemann (weakly reflective) boundary conditions with astronomic forcing
- Tidal constituents:
 - OSU global model of ocean tides based on TOPEX7.2 satellite altimeter data
- Initial water level: 0.11 m – seasonal trends
- Wave coupling every 60 minutes



Baseline Simulation

Wind

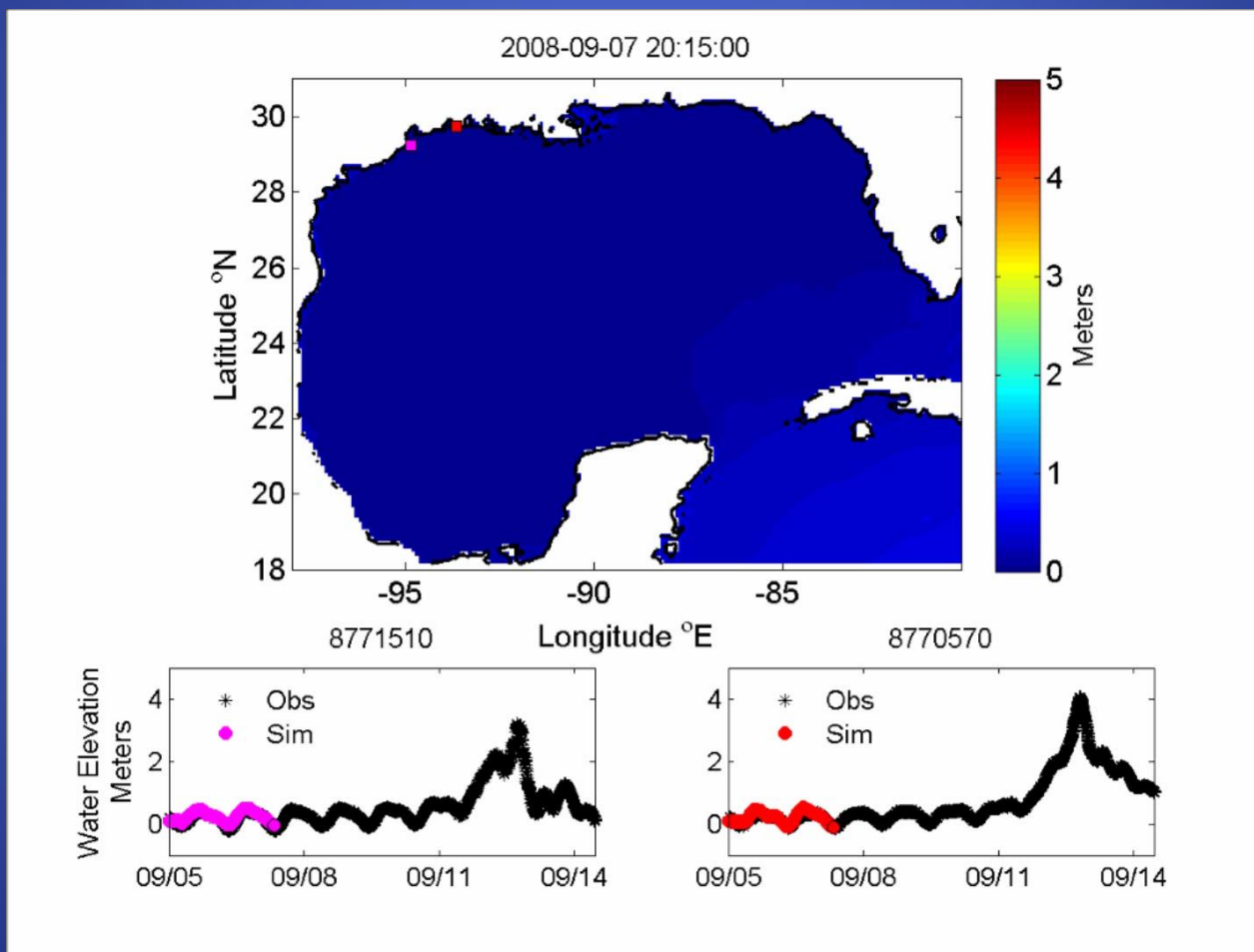
- Atmospheric forcing provided by Oceanweather Inc.
 - Interactive Objective Kinematic Analysis (IOKA)
 - Hwind blended and local measurements are blended with large scale wind and pressure field
- Considered 12 drag coefficient formulations
- Formulation of Holthuijsen et al. (2012) produced the best results



C_D Formulation	Peak Water Level Percent Error				
	LAWMA, Amerada Pass	Freshwater Canal Locks	Calcasieu Pass	Sabine Pass North	Galveston Pleasure Pier
Garratt (1977)	5.48	17.12	20.26	25.79	15.97
Amorcho and DeVries (1980)	7.12	15.42	17.80	22.56	12.93
Large and Pond (1981)	-1.62	8.19	9.23	13.13	6.80
Wu (1982)	5.70	18.01	20.60	26.38	16.72
Powell et al. (2003)	-10.35	2.36	3.15	6.94	3.62
Donelan et al. (2004)	-6.63	4.70	5.85	9.89	5.52
Jarosz et al. (2007)	-8.13	7.73	10.01	14.93	9.45
Moon et al. (2007)	-0.02	9.82	11.04	15.38	8.65
Powell (2008)	-7.81	5.70	6.69	11.33	7.57
Zachry et al. (2009)	1.13	9.35	11.33	15.49	8.30
Zijlema et al. (2012)	-2.17	6.98	7.74	11.47	5.62
Holthuijsen et al. (2012)	-12.34	-0.59	0.78	4.49	1.72

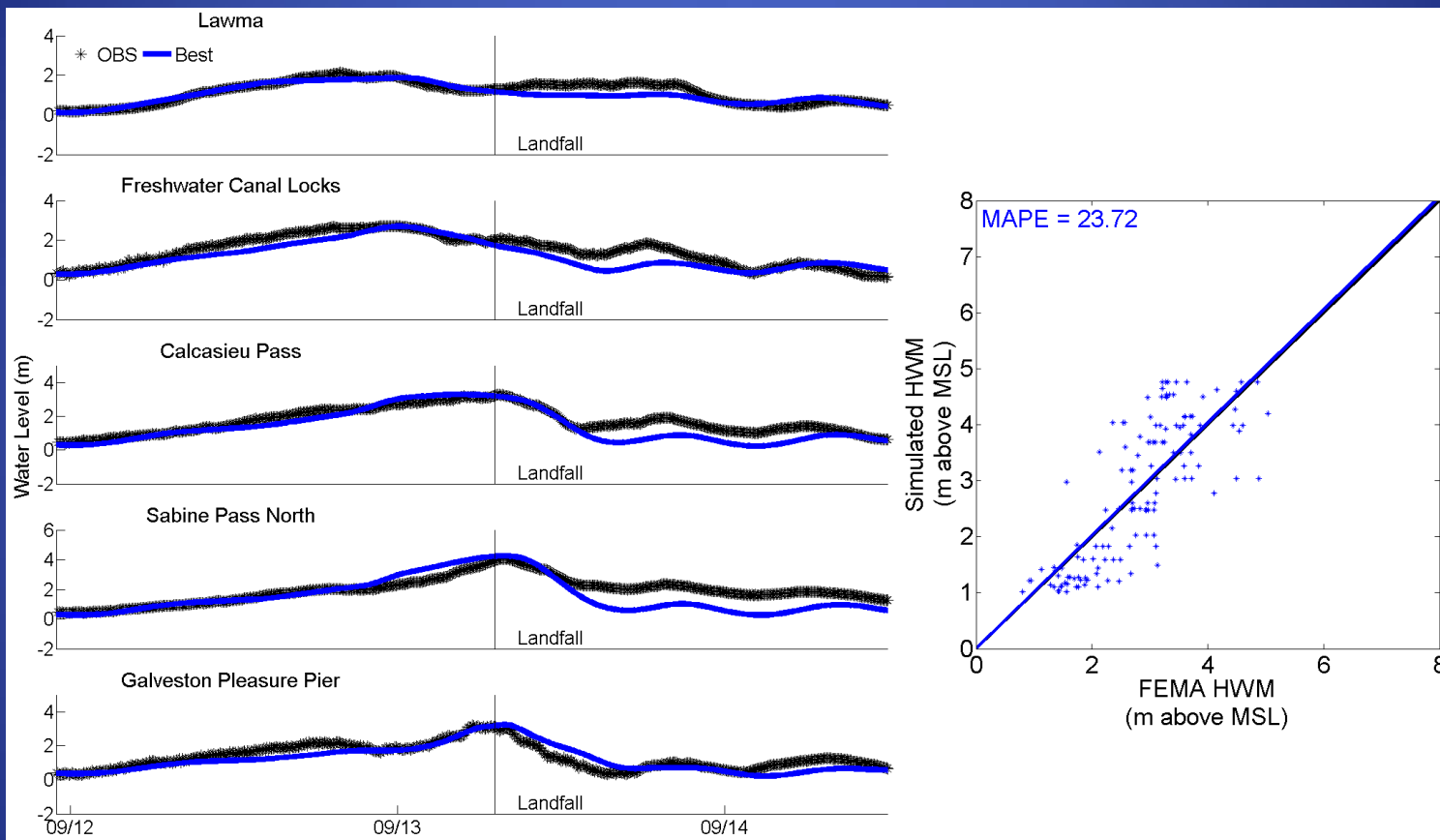


Baseline Simulation Results





Baseline Simulation Results

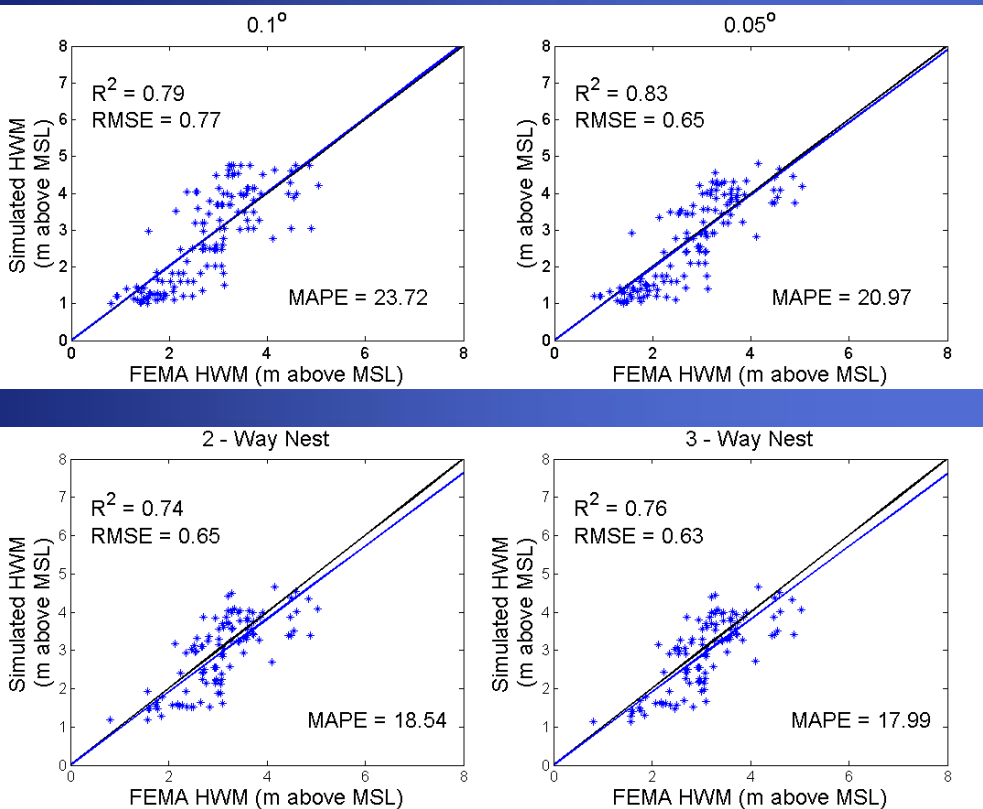


Peak Water Level Percent Error

LAWMA, Amerada Pass	Freshwater Canal Locks	Calcasieu Pass	Sabine Pass North	Galveston Pleasure Pier	High Water Marks
-12.34	-0.59	0.78	4.49	1.72	23.72



Sensitivity Studies Grid Resolution



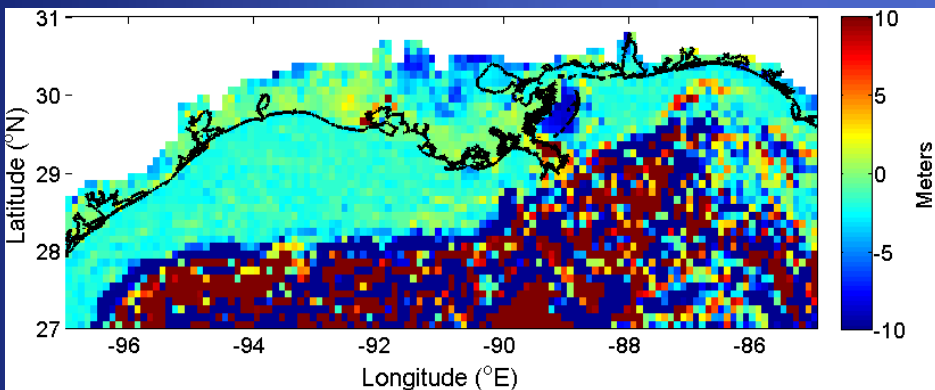
- Water level results good with coarse resolution
- Inundation results improve with increasing resolution
- 0.5° domain
- 2 – way nesting
 - 0.1° to 0.004°
- 3 – way nesting
 - 0.1° to 0.02° to 0.004°



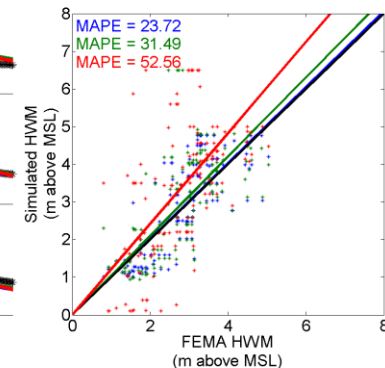
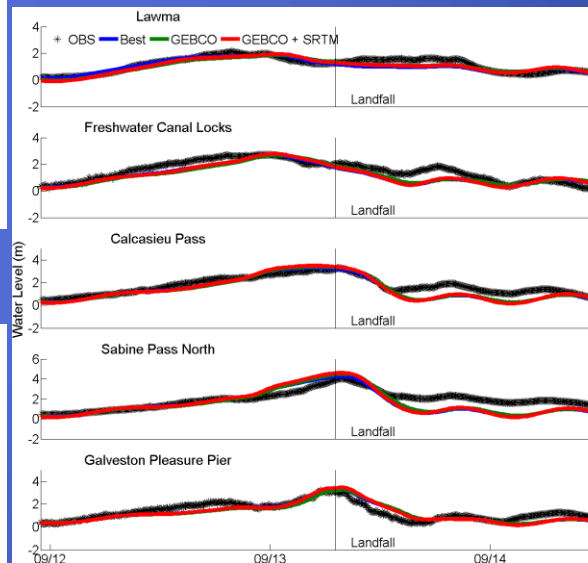
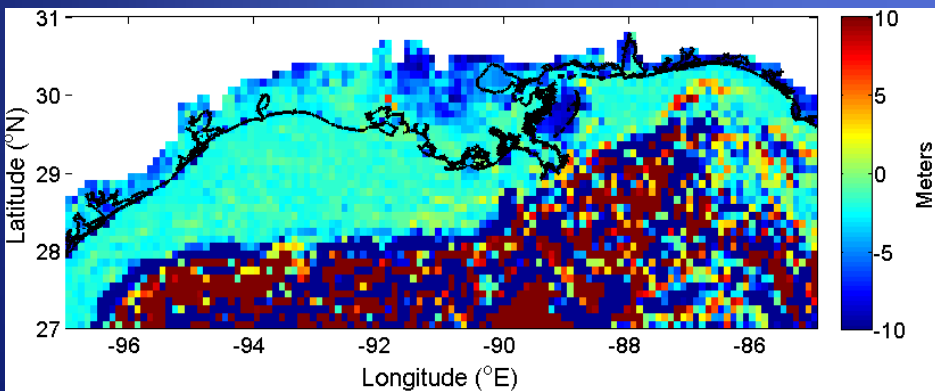
Sensitivity Studies

Bathymetry / Topography

Baseline - GEBCO

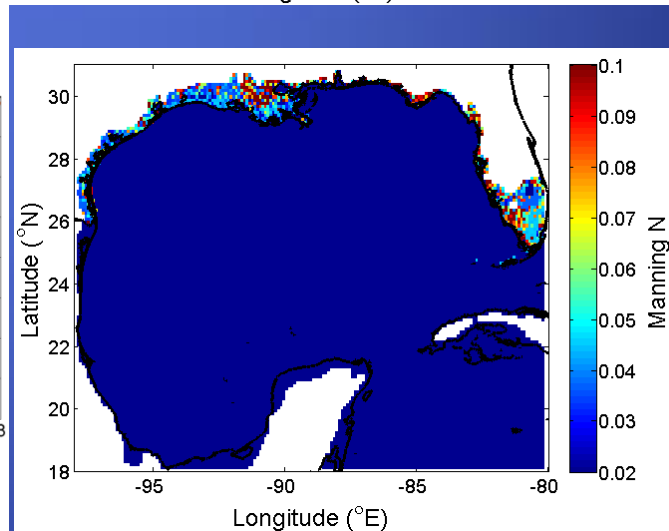
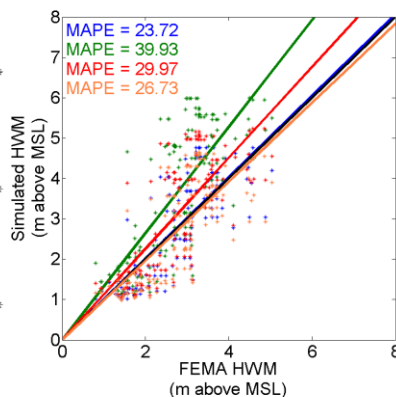
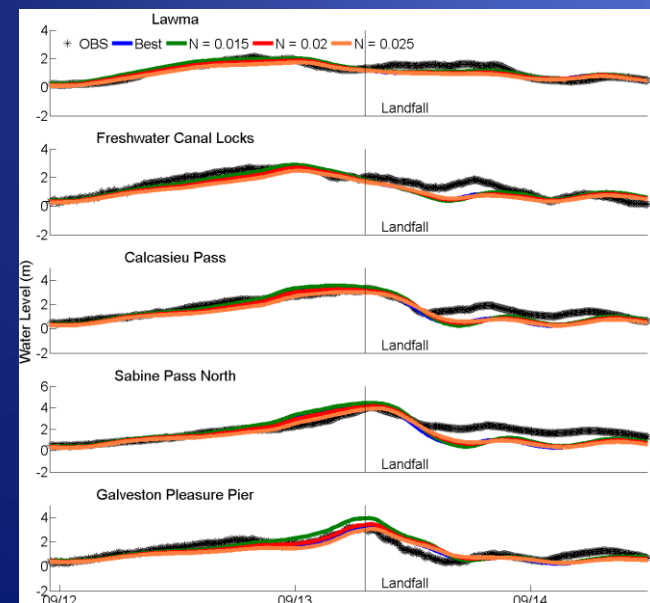
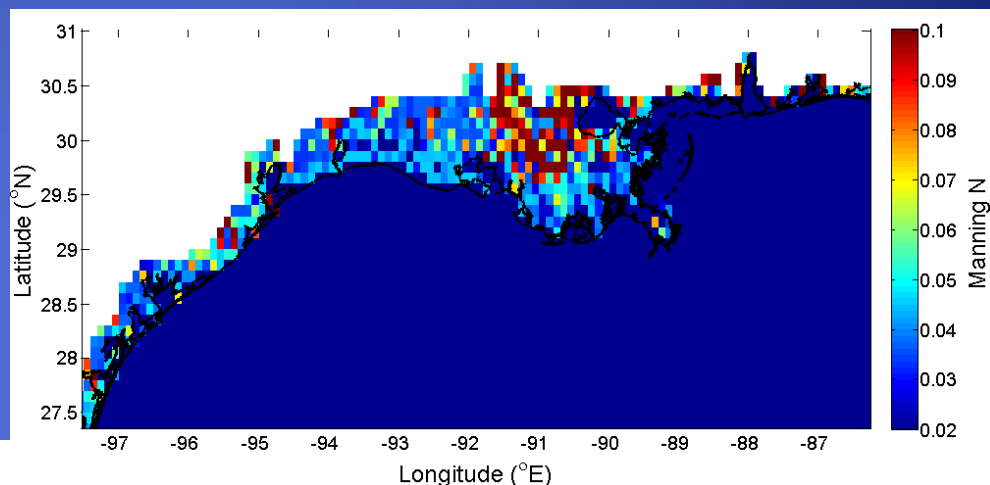


Baseline - GEBCO+SRTM



Sensitivity Studies Bottom Roughness

- Variable Manning's N coefficient based on land use data
- Offshore value of 0.02





Sensitivity Studies

Waves

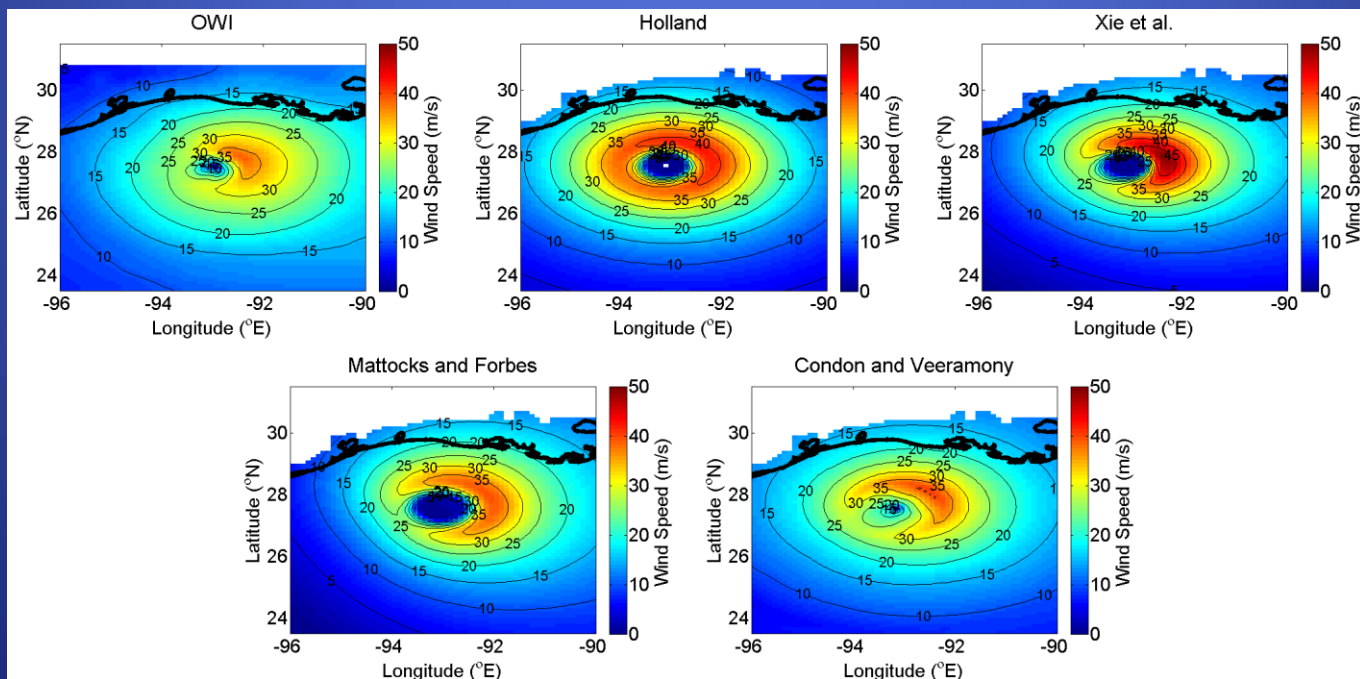
- Wave coupling defined by communication time between FLOW and WAVE modules

Run	Water Level – Percent Error of Peak					HWM MAPE
	Lawma, Armeda Pass	Freshwater Canal Locks	Calcasieu Pass	Sabine Pass North	Galveston Pleasure Pier	
Baseline (60 Min Coupling)	12.34	0.59	0.79	4.49	1.72	23.72
No Waves	48.77	46.25	37.33	32.76	25.81	32.94
20 Min Coupling	9.00	4.06	3.55	4.50	3.43	23.37
30 Min Coupling	8.98	4.04	0.52	4.36	1.40	23.97
120 Min Coupling	13.86	5.09	3.27	6.51	3.25	23.92
180 Min Coupling	10.67	3.69	2.67	6.66	2.51	23.89
360 Min Coupling	16.06	15.69	3.33	4.44	0.74	22.93



Wind Model

- Tested four analytic models using NHC Best Track data
 - Holland (1980)
 - Xie et al. (2006)
 - Mattocks and Forbes (2008)
 - Condon and Veeramony





Wind Model

Condon and Veeramony

Example: $W_s = 95$ KT, $R_{max} = 50$ n. mi., $P_n = 1007$ hPa, $P_c = 954$ hPa, $R_o = 300$ n. mi.

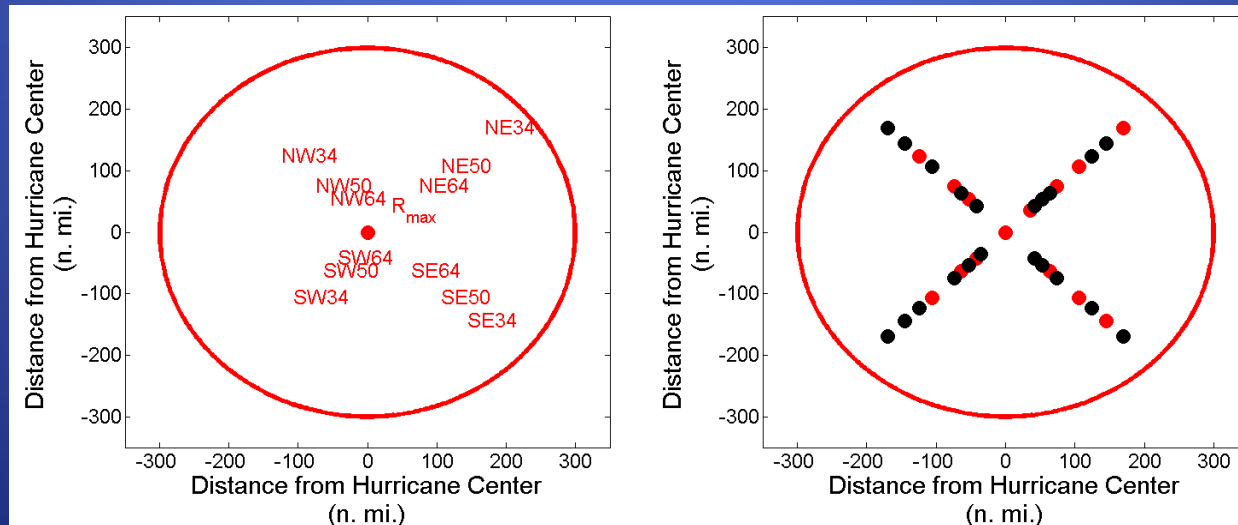
64 KT... 105NE 90SE 60SW 75NW

50 KT... 150NE 150SE 90SW 105NW

34 KT... 240NE 205SE 150SW 175NW

$$V(r) = \left[\frac{B}{\rho_a} \left(\frac{R_{max}}{r} \right)^B (P_n - P_c) \exp^{-(R_{max}/r)^B} + \left(\frac{rf}{2} \right)^2 \right]^{1/2} - \left(\frac{rf}{2} \right)$$

$$B = \frac{(V_R^2 + V_R Rf) \rho_a e}{P_n - P_c}$$



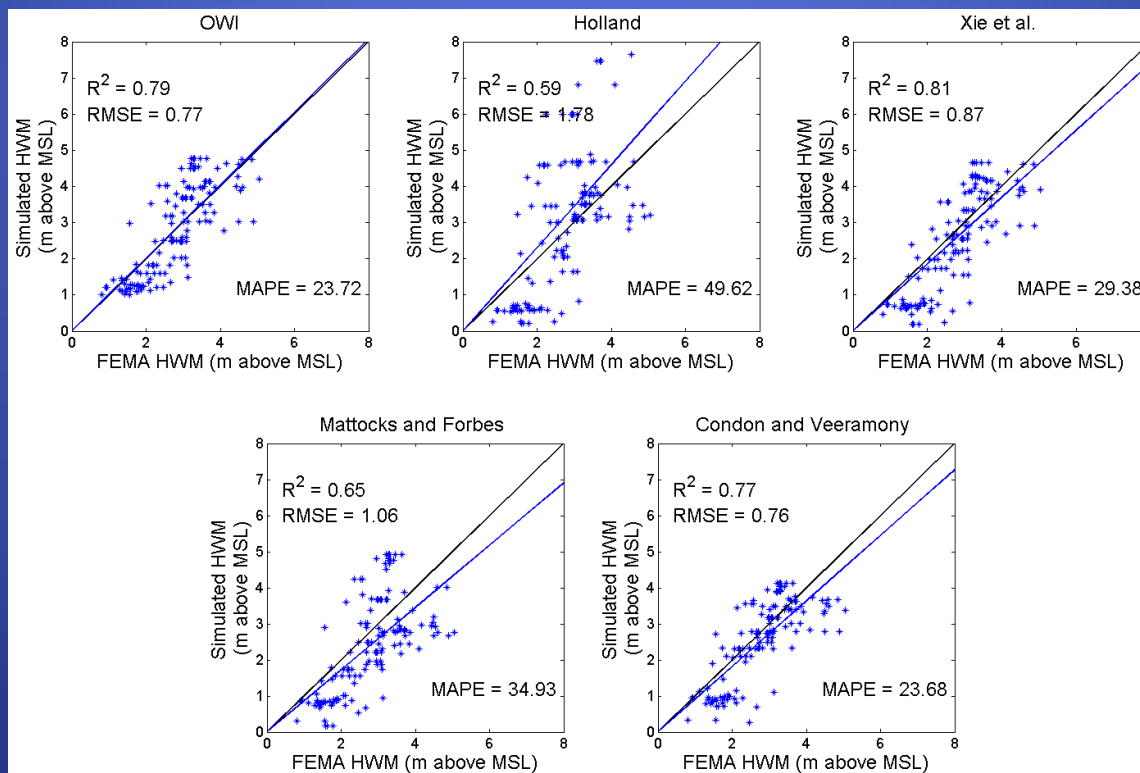


Wind Model Results



Wind Speed (m/s)	H80	X06	MF07	CV12
0 – 10	3	2	1	4
10 – 20	1	2	3	4
20 – 30	2	1	3	4
30 – 40	1	3	2	4
40 – 50	1	2	3	4
Total	8	10	12	20

Ranking based on comparison to Hwind of the Integrated Kinetic Energy – by wind speed band





Conclusions

- Delft Dashboard coupled with the CSIPS toolbox provides the framework to create and run storm surge and inundation forecasts
- As expected the model results are very sensitive to a number of input parameters (You need good data!)
 - Proper grid resolution is necessary for quality inundation results, can get by with coarse resolution to model coastal water levels
 - Bathymetry / Topography data matter – High resolution data can have a large influence even on a coarse grid
 - Land cover / bottom roughness data is needed to improve inundation simulation results
- Proper wind forcing is needed
 - Many modeling studies use older drag formulations with a simple cap; newer formulations may offer better results
 - Various analytic wind models can offer very different results
 - New model offers promising results ... more testing is needed



Ongoing Work

- Validation with Hurricane Irene and Typhoon Pongsona
- Including new wind model in Dashboard framework
- Spatially variable resolution grid generation in Dashboard – test vs. nesting
- Streamline everything for operational use
 - Testing to begin this coming hurricane season



Thank you

Questions?

Contact: andrew.condon.ctr@nrlssc.navy.mil

References

- J. R. Garratt, "Review of drag coefficients over oceans and continents," *Monthly Weather Review*, vol. 105, pp. 915 - 929, 1977.
- J. Amorochio and J. J. DeVries, "A new evaluation of the wind stress coefficient over water surfaces," *Journal of Geophysical Research*, vol. 85, no. C1, pp. 433 - 442, 1980.
- W. G. Large and S. Pond, "Open ocean momentum flux measurements in moderate to strong winds," *Journal of Physical Oceanography*, vol. 11, pp. 324 - 336, 1981.
- J. Wu, "Wind-stress coefficients over sea surface from breeze to hurricane," *Journal of Geophysical Research*, vol. 87, no. C12, pp. 9704 - 9706, 1982.
- M. D. Powell, P. J. Vickery and T. A. Reinhold, "Reduced drag coefficient for high wind speeds in tropical cyclones," *Nature*, vol. 422, pp. 279 - 283, 2003.
- M. A. Donelan, B. K. Haus, N. Reul, W. J. Plant, M. Stiassnie, H. C. Graber, O. B. Brown and E. S. Saltzman, "On the limiting aerodynamic roughness of the ocean in very strong winds," *Geophysical Research Letters*, vol. 31, no. L18306, 2004.
- E. Jarosz, D. A. Mitchell, D. W. Wang and W. J. Teague, "Bottom-up determination of air-sea momentum exchange under a major tropical cyclone," *Science*, vol. 315, pp. 1707 - 1709, 2007.
- I. J. Moon, I. Ginis, T. Hara and B. Thomas, "A physics-based parameterization of air-sea momentum flux at high wind speeds and its impact of hurricane intensity predictions," *Monthly Weather Review*, vol. 135, pp. 2869 - 2878, 2007.
- M. D. Powell, "High wind drag coefficient and sea surface roughness in shallow water," Final Report to the Joint Hurricane Testbed, NOAA HRD-AOML, 2008.
- B. C. Zachry, C. W. Letchford, D. Zuo, J. L. Schroeder and A. B. Kennedy, "Surface drag coefficient behavior during Hurricane Ike," in 11th Americas Conference on Wind Engineering, San Juan, PR, 2009.
- M. Zijlema, G. P. van Vledder and L. H. Holthuijsen, "Bottom friction and wind drag for wave models," *Coastal Engineering*, vol. 65, pp. 19-26, 2012.
- M. D. Powell, L. Holthuijsen and J. Pietrzak, "Spatial variation of surface drag coefficient in tropical cyclones," unpublished, 2012.
- G. J. Holland, "An analytic model of the wind and pressure profiles in hurricanes," *Monthly Weather Review*, vol. 108, pp. 1212 - 1218, 1980.
- L. Xie, S. Bao, L. J. Pietrafesa, K. Foley and M. Fuentes, "A real-time hurricane surface wind forecasting model: Formulation and verification," *Monthly Weather Review*, vol. 134, pp. 1355 - 1370, 2006.
- C. Mattocks and C. Forbes, "A real-time, event-triggered storm surge forecasting system for the state of North Carolina," *Ocean Modelling*, vol. 25, pp. 95 - 119, 2008.

- Delft3D – FLOW: solves the shallow water equations with a finite difference scheme in 2 (depth averaged) or 3 dimensions. It computes the non-steady flow resulting from tidal forcing along the open boundaries, wind stress and atmospheric pressure along the free surface, and forcing from pressure (barotropic) or density (baroclinic) gradients
- Delft3D – WAVE: Based on the third generation wave model, SWAN, it computes the full wave spectrum by considering a number of processes including: wave refraction; generation by wind; depth and current induced shoaling; dissipation due to whitecapping, bottom friction, and breaking; nonlinear interactions; transmission and blocking by flow and obstacles; and diffraction



Sensitivity Studies

Boundary Forcing / Water Level

- Initial water level ~ 0.11 m
- Constant boundary forcing (A_0) of 0.055 m along with tides
- TPXO 7.2 vs. TPXO 6.2

