An Ensemble based Reliable Storm Surge Forecasting for Gulf of Mexico

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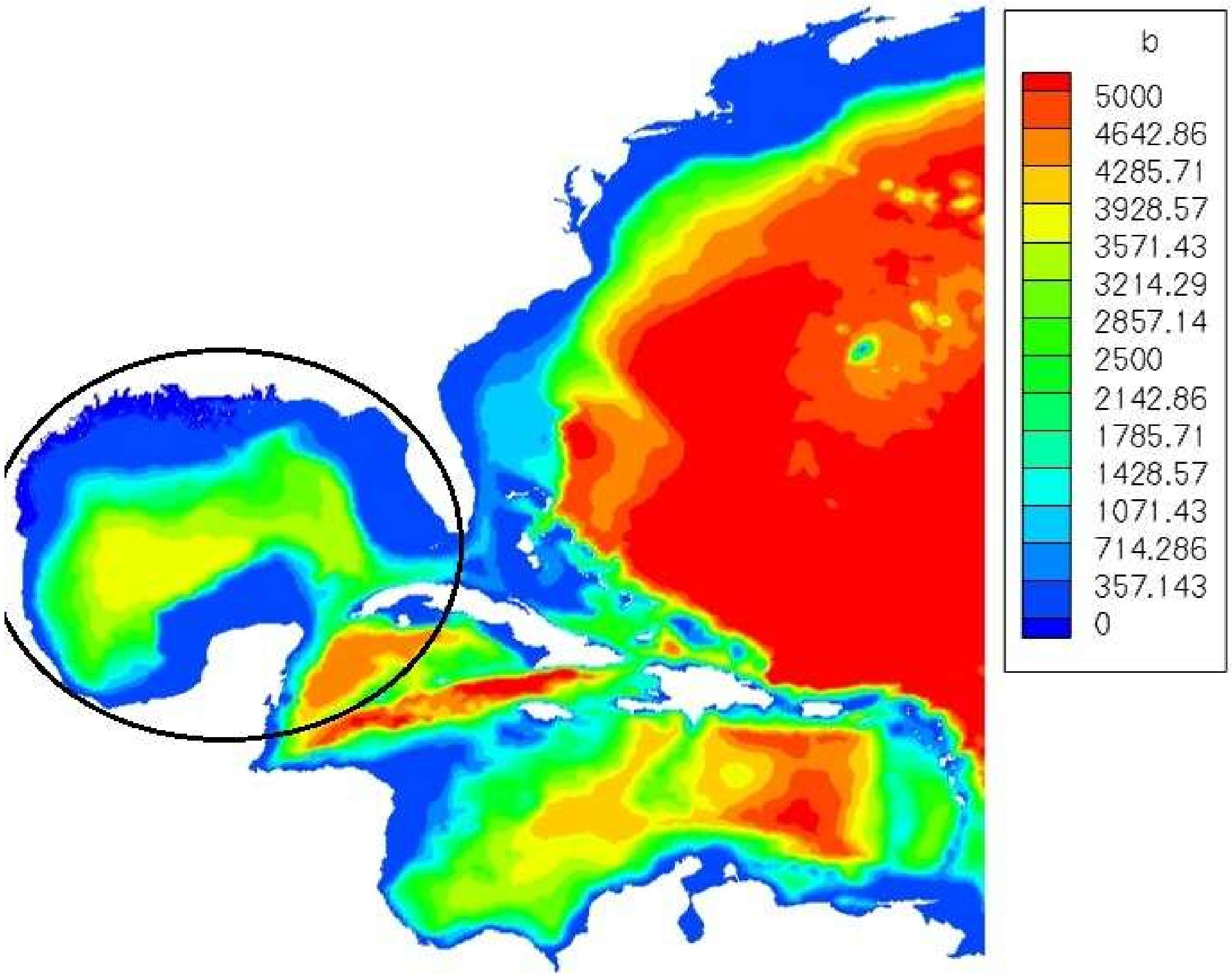
Outline

- Background
- ADCIRC Model
- Kalman Filter
- Numerical Experiment
- Time Local Hinfinity Filter
- Conclusion

Background

- Storm surge have recently seen an attention due to the devastating 2005 hurricane season.
- There have been substantial efforts to place instruments capable of measuring water levels, wind speeds, and wave heights particularly along the Texas, Louisiana and Mississippi coasts.
- These data collection efforts have been particularly useful for hind-casting recent hurricane events, for the purpose of better under-standing the coastal impact, and designing improved coastal pro-tection systems.
- Based on these studies and data a real-time forecasting system is developed.

Background



North Atlantic

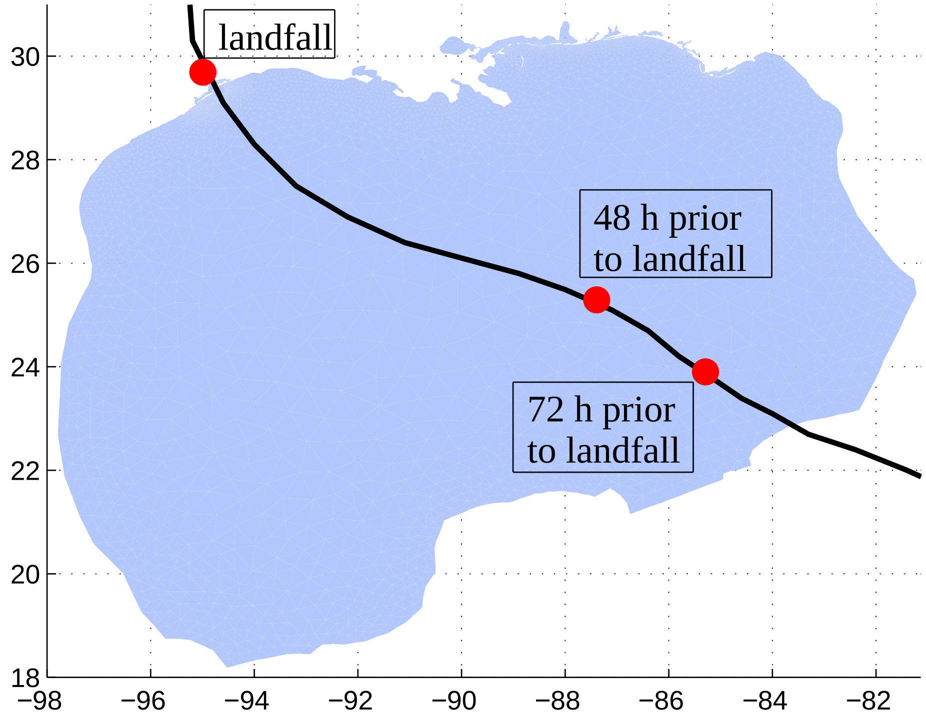
Bathymetry

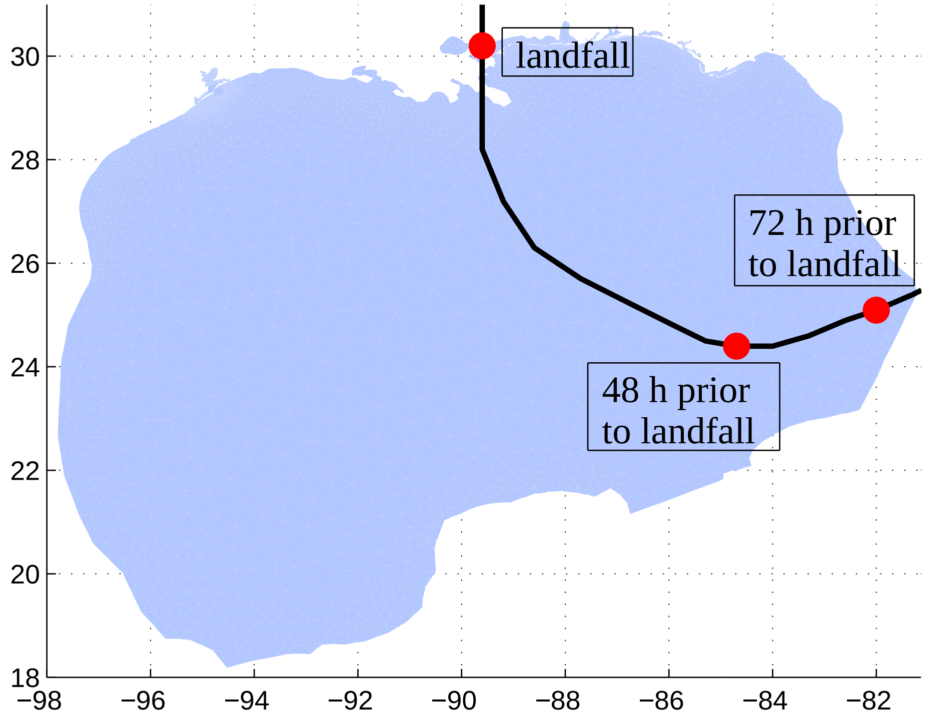
Gulf of Mexico

ADCIRC Model

- Advanced Circulation (ADCIRC) model the shallow water equations
- It uses finite element methods defined on unstructured meshes in space and difference schemes in time.
- Coupled with a wind-wave model for capturing wave-induced setup.
- Typical domain Gulf of Mexico possibly including the western north Atlantic
- Recently used for many hindcast studies of recent hurricanes.
- Aim to compute predicted water level along the coast within 1-2 hour time window.

Hurricanes





- Left: Hurricane Ike. Landfall on Sept. 13, 2008 at 07:10 UTC and the locations of the hurricane approximately 48 and 72 h before landfall.
- Right: Hurricane Katrina. Landfall on Aug. 29, 2005 at 11:10 UTC and the locations of the hurricane approximately 48 and 72 h before landfall.

Hindcast studies

- Example:

	Ike	Katrina
Domain	Western North Atlantic	Western North Atlantic
Avg. Mesh Element Size	1.34 km^2	1.34 km^2
Time Step	1 s	1 s
Wind Field	OWI	OWI
Nodes	$3,322,439$	$5,035,113$
CPUs	2038	2038

- Summary of hindcast (truth) simulation used for Hurricanes Ike and Katrina to generate data.

Why Data Assimilation

- The ADCIRC model has been used successfully in hindcast mode to study many Hurricanes (Betsy, Katrina, Rita, Gustav and Ike).
- This help developed very accurate descriptions of the Texas, Louisiana and Mississippi coasts, which include accurate bathymetries, coastal features.
- These hindcast models require highly resolved finite element meshes, ($10^7 - 10^8$) and require small time steps to resolve wetting and drying fronts.
- running hindcast in forecast thus require significant computational resources just to run one forecast.
- The goal is clear: To improve storm surge forecasts by a data assimilation using only a small ensemble of states on a coarser grid.

Kalman Filtering

Model: $\mathbf{x}_{k+1} = \mathcal{M}_k(\mathbf{x}_k) + \mathbf{u}_k$

Observation model: $\mathbf{y}_k = \mathcal{H}_k(\mathbf{x}_k) + \mathbf{v}_k$

- Prediction step

$$\mathbf{x}_k^b = \mathbf{M}_k \mathbf{x}_{k-1}^a \quad (1)$$

$$\mathbf{P}_k^b = \mathbf{M}_k \mathbf{P}_{k-1}^a \mathbf{M}_k^T + \mathbf{Q}_{k-1} \quad (2)$$

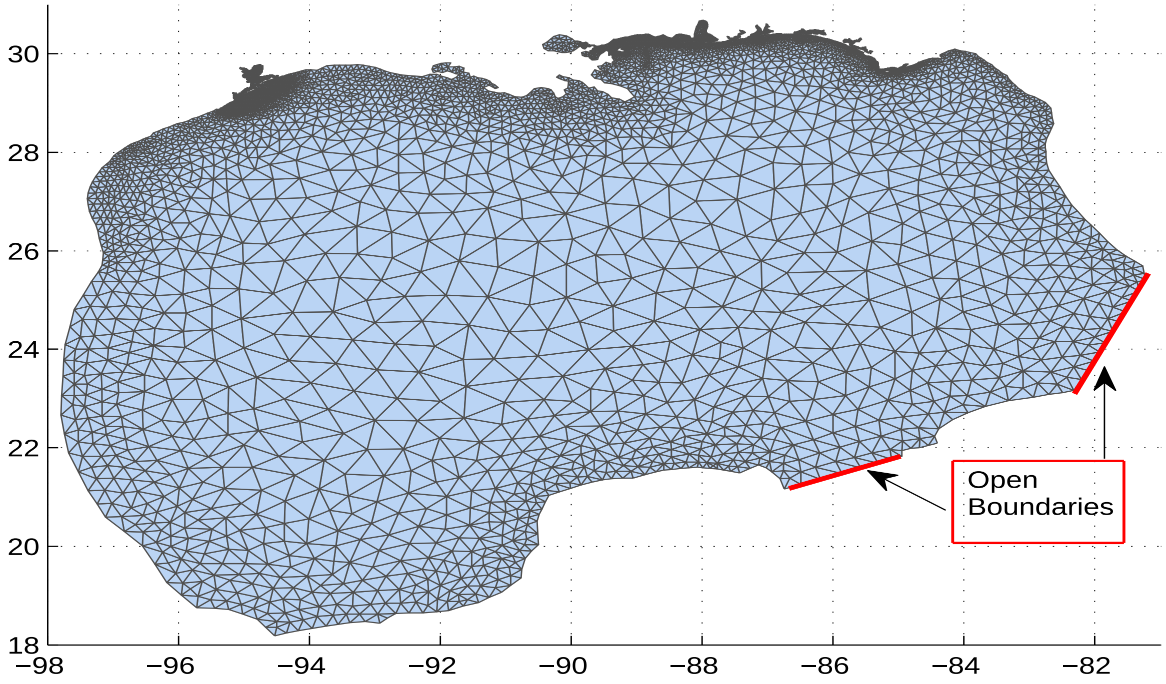
- Update:

$$\mathbf{K}_k = \mathbf{P}_k^b \mathbf{H}_k^T (\mathbf{H}_k \mathbf{P}_k^b \mathbf{H}_k^T + \mathbf{R}_k)^{-1} \quad (3)$$

$$\mathbf{x}_k^a = \mathbf{x}_k^b + \mathbf{K}_k (\mathbf{y}_k - \mathbf{H}_k \mathbf{x}_k^b) \quad (4)$$

$$\mathbf{P}_k^a = \mathbf{P}_k^b - \mathbf{K}_k \mathbf{H}_k \mathbf{P}_k^b \quad (5)$$

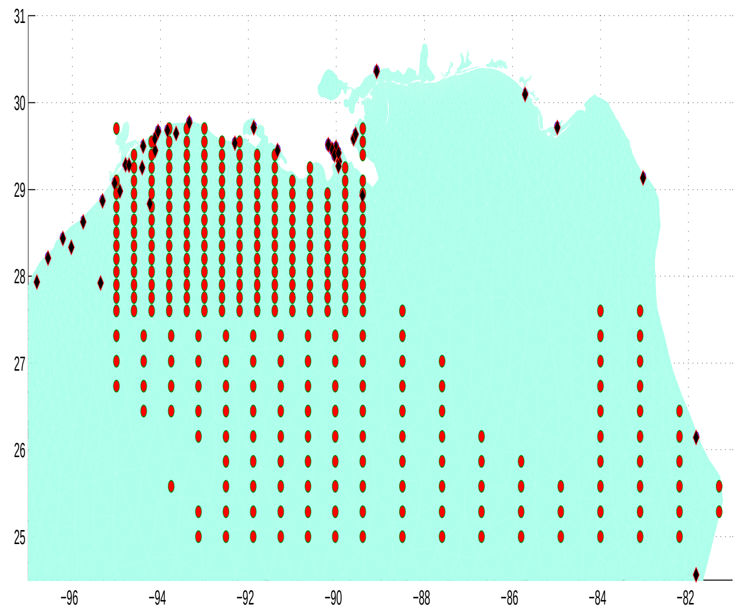
The Experimental Setup



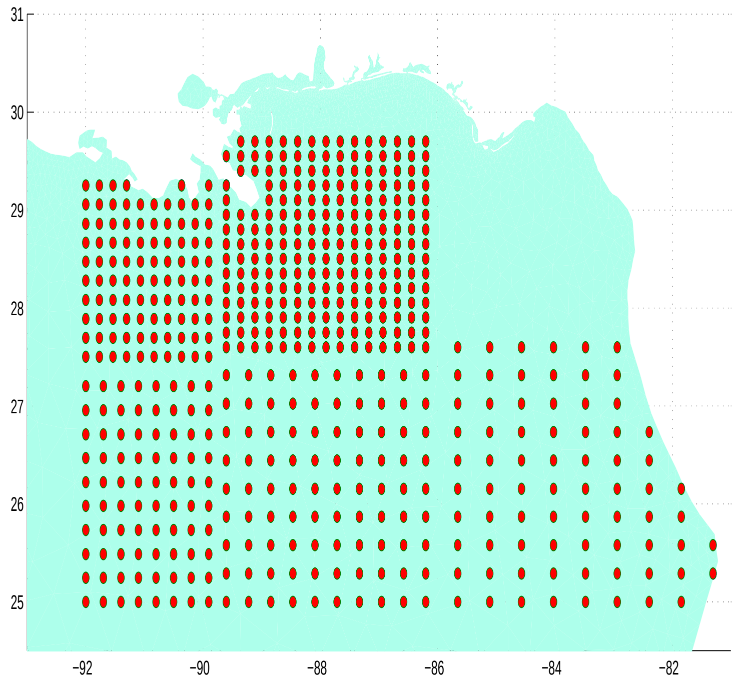
- Discretization of the Gulf of Mexico domain containing 8006 nodes and 14,269 elements.
- The open boundaries are forced by the 5 tidal constituents: K1, O1, P1, M2, and S2.
- timestep 10s

The Experimental Setup

Ike



Katrina



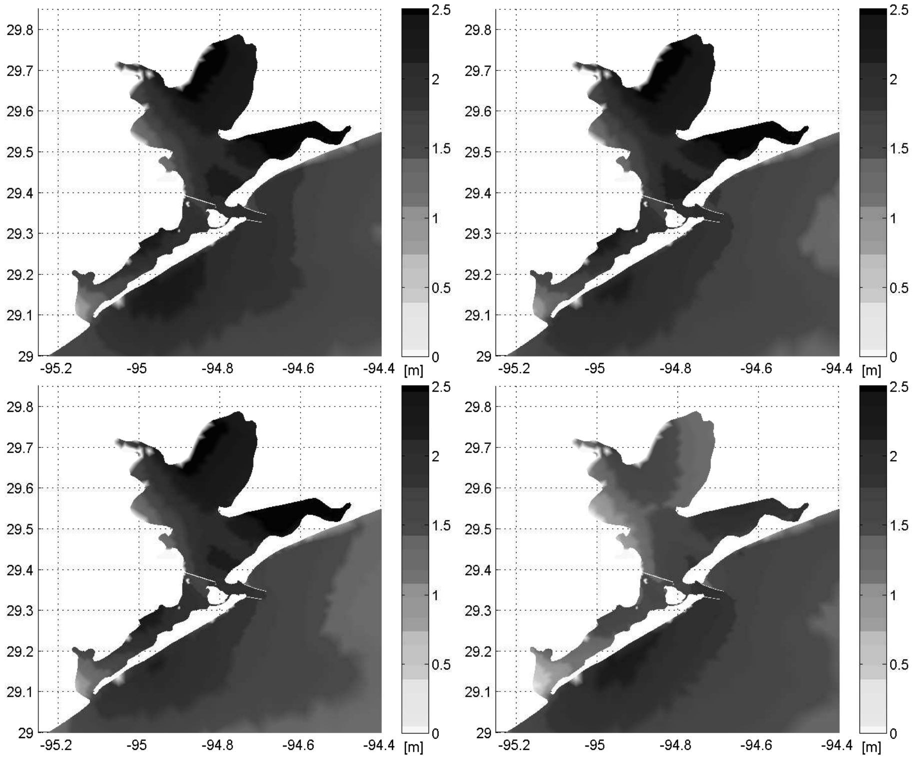
371 observation stations

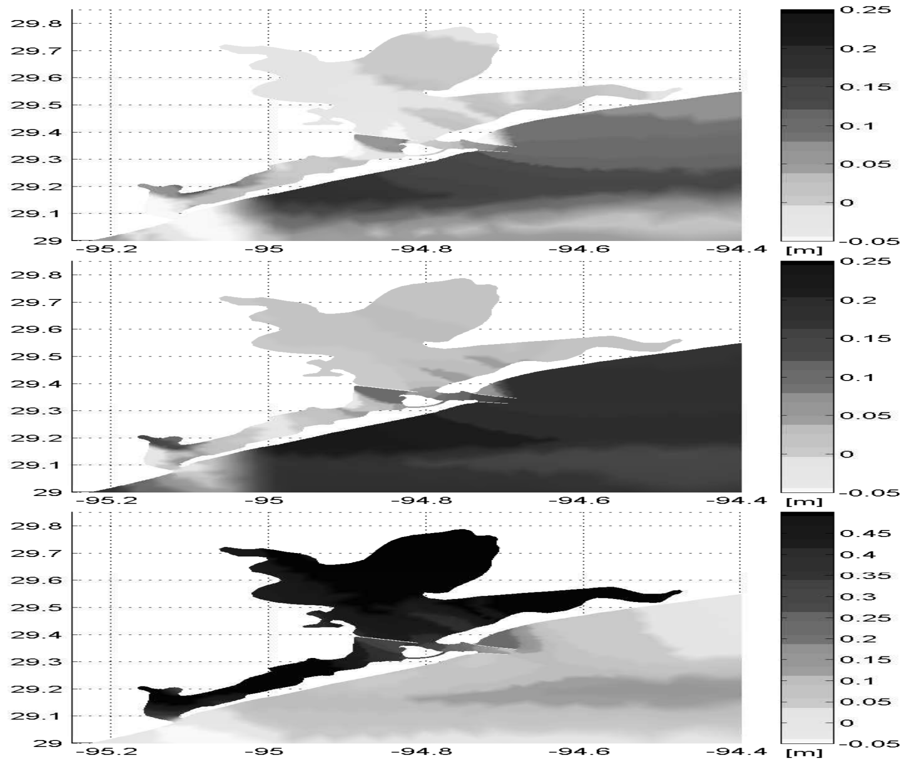
559 observation stations

- Assimilation step: 2h   Ensembles: 10

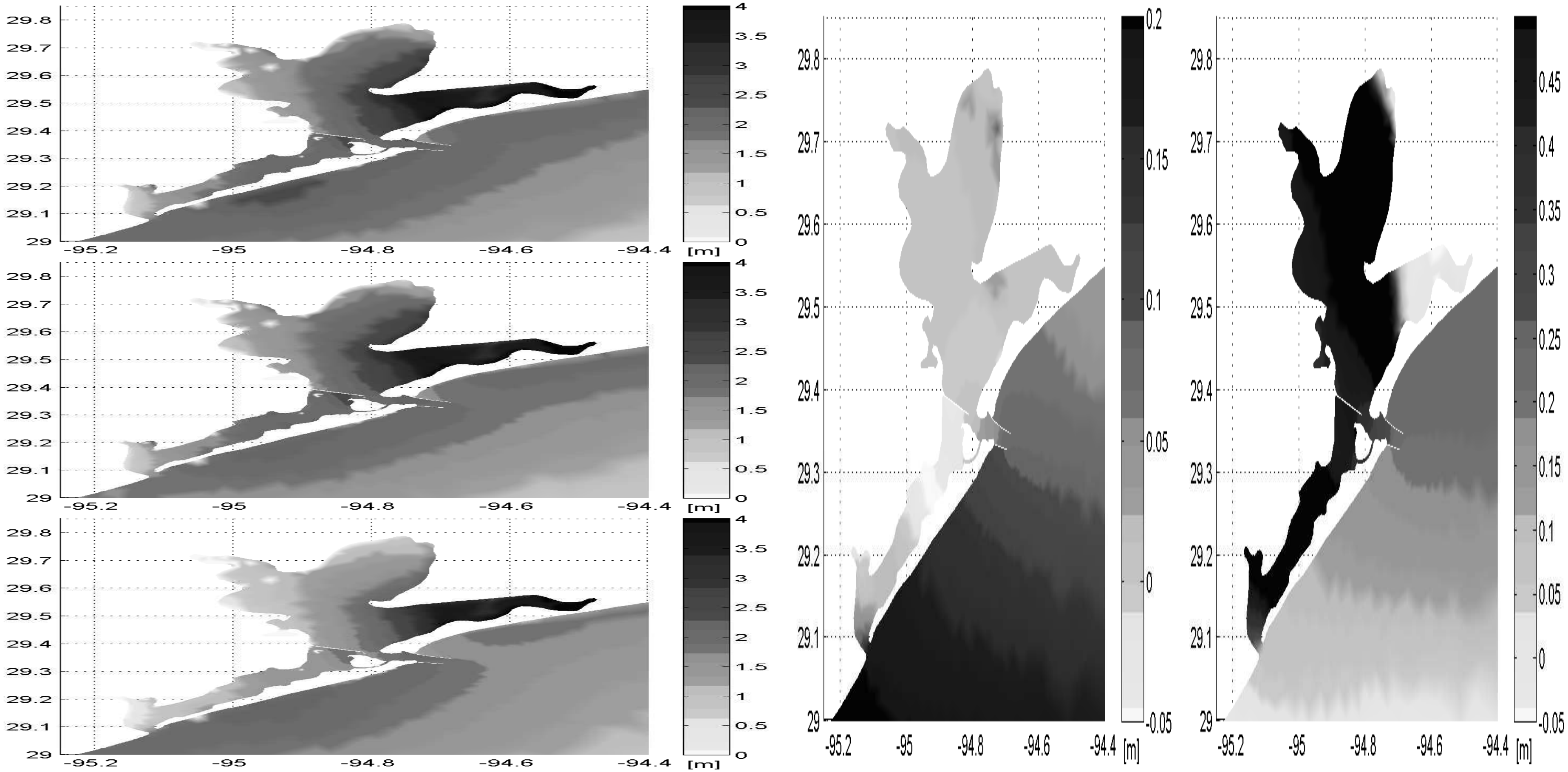
Results (Ike)

Simulation	Coastal RMS-Error	RMS-Error for Surge > 3 m
ISim-ND	1.92	1.91
ISim-48	1.86	1.81
ISim-24	1.82	1.80
ISim-FD	1.65	1.62





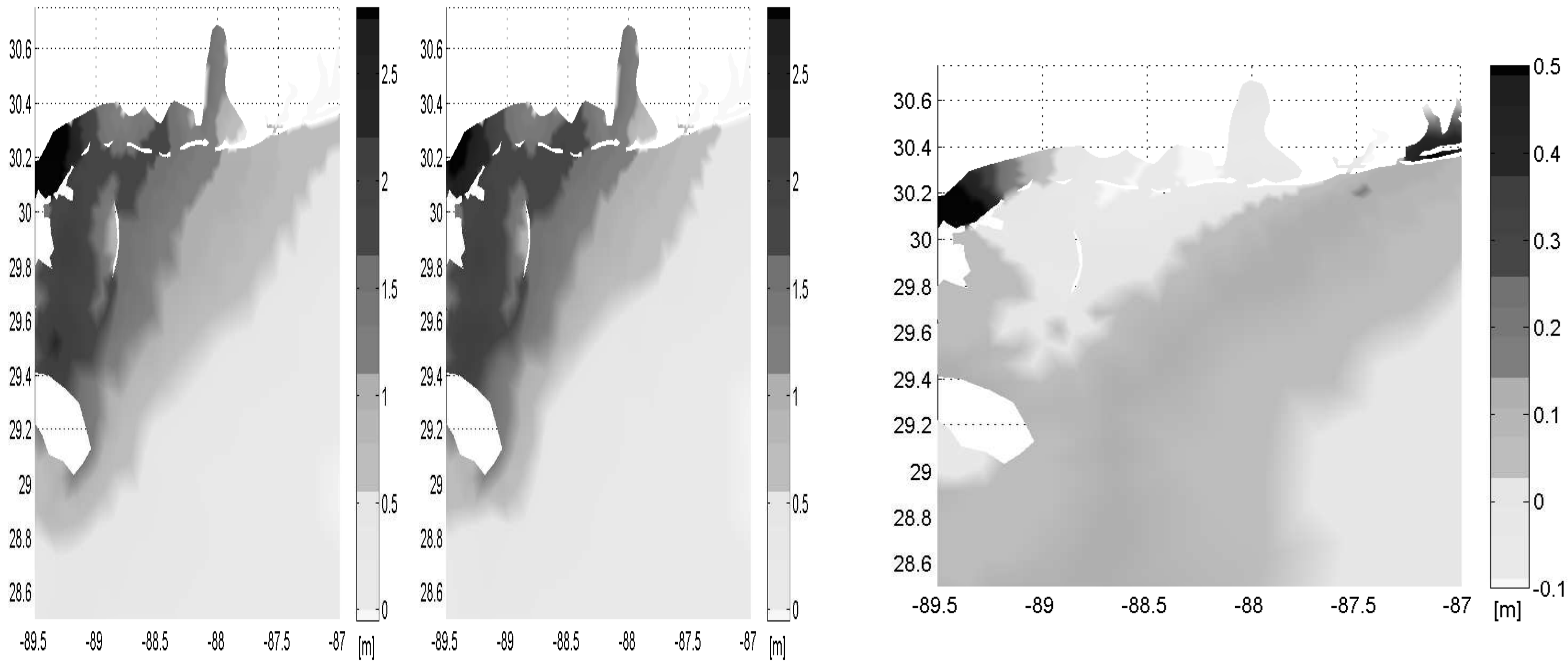
Results (Ike)



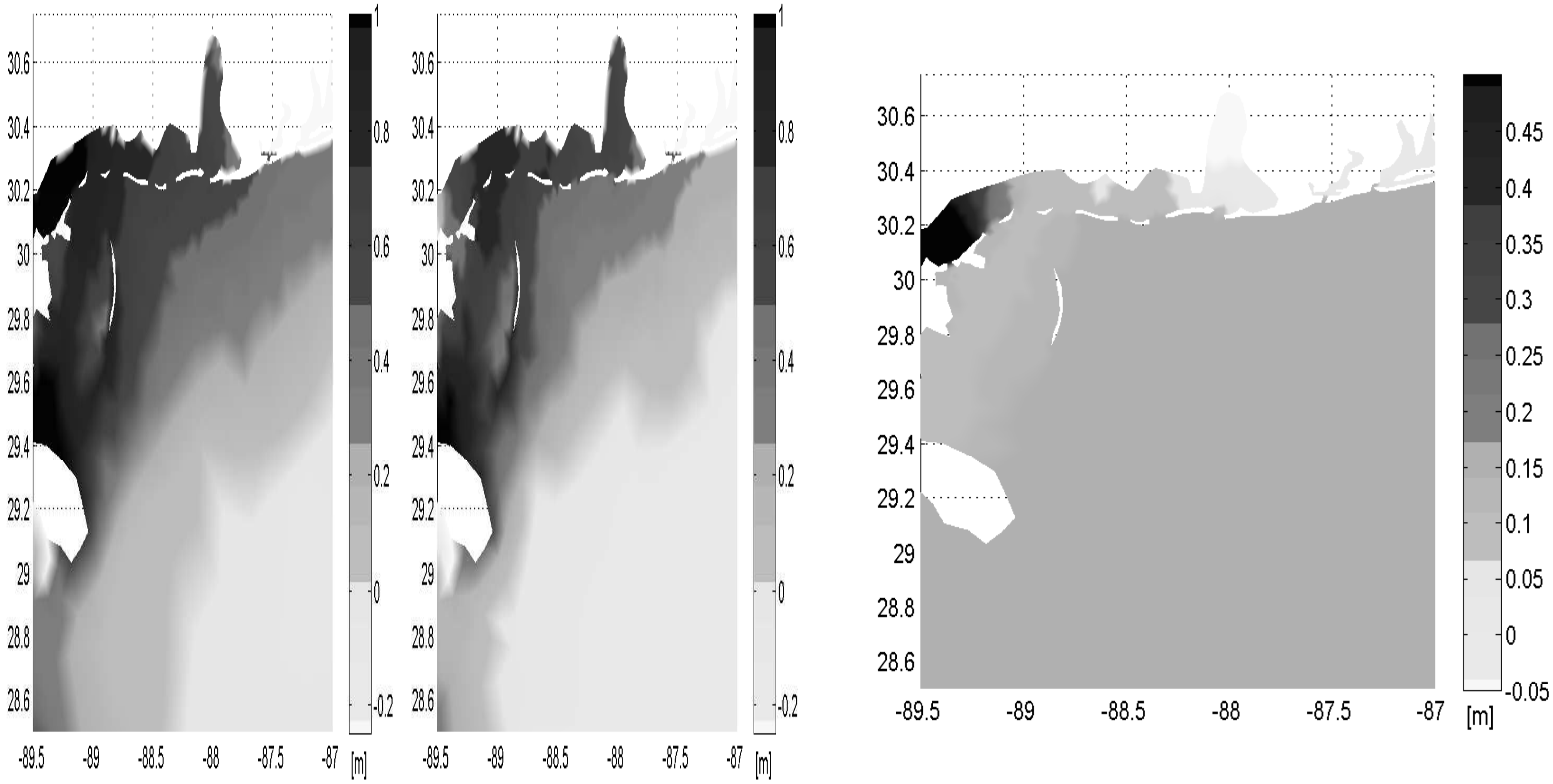
- Free surface elevation error on Sept. 13, 2008, at 07:00 UTC, from truth for ISim-ND (top), ISim-24 (middle), and ISim-FD (bottom).

Results (Katrina)

Simulation	RMS-Error for Surge > 4 m	RMS-Error for Surge > 5 m
KSim-ND	2.43	2.94
KSim-36	2.03	2.48
KSim-24	1.99	2.48
KSim-FD	1.92	1.89



Results (Katrina)



- Free surface elevation error on August. 29, 2005, before Landfall, from truth for ISim-ND (top), and ISim-FD (bottom).

Time Local H_∞ Filtering

Model: $$\mathbf{x}_{k+1} = \mathcal{M}_k(\mathbf{x}_k) + \mathbf{u}_k$$

Observation model: $$\mathbf{y}_k = \mathcal{H}_k(\mathbf{x}_k) + \mathbf{v}_k$$

- Prediction step

$$\mathbf{x}_k^b = \mathbf{M}_k \mathbf{x}_{k-1}^a \tag{6}$$

$$\triangle_k^b = \mathbf{M}_k \triangle_{k-1}^a \mathbf{M}_k^T + \mathbf{Q}_{k-1} \tag{7}$$

- Update:

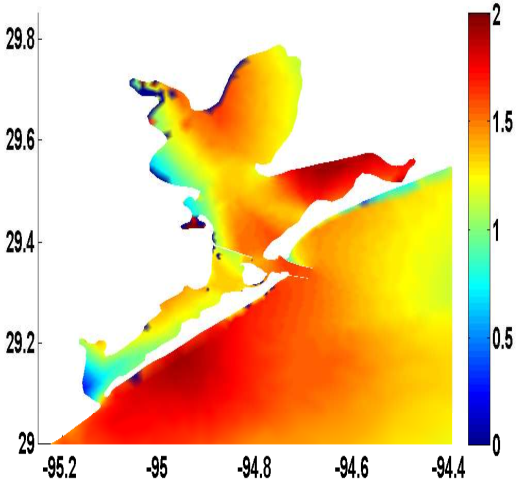
$$\mathbf{x}_k^a = \mathbf{x}_k^b + \mathbf{K}_k(\mathbf{y}_k - \mathbf{H}_k \mathbf{x}_k^b) \tag{8}$$

$$\mathbf{K}_k = \triangle_k^a \mathbf{H}_k^T \mathbf{R}_k^{-1} \tag{9}$$

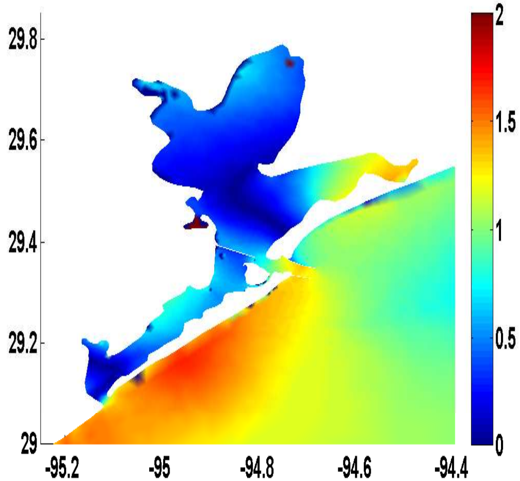
$$(\triangle_k^a)^{-1} = (\triangle_k^b)^{-1} + \mathbf{H}_k^T \mathbf{R}_k^{-1} \mathbf{H}_k - \gamma_k \mathbf{L}_k^T \mathbf{S}_k \mathbf{L}_k \tag{10}$$

Results (Ike)

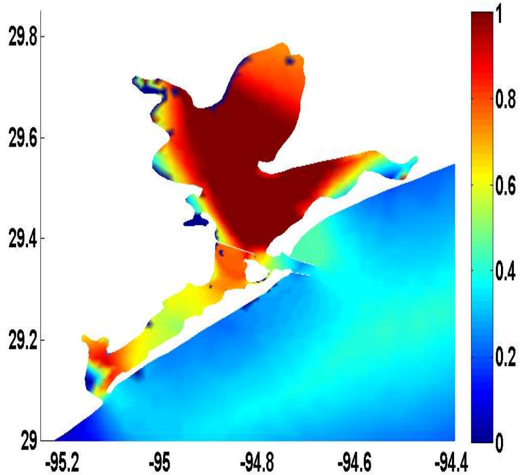
Simulation	Coastal RMS-Error	RMS-Error for Surge > 3 m
ISim-ND	1.92	1.91
SEIK	1.62	1.65
H_∞	0.80	0.87



EnKF

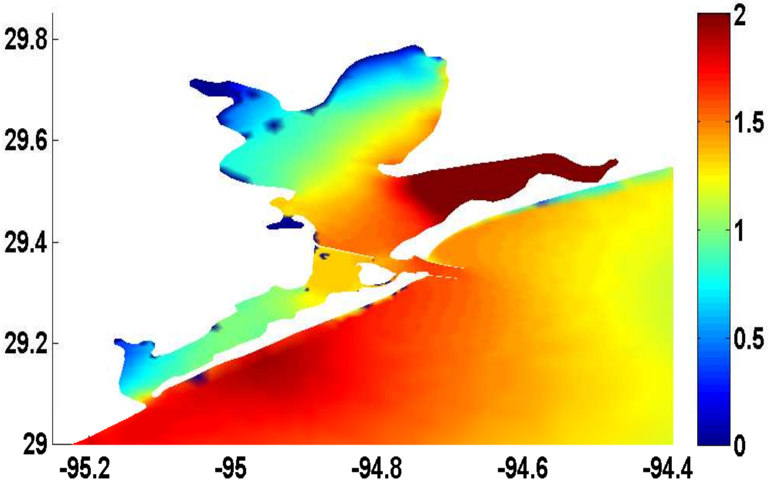


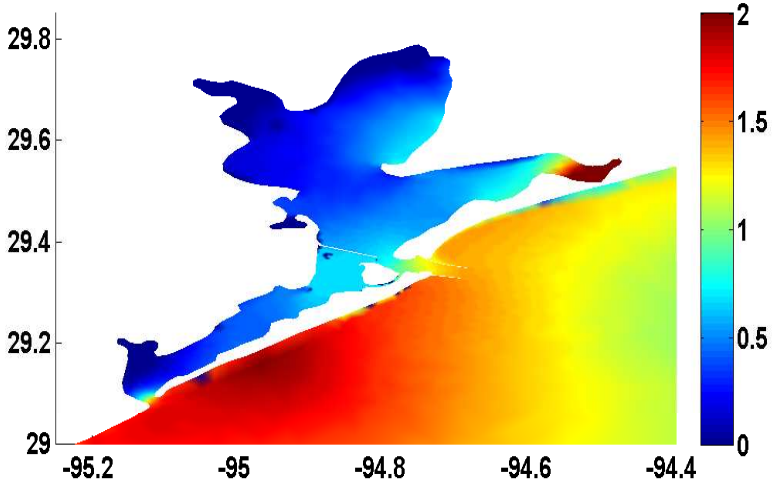
TLHF

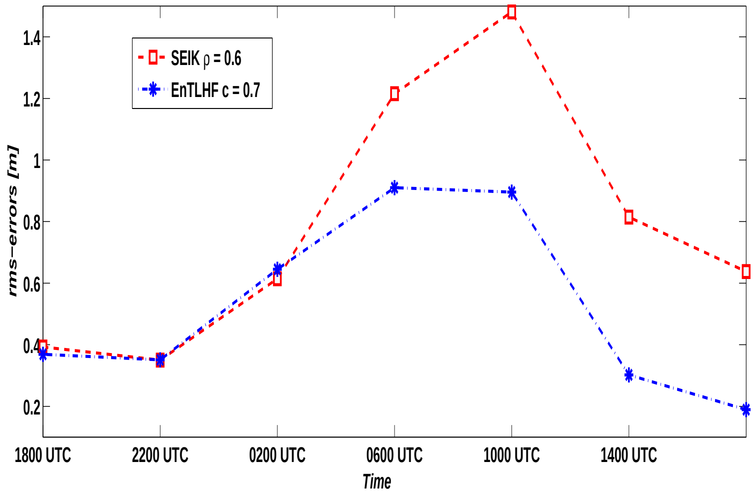


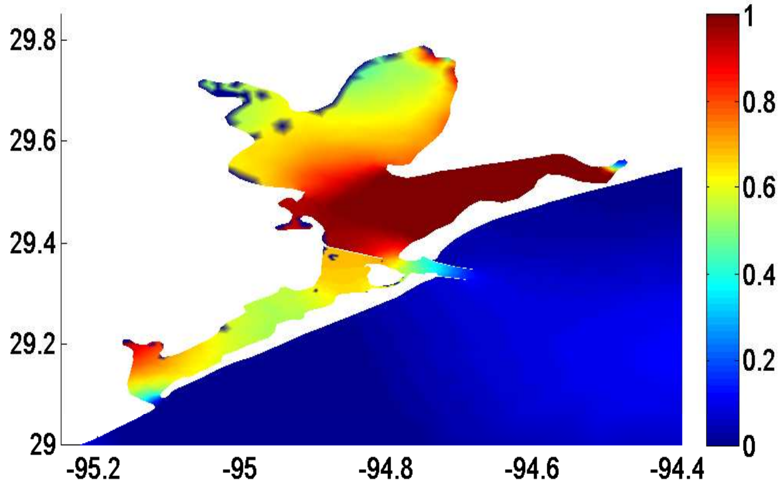
Difference

Results (Ike)





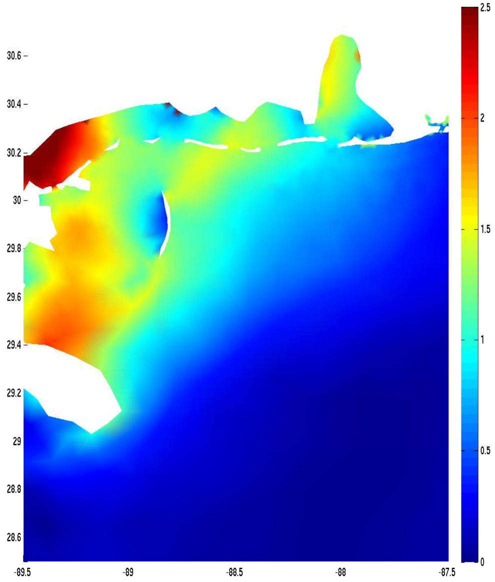




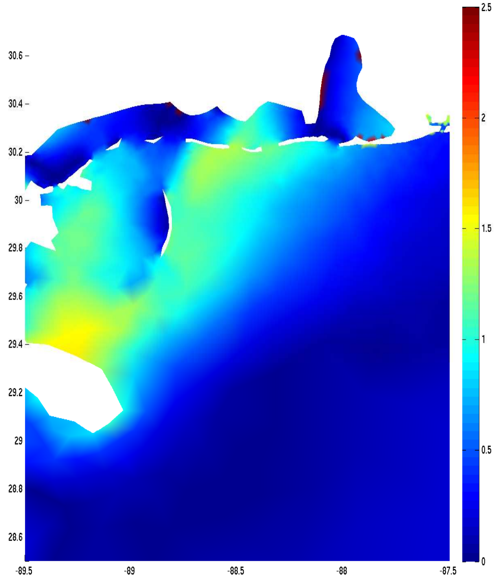
- Top: Free surface elevation error on Sept. 13, 2008, before Landfall.

Results (Katrina)

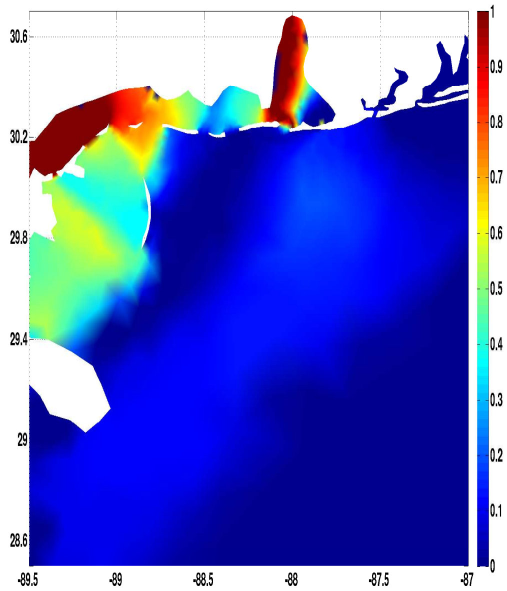
Simulation	RMS-Error for Surge > 4 m	RMS-Error for Surge > 5 m
ISim-ND	2.38	2.87
SEIK	1.92	1.89
H_∞	0.72	0.45



EnKF

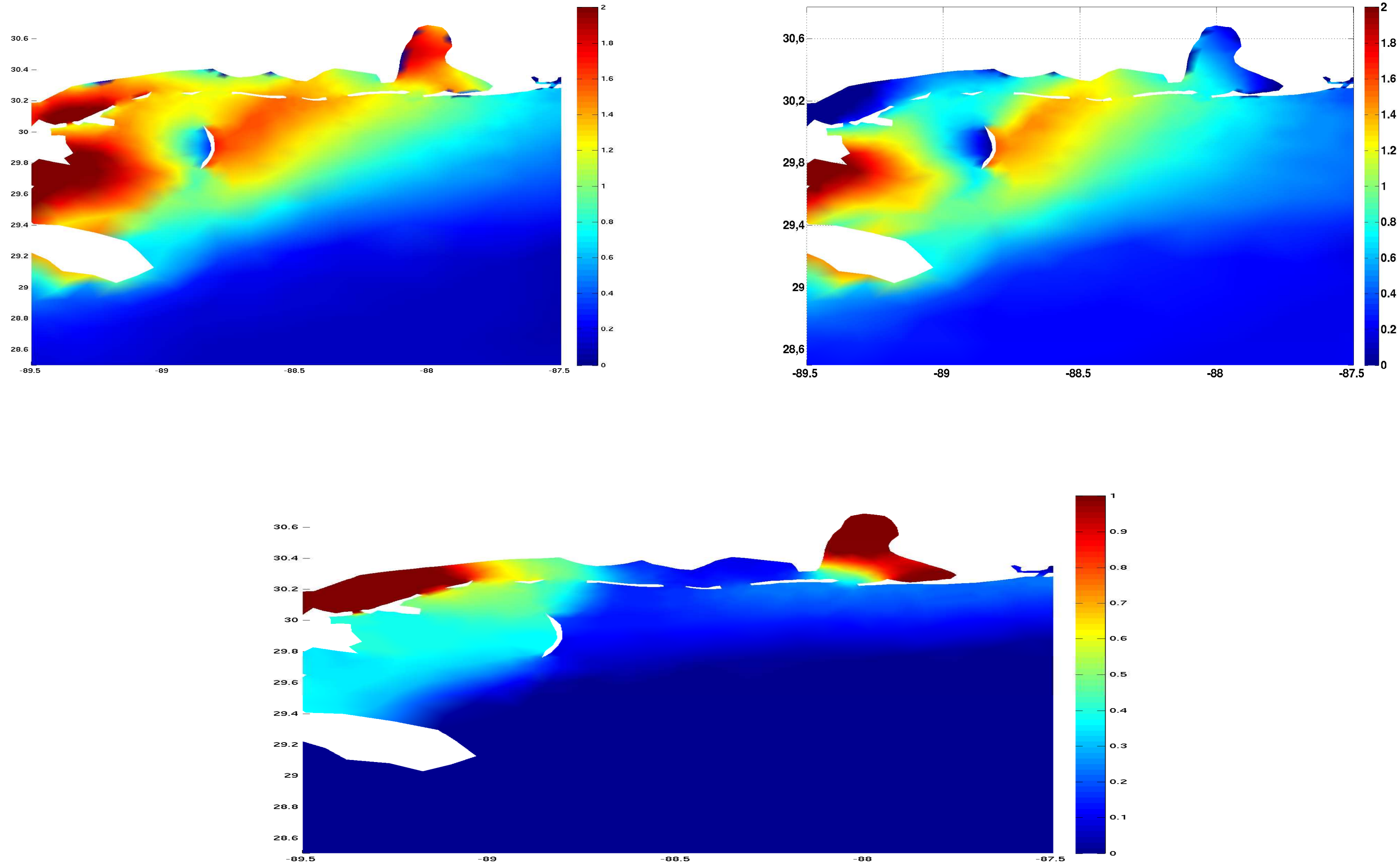


TLHF



Difference

Results (Katrina)



- Top: Free surface elevation error on August. 29, 2005, at Landfall.

Conclusions

- Successfully implemented and tested DA methodology within ADCIRC model.

- Ensemble based Kalman filtering shows underestimation.

- Ensemble based H_∞ filtering shows significant improvements to EnKF.

- Lots need to be done for an operational storm surge system.
- References:

Butler et. al 2012, Data assimilation within the framework of Advanced Circulation Model., Monthly Weather Review.
Altaf et. al 2012, An Ensemble based time-local H_∞ filter for reliable storm surge forecasting, Computer and Geosciences

Future of Data Assimilation is

OpenDA

THANK YOU