Application of the Hypercube Method for the Efficient Simulation of Long-Term, Nearshore Wave Records

Case Study and Verification Using Observed Wave Data Near the Mississippi/Alabama Coast

Christopher M. Day, PE, D.CE
Joao Dobrochinski

Long-Term Nearshore Wave Records

APPLICATIONS

- **Beach erosion modeling:**
  - **GENESIS – Transformation of the 5-20 year offshore wave record to the depth of closure or breaking depth.**
  - **Delft3D & DNRBS – Selection of offshore wave case(s) based on the resulting wave energy in the nearshore zone.**
- **Structural design of groins, jetties, and port structures:**
  - **Average and extremal (storm) wave statistics near beaches, inlets, and harbors.**

Long-Term Nearshore Wave Records

APPLICATIONS

- **Nearshore Wave Forecasting:**
  - **RECREATION – Transform an offshore forecast to predict the nearshore wave conditions for surfing conditions and the green, yellow, and red wave condition flags at public beaches.**
  - **NAVIGATION – Apply a similar method to predict wave conditions near inlets and harbors for boat and ship traffic, small craft warnings, etc.**

Long-Term Nearshore Wave Records

GENERAL APPROACHES

- **Forecast / Hindcast Model Databases –**
  - **– U.S. Army Corps of Engineers Wave Information Studies.**
  - **– NOAA National Centers for Environmental Prediction Databases & Forecasts ("WAVEWATCH")**
  - **– Good resolution and physics at "deep water" and intermediate depths (below "depth of closure").**
  - **– Nearshore records (near or above depth of closure) are either not available (WIS) or spaced at a relatively wide resolution (WAVEWATCH database).**
  - **– Shallow water processes are only accounted for in the most recent hindcasts (i.e.: 2009-present).**

Long-Term Nearshore Wave Records

GENERAL APPROACHES

- Nearshore wave measurements
  - Describes the waves at 1-2 locations.
- Time-dependent wave modeling
  - Can provide continuous coverage and specifically account for shallow water wave processes, however…
  - Computational time becomes excessive or prohibitive for very long wave records (5-20 years).
- "Hypercube Method"
  - Can account for shallow water wave processes, and…
  - Saves time by using 300-1200 of wave cases to summarize the long-term wave record instead of 10,000-500,000 individual time steps.

Hypercube Method

NEWTON & LEIBNIZ AT SEA

Who developed Hypercube method?

Hanson & Kraus (1989) – "Look-up" method used in GENESIS model. However, they did not attach the name "Hypercube" to the lookup method.

Instituto de Hidraulica Ambiental de la Universidad de Cantabria (IH Cantabria) (2009) – Independently developed a very similar method, but for a broader range of applications (coastal structures, port design, etc.). Coined the term "Hypercube".

Hypercube Method

NEWTON & LEIBNIZ AT SEA

Hanson & Kraus (1989), *GENESIS Report 1* –

> **'Rather than running the external wave model at every time step, a time savings technique is used in which the offshore wave conditions are divided into period and direction bands (Kraus et al. 1988)….This procedure gives on the order of 50 to 100 period-direction bands, and refraction runs are made with the external wave model using unit wave height to provide what are termed "transformation coefficients" along the nearshore reference line'.**

The "lookup" method, an early form of Hypercube, is a standard feature of GENESIS. It transforms a 5 to 20 year sequence of offshore waves at each time step to the depth of closure or breaking depth using a relatively small number of wave cases instead of every wave record.

Hypercube Method

NEWTON & LEIBNIZ AT SEA

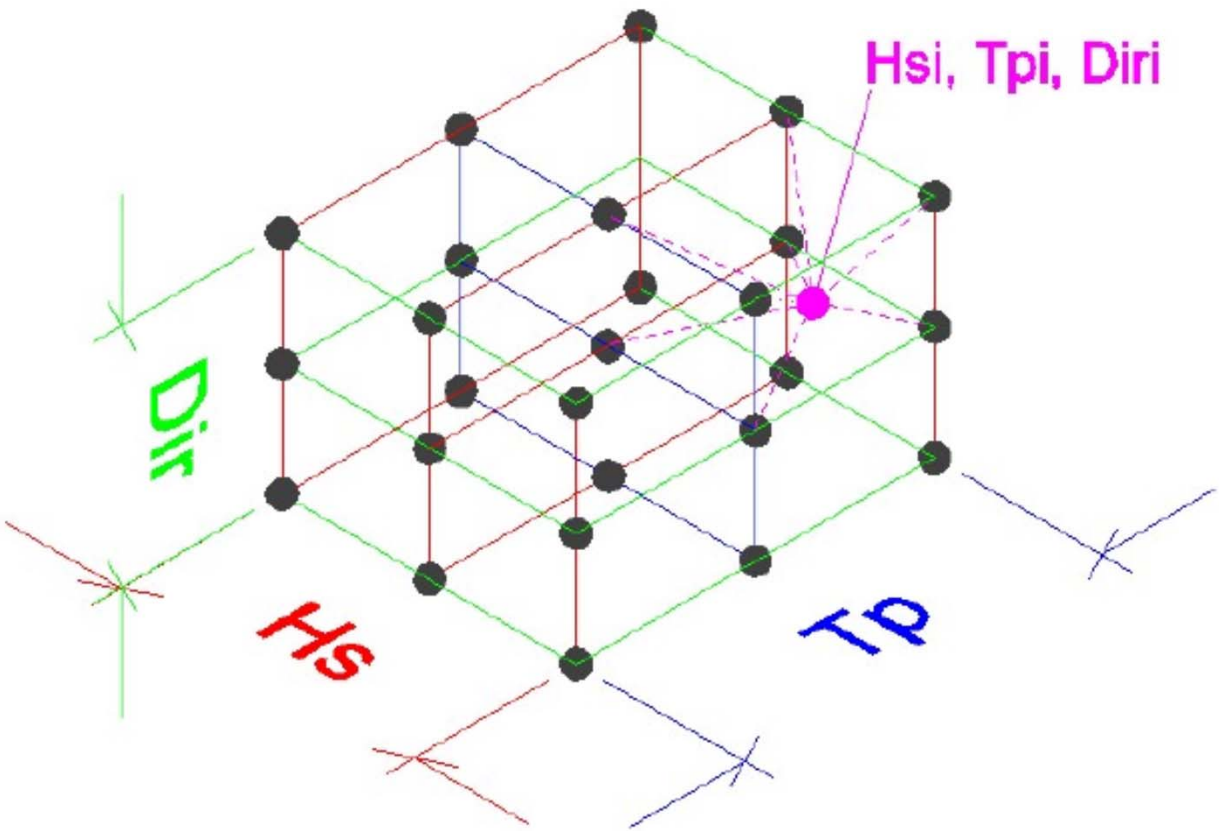
Bonanata, Medina, Silveira, & Benedet (2010) –

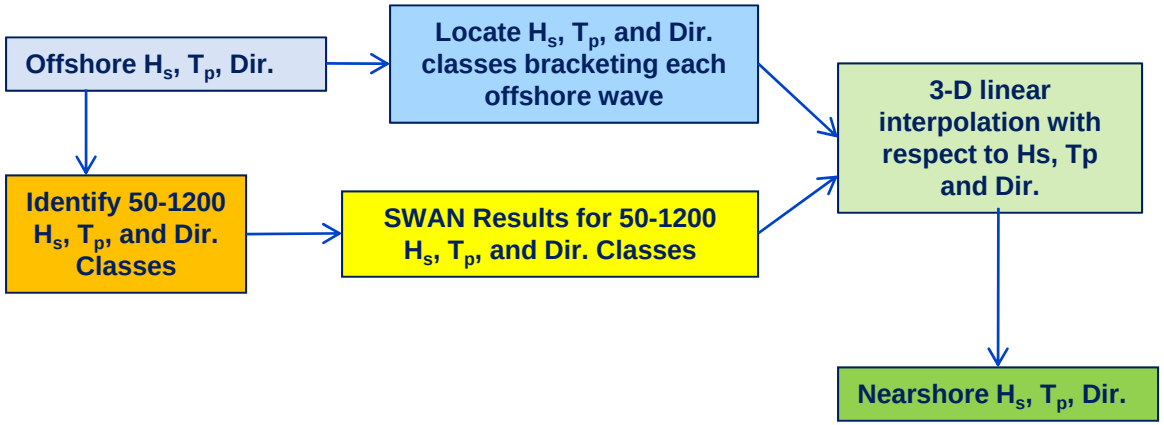
"One must propagate all the sea states that are likely to be produced. Nevertheless, today, computational time makes the propagation of all sea states for the reanalysis series impossible. Thus, the following procedure is adopted:

a) Propagation of a matrix of possible wave cases with a distinct height, direction, period, and water level;

b) Calculation of a propagation coefficient and angle for these cases;

c) Interpolation of the propagation coefficient and angle for each event recorded at the point of reanalysis. For each water level, one may perform an interpolation in three dimensions (Hs, Tp, Dir.) to obtain the propagation coefficient and angle of that event in the study area."


Hsi, Tpi, Diri
Dir
Hs
Tp


Offshore H_s, T_p, Dir.
Locate H_s, T_p, and Dir. classes bracketing each offshore wave
3-D linear interpolation with respect to Hs, Tp and Dir.
Identify 50-1200 H_s, T_p, and Dir. Classes
SWAN Results for 50-1200 H_s, T_p, and Dir. Classes
Nearshore H_s, T_p, Dir.

ADVANTAGES

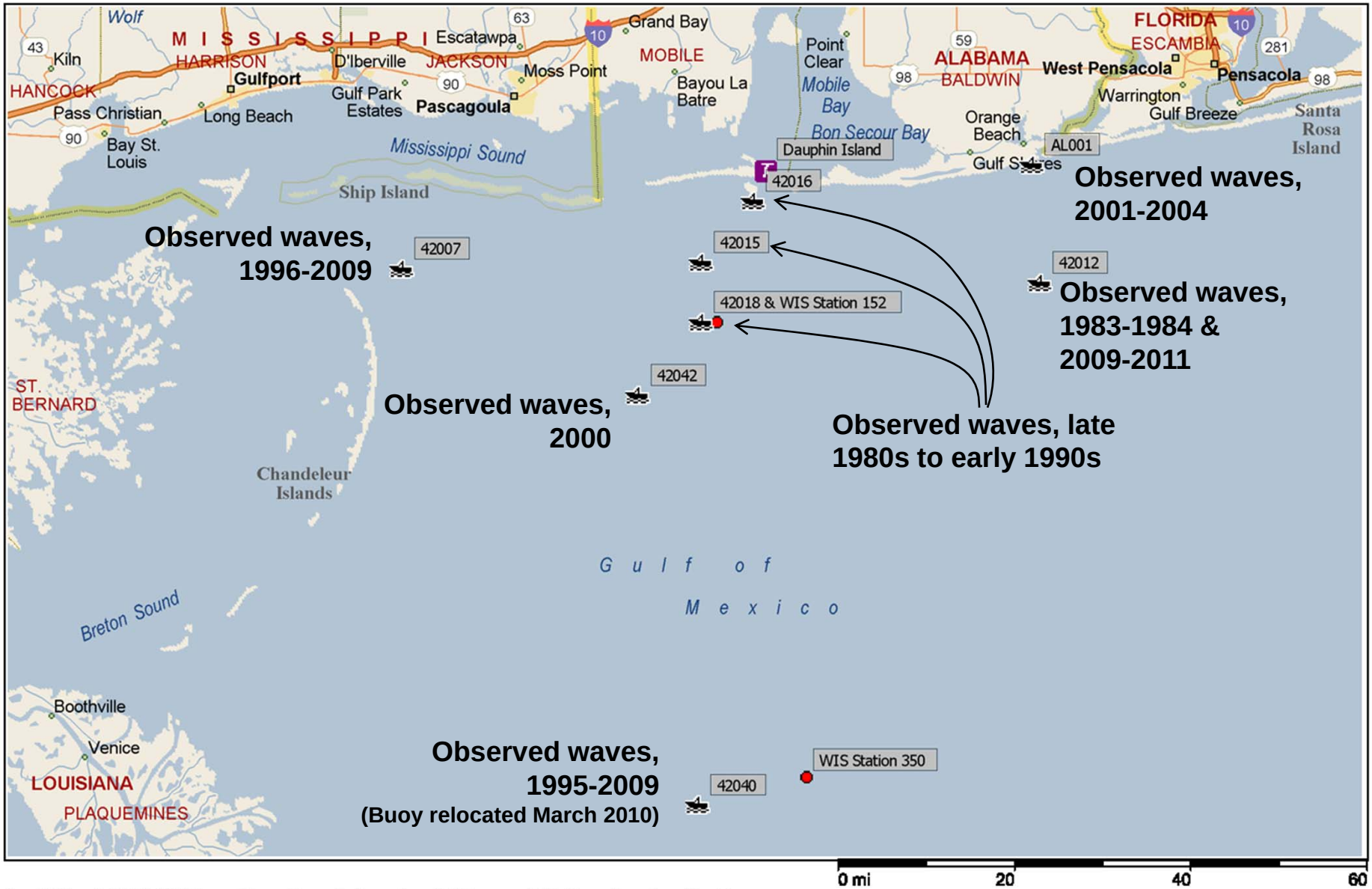
- Flexible. Can be used with any wave transformation model that incorporates shallow water physics:
  - Refraction, Shoaling, Breaking, Diffraction, etc.
  - In Hypercube applications, SWAN is most commonly used, but other models (STWAVE, Mike21 models) can also be used.
- Substantial reductions (95-99%) in the number of Hypercube wave cases vs. the number of time steps in a time dependent wave model.
- If used as a forecast tool, there is no need to re-run the wave transformation model itself. Only a re-run of the 3-D interpolation is required.
- Has been used successfully in a wide variety of locations – Gulf Coast, Chesapeake Bay Entrance, Brazil, Spain.

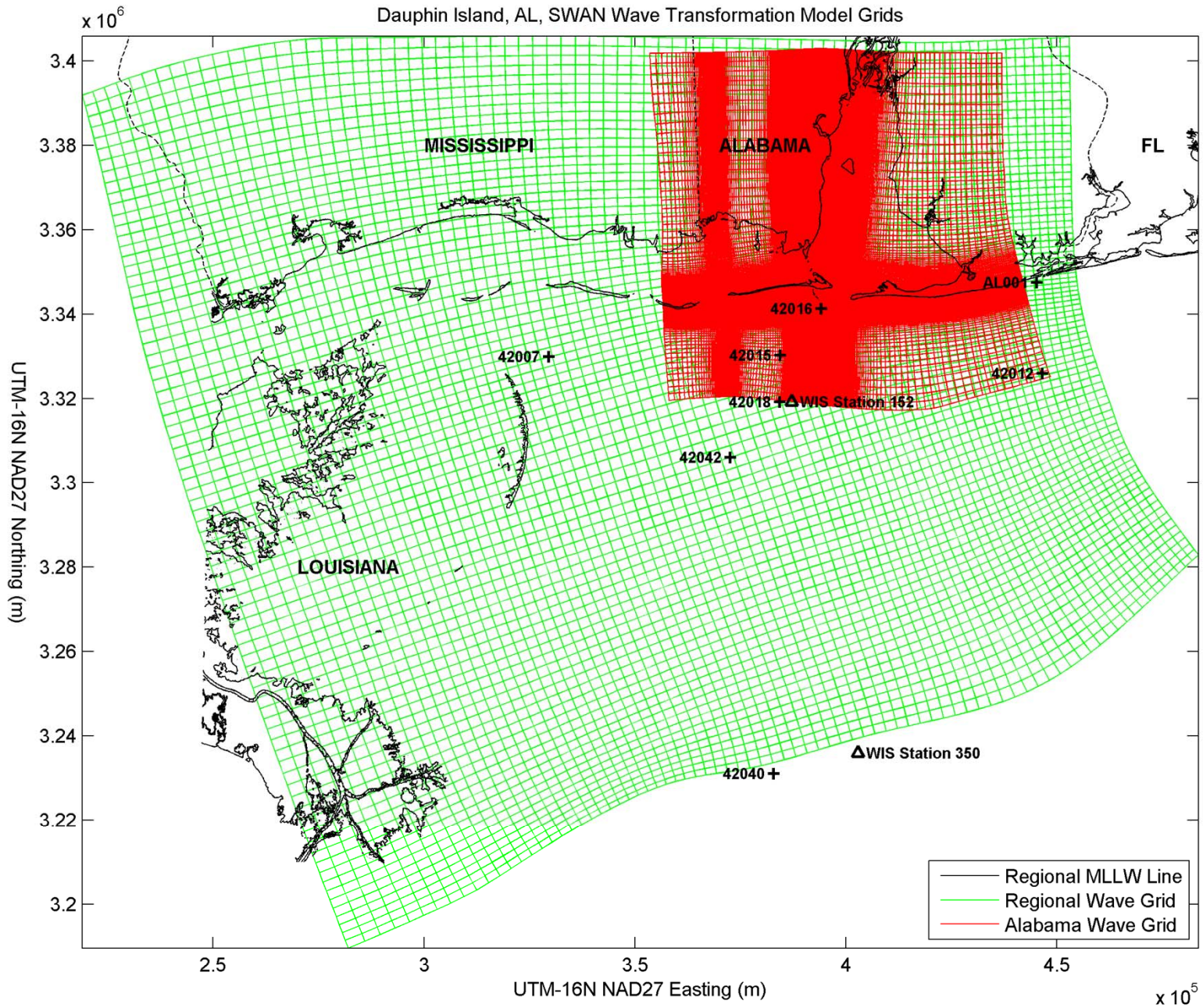
LIMITATIONS

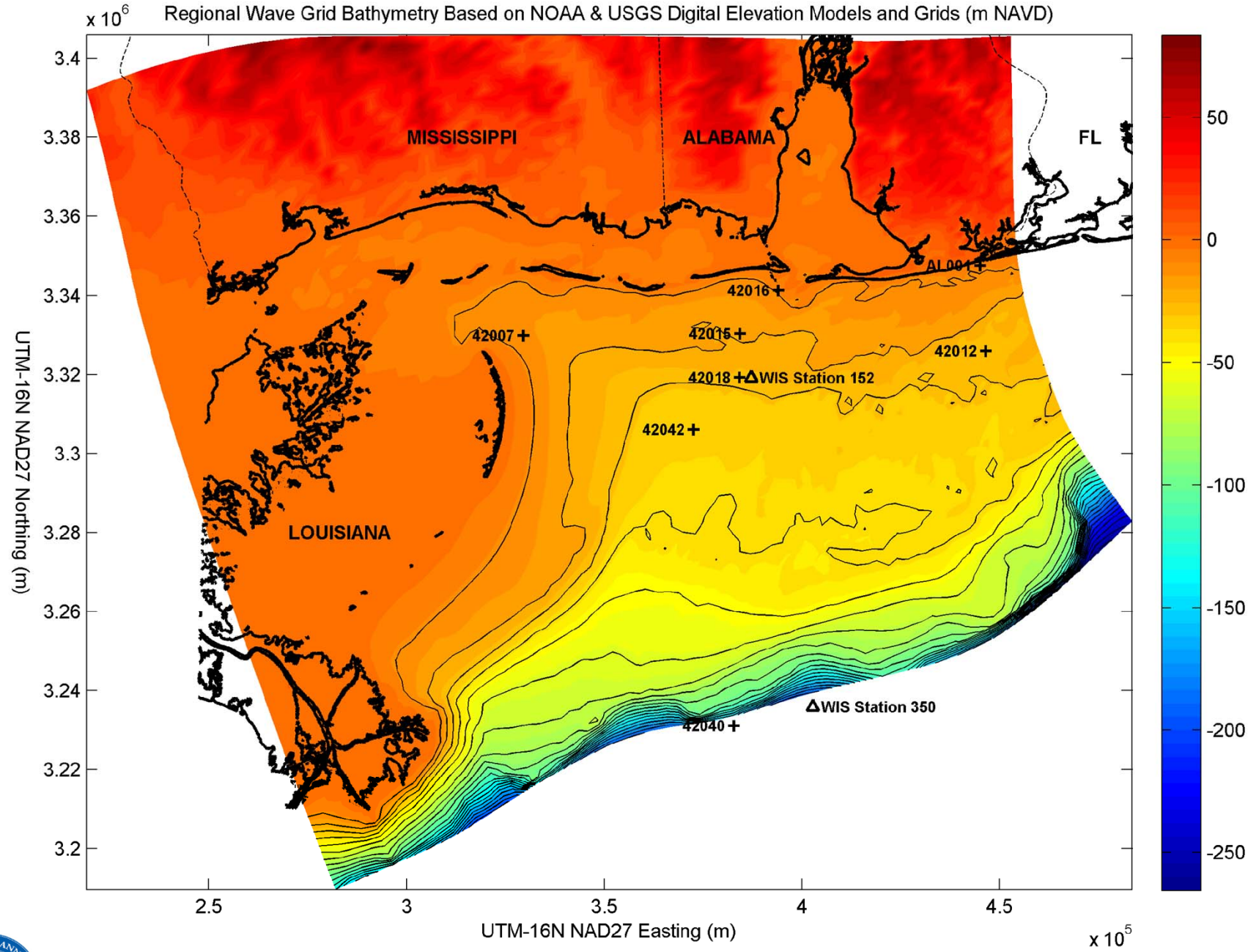
- The wave transformation model is run for cases in stationary (non-time dependent) mode.
- Several hours may be required for a wave to cross a very large area (i.e. several hundred miles). If the waves change at time scales that are faster than the “crossing time”, the stationary wave assumption can break down.
- When wind stress and/or storm surge is included, uniform wind velocities and/or water levels are usually assumed for each case. However, wind speeds and water levels can vary within each case with respect to both space & time.

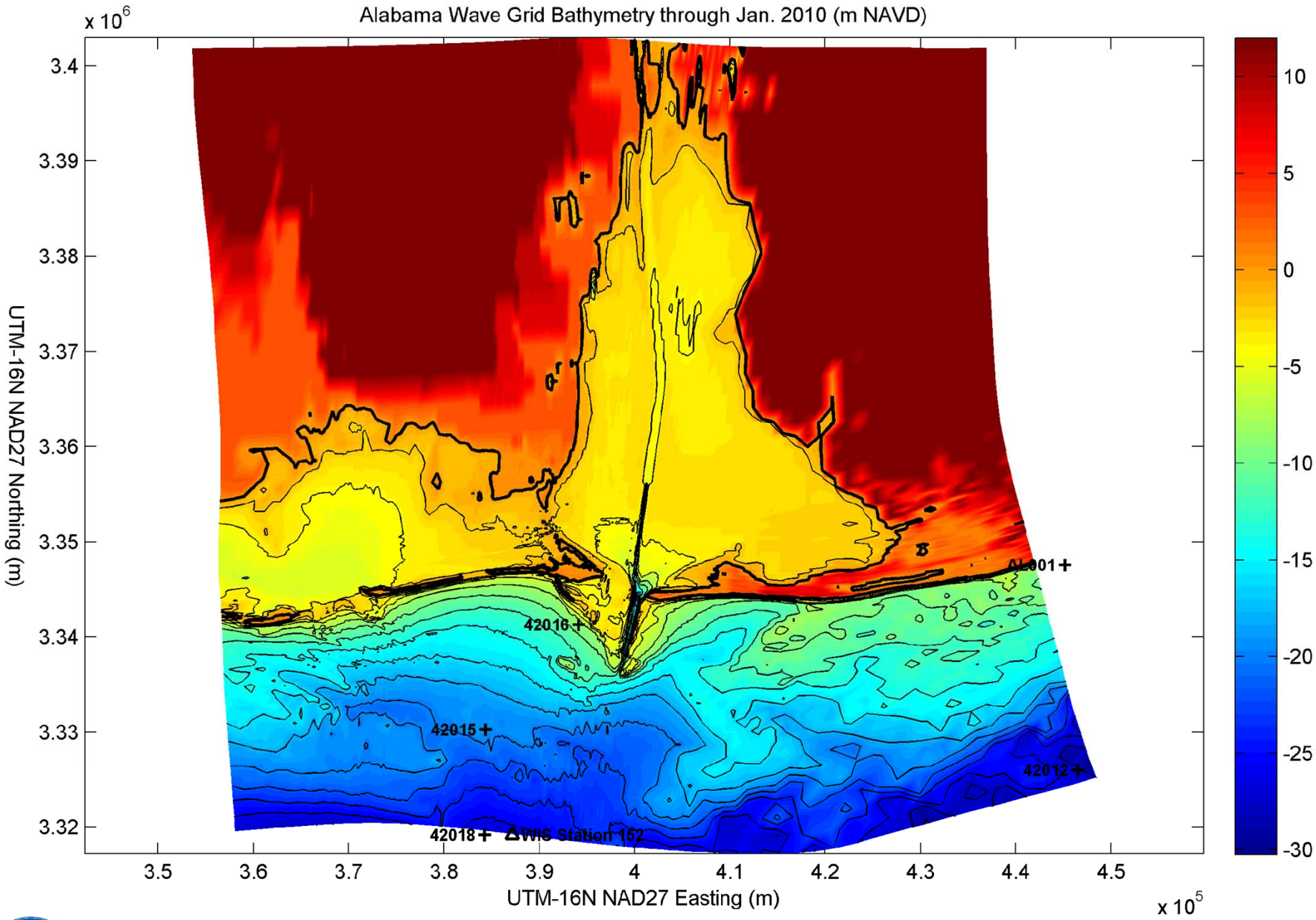
CASE STUDY – AL / MS COAST

- Large collection of observed wave data over long periods of time (1990s – present).
- Wide range of applications for the results:
  - Dauphin Island, AL erosion control projects.
  - Navigation to/from Mobile Bay, Gulfport, Biloxi, etc.
  - Barrier island restoration & Deepwater Horizon “Berms” project at Chandeleur Islands, LA.
- Simulating Waves Nearshore (SWAN) model calibrated and verified for Dauphin Island, AL using observed offshore and nearshore wave data.
- Hypercube used to estimate 13 year series of waves near Dauphin Island, Mississippi barrier islands, & Chandeleur Islands.




Dauphin Island, AL, SWAN Wave Transformation Model Grids
x 10^6
3.4
3.38
3.36
3.34
3.32
3.3
3.28
3.26
3.24
3.22
3.2
UTM-16N NAD27 Northing (m)
2.5
3
3.5
4
4.5
UTM-16N NAD27 Easting (m)
x 10^5
MISSISSIPPI
ALABAMA
FL
LOUISIANA
AL001
42016
42015
42012
42018
WIS Station 152
42007
42042
WIS Station 350
42040
Regional MLLW Line
Regional Wave Grid
Alabama Wave Grid


Regional Wave Grid Bathymetry Based on NOAA & USGS Digital Elevation Models and Grids (m NAVD)
x 10^6
3.4
3.38
3.36
3.34
3.32
3.3
3.28
3.26
3.24
3.22
3.2
UTM-16N NAD27 Northing (m)
2.5
3
3.5
4
4.5
UTM-16N NAD27 Easting (m)
x 10^5
MISSISSIPPI
ALABAMA
FL
LOUISIANA
AL001
42016
42015
42007
42012
42018
WIS Station 152
42042
WIS Station 350
42040
50
0
-50
-100
-150
-200
-250


Alabama Wave Grid Bathymetry through Jan. 2010 (m NAVD)
x 10^6
3.4
3.39
3.38
3.37
3.36
3.35
3.34
3.33
3.32
UTM-16N NAD27 Northing (m)
3.5
3.6
3.7
3.8
3.9
4
4.1
4.2
4.3
4.4
4.5
UTM-16N NAD27 Easting (m)
x 10^5
10
5
0
-5
-10
-15
-20
-25
-30
AL001
42016
42015
42012
42018
WIS Station 152

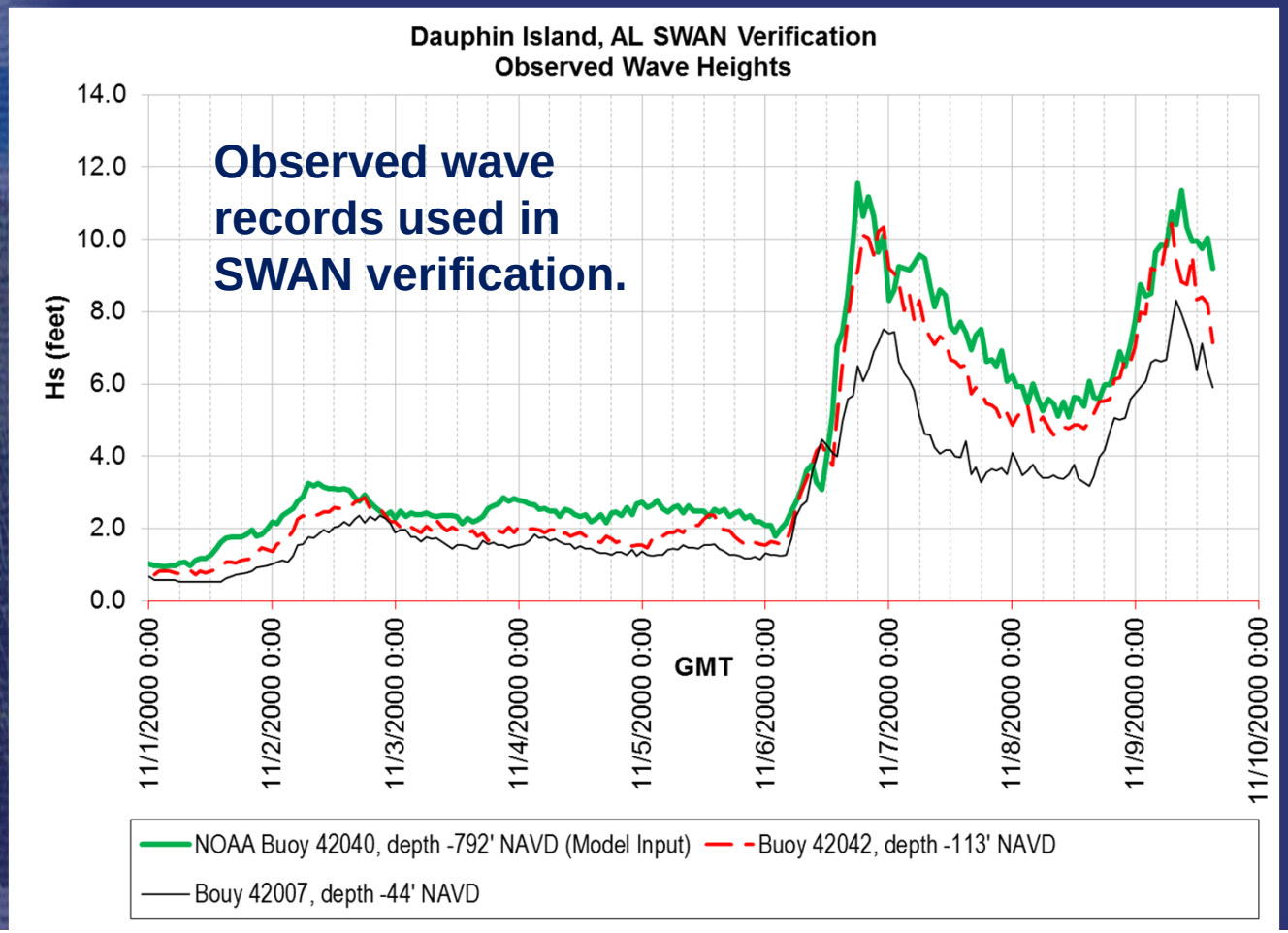
MODEL CALIBRATION / VERIFICATION

- Original calibration & verification of SWAN model performed using conventional methods – time dependent (non-stationary) wave simulations over 1-2 week periods.

- Processes included in SWAN –
  - Spectral waves – Each wave or wave case is an overlap of multiple wave components, each with its own period (frequency) and direction.
  - Refraction – Change in wave direction with depth.
  - Shoaling – Change in wave height with depth.
  - Diffraction – Lateral spreading of wave energy into bays, harbors, etc.
  - Whitecapping
  - Bottom friction
  - Breaking
  - Non-linear triads – Transfer of wave energy from low to high frequencies (or from long to short wavelengths) in shallow water.
  - Local, wind-generated wave growth (wind stress).

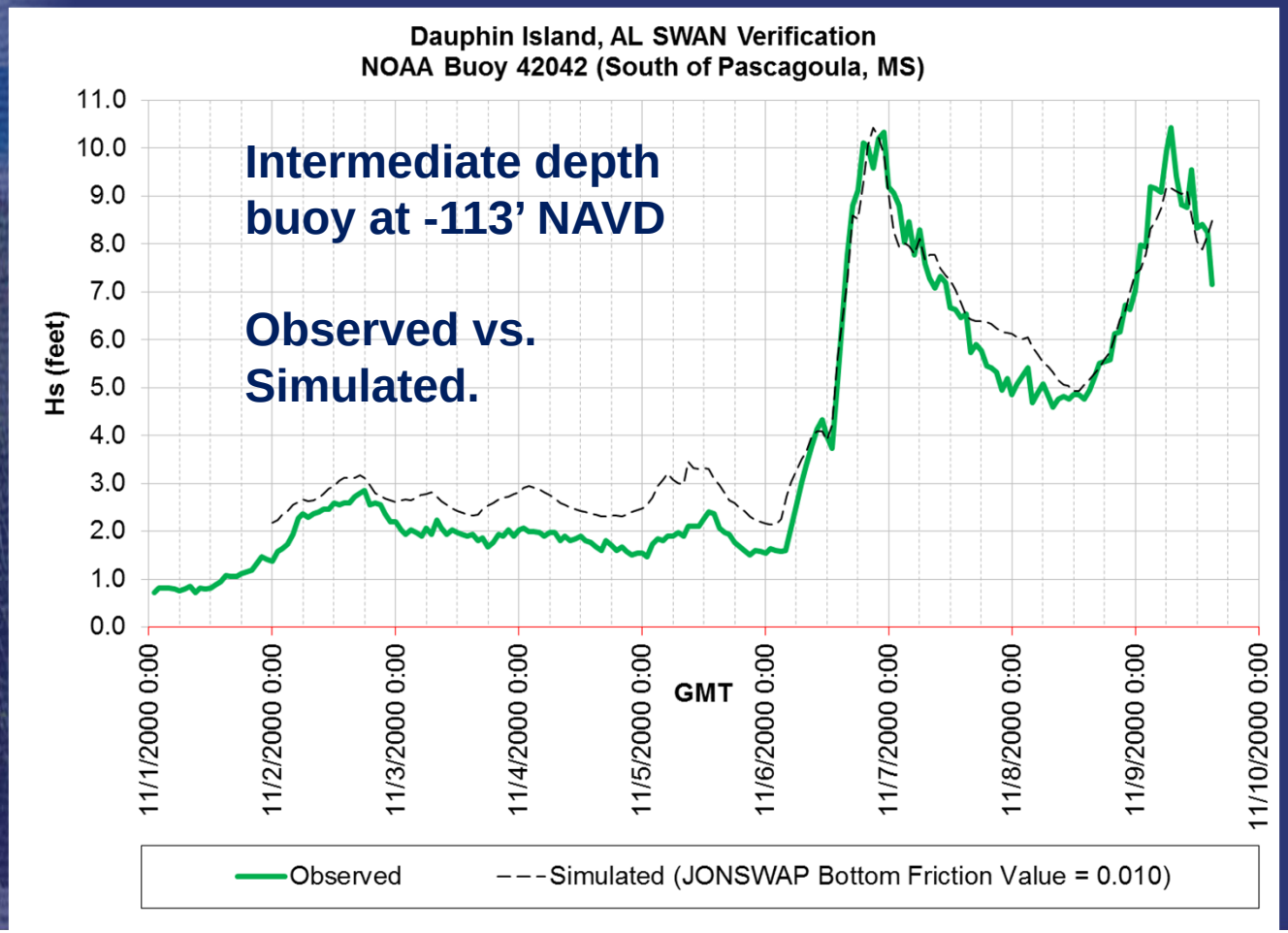
MODEL CALIBRATION / VERIFICATION

- **Original calibration & verification of SWAN model performed using conventional methods – time dependent (non-stationary) wave simulations over 1-2 week periods.**



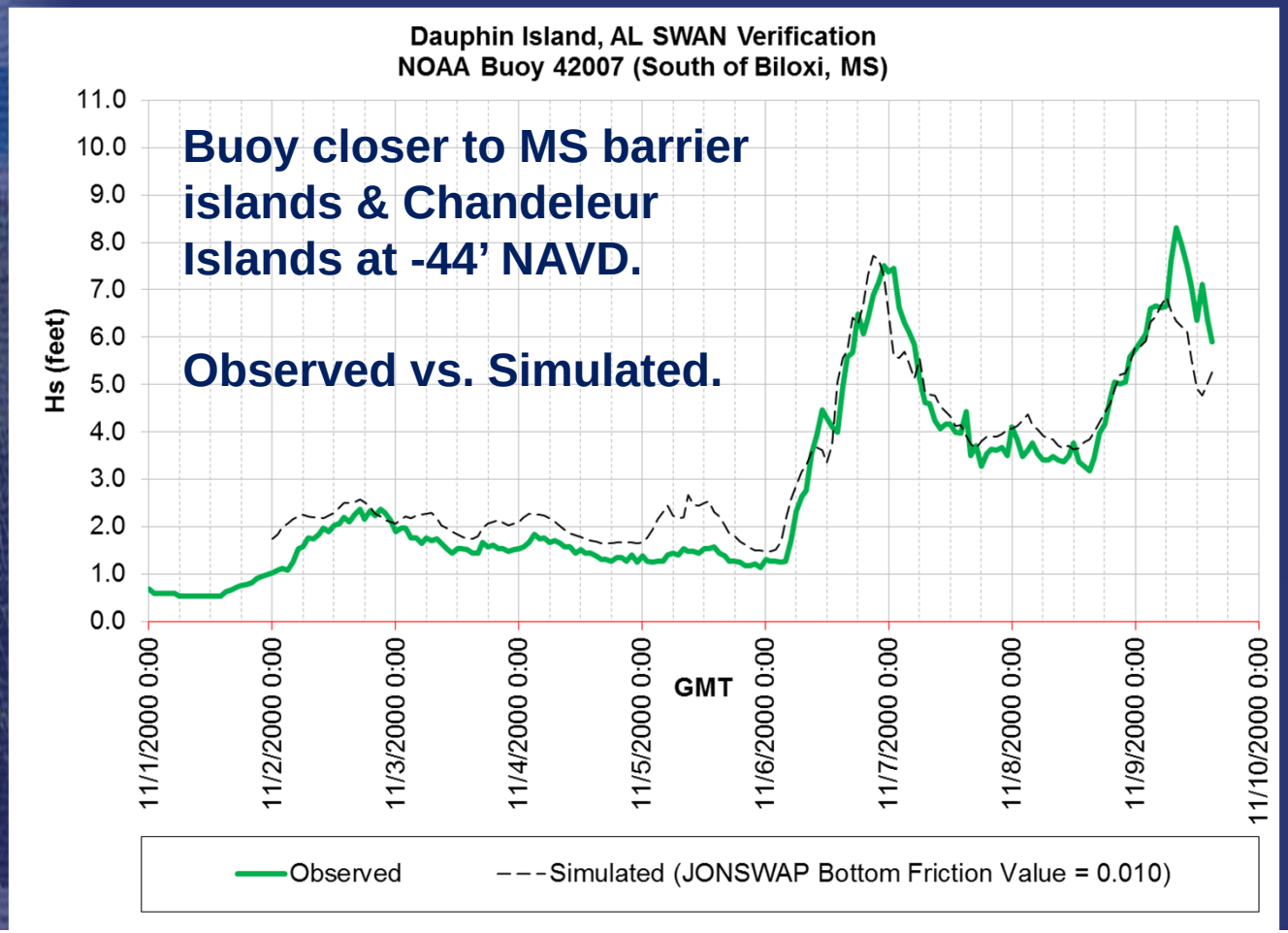
MODEL CALIBRATION / VERIFICATION

- **Original calibration & verification of SWAN model performed using conventional methods – time dependent (non-stationary) wave simulations over 1-2 week periods.**



MODEL CALIBRATION / VERIFICATION

- **Original calibration & verification of SWAN model performed using conventional methods – time dependent (non-stationary) wave simulations over 1-2 week periods.**



OFFSHORE WAVE RECORD

- Primary data source were observed waves at Buoy 42040 (-792’ NAVD) from Dec. 4, 1995 to Dec. 31, 2008. Measurements included wave direction after Nov. 1, 2000.
- Missing height, period, and direction values were filled in using:
  - NOAA National Centers for Environmental Prediction, Western North Atlantic WAVEWATCH III hindcast at buoy after July 1, 1999.
  - Wave Information Studies (WIS) hindcast at nearby Station 350 (73350) before July 1, 1999.

ADDITIONAL DATA

- Observed winds at Buoy 42040. Gaps in wind record were filled in using:
  - Wave Information Studies (WIS) hindcast at nearby Station 350 (73350) prior to Jan. 1, 2000.
  - Dauphin Island Tide Gage (NOAA #8735180) wind observations after Jan. 1, 2000.
- Observed water levels at Dauphin Island Tide Gage were added to the wave & wind record at Buoy 42040.

HYPERCUBE CASES

Sign. Wave Height (feet)	(meters)	Peak Period (sec.)	Offshore Direction (deg.)
0.3	0.1	2	0
3.3	1	4	22.5
6.6	2	6	45
9.8	3	8	67.5
13.1	4	10	90
16.4	5	12	112.5
19.7	6	14	135
23.0	7	16	157.5
26.2	8	18	180
29.5	9	20	202.5
32.8	10		225
36.1	11		247.5
39.4	12		270
42.7	13		
45.9	14		
49.2	15		
52.5	16		
55.8	17		

Large variety of wave cases, including the 52+ foot waves measured during Hurricanes Ivan (2004) & Katrina (2005).

Theoretical # of cases would be 2,340 (18 x 10 x 13).

Actual # of cases required based on wave record was 773.

HYPERCUBE CASES

Sign. Wave Height (feet)	(meters)	Peak Period (sec.)	Offshore Direction (deg.)
0.3	0.1	2	0
3.3	1	4	22.5
6.6	2	6	45
9.8	3	8	67.5
13.1	4	10	90
16.4	5	12	112.5
19.7	6	14	135
23.0	7	16	157.5
26.2	8	18	180
29.5	9	20	202.5
32.8	10		225
36.1	11		247.5
39.4	12		270
42.7	13		
45.9	14		
49.2	15		
52.5	16		
55.8	17		

SWAN model was used to estimate wave height & direction over the two modeling grids for each of the 773 cases.

Time steps assuming 10 minute intervals for entire 13 year record = 687,751.

% input reduction = 1 – (773/687,751) = 99.89%

HYPERCUBE CASES

ADDITIONAL INPUT FOR EACH CASE

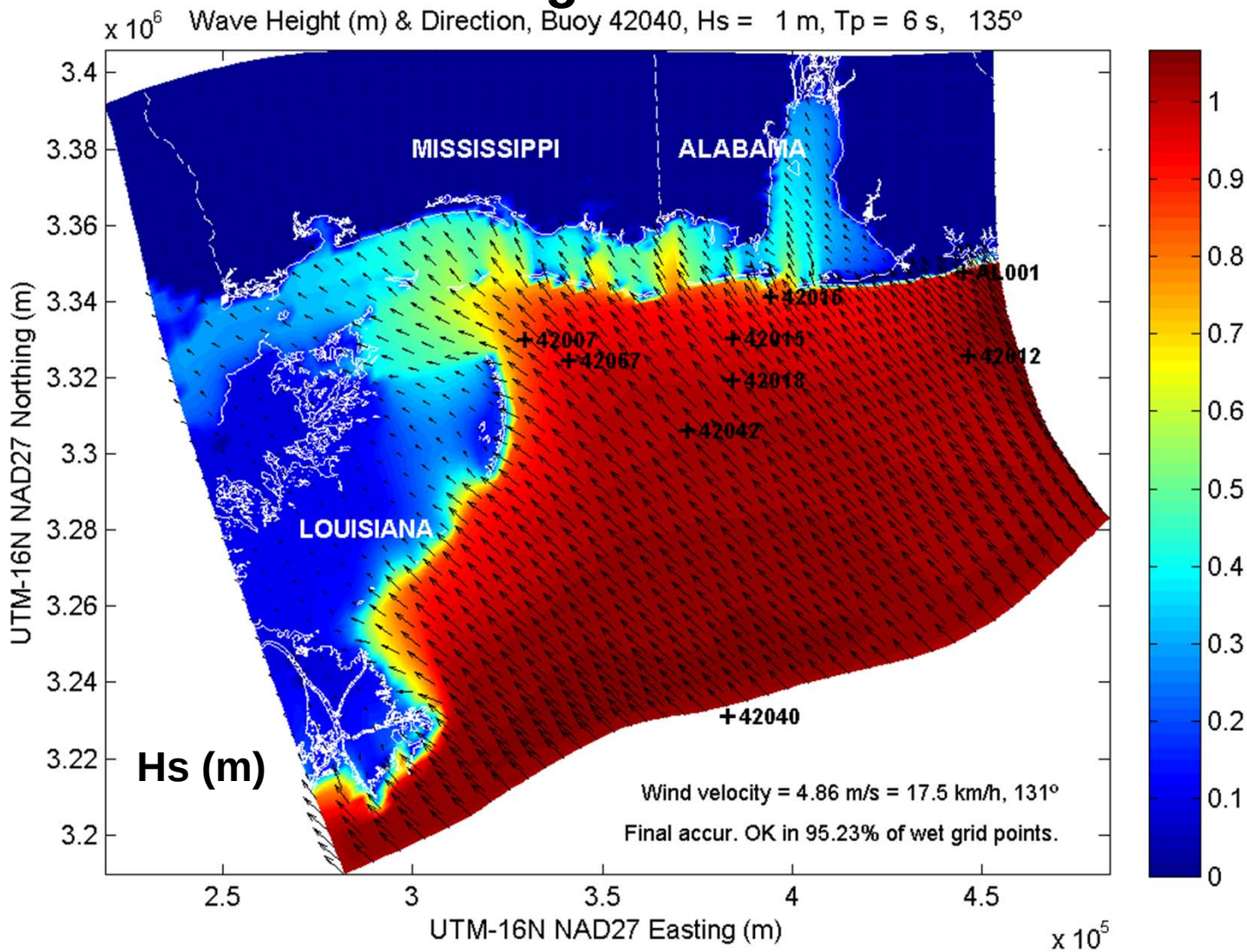
- **Directional spreading for Buoy 42040 cases:**
  - **Tp < 5 s, 25° Tp = 5-7 s, 14° Tp > 7 s, 11°**
- **Water levels:**
  - **Average of concurrent water levels for each wave case based on Dauphin Island Tide Gage, when available (738 of 773 cases).**
  - **Water levels for remaining 35 cases when tide gage was offline (post-storm periods) based on Hs & Storm Surge vs. return period curves or Mean Tide Level, whichever was higher.**
- **Winds – average of concurrent winds during each wave case.**

QUALITY CONTROL

- **Domain size:**
  - **249 km (154 miles) from SW grid corner to north end of Mobile Bay.**
  - **For 6 second wave and a 30 m depth, the wave speed is roughly 9.3 m/s (21 mph).**
  - **Travel time for distance and wave above is on the order of 7.4 hours.**
- **Variation of water levels associated with each case:**
  - **Standard deviation for all 773 cases average 0.19 m (0.63 feet).**
- **Variation of wind velocities associated with each case:**
  - **Standard deviation for all 773 cases averages 47° for directions and 2.3 m/s (5.1 mph) for speeds.**

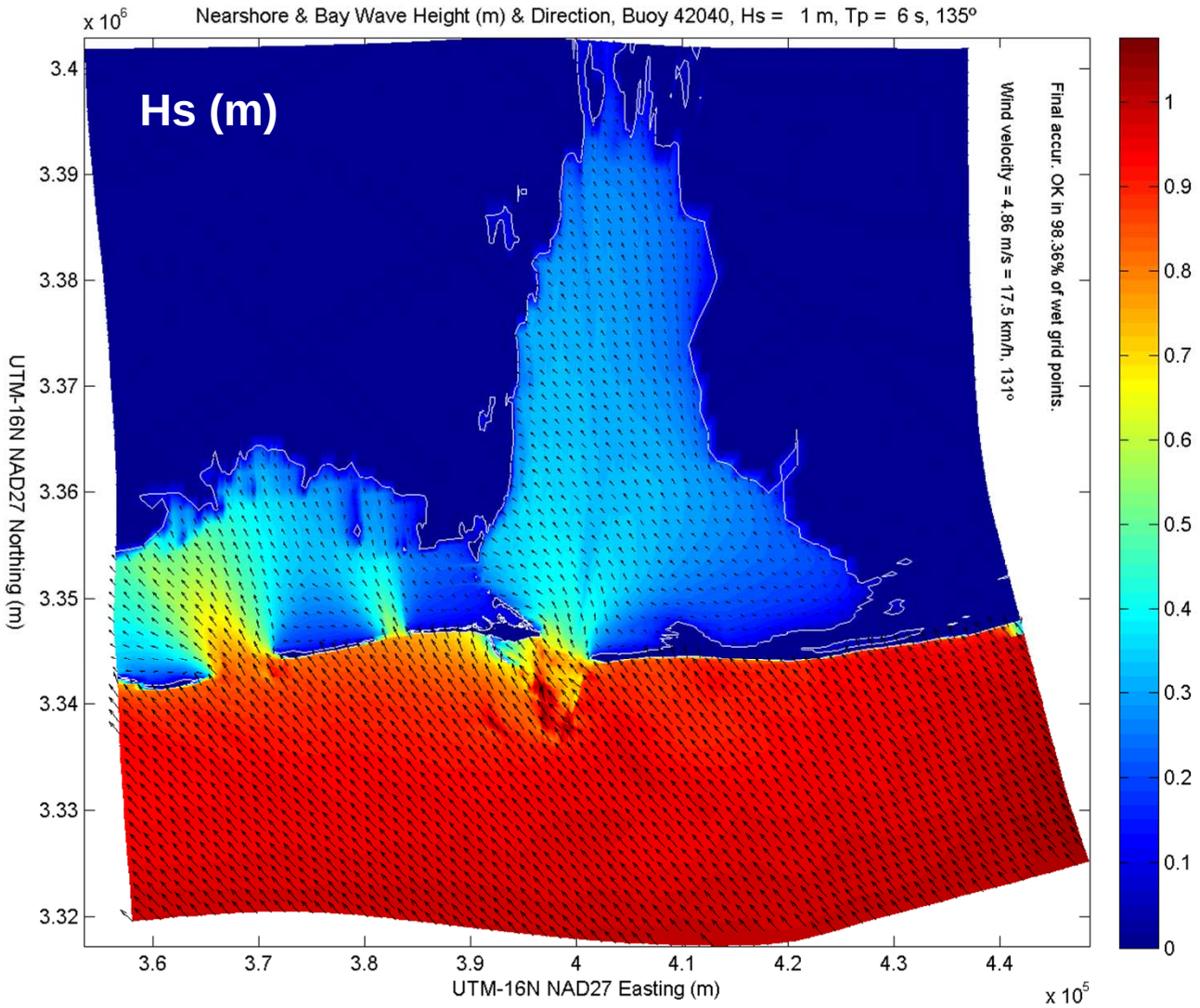
SWAN RESULTS

Average Conditions



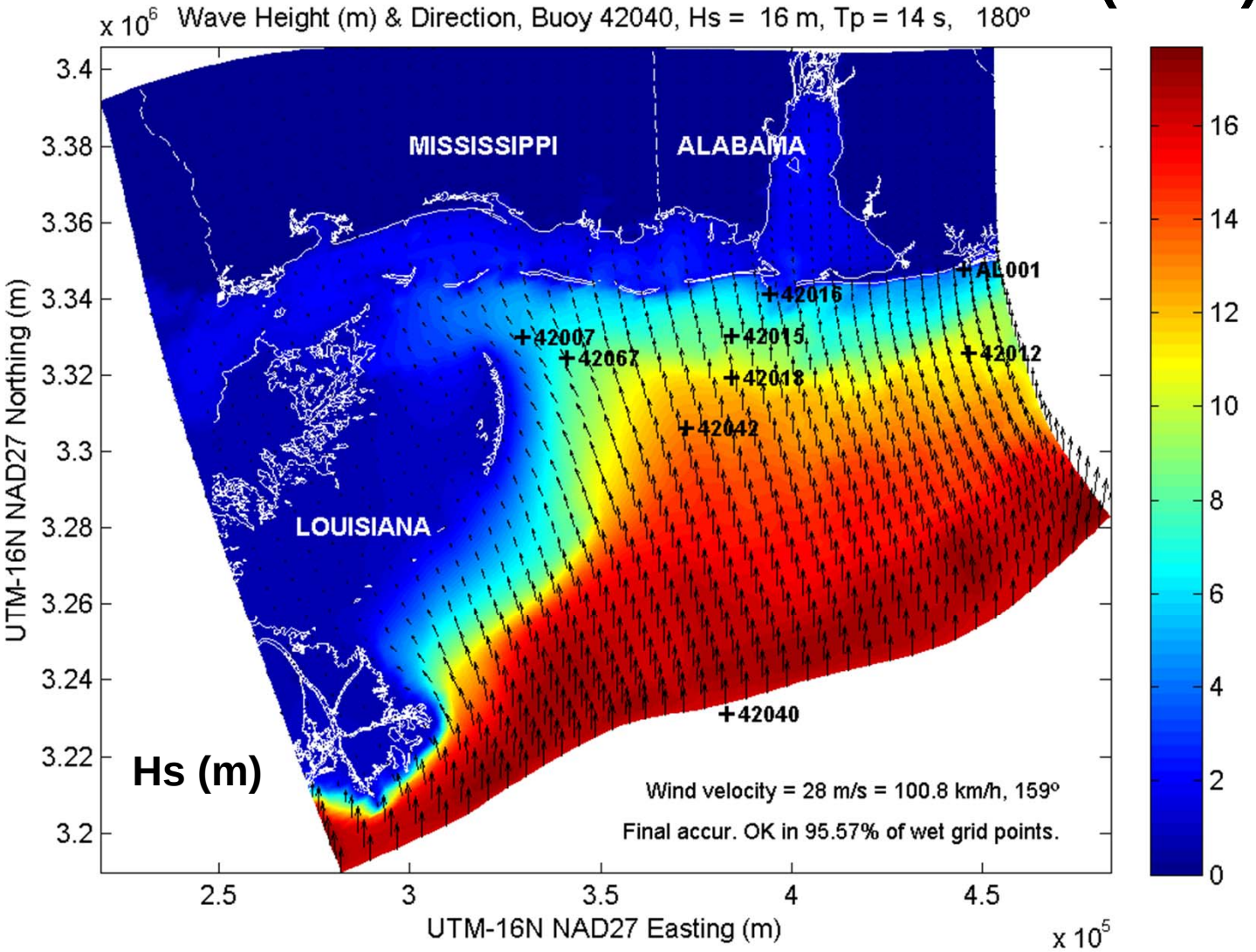
SWAN RESULTS

Average Conditions



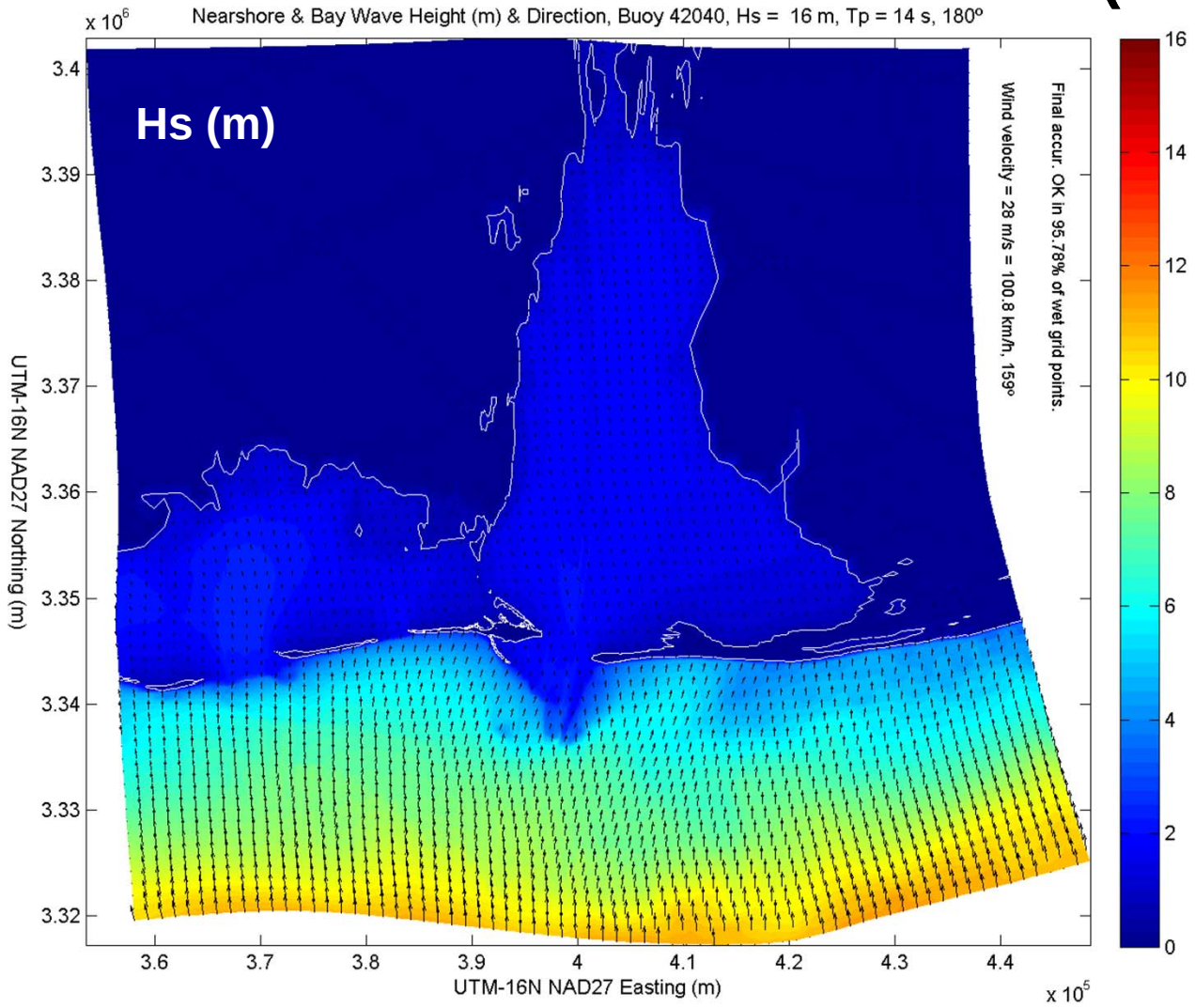
SWAN RESULTS

Conditions similar to Hurricane Katrina (2005)

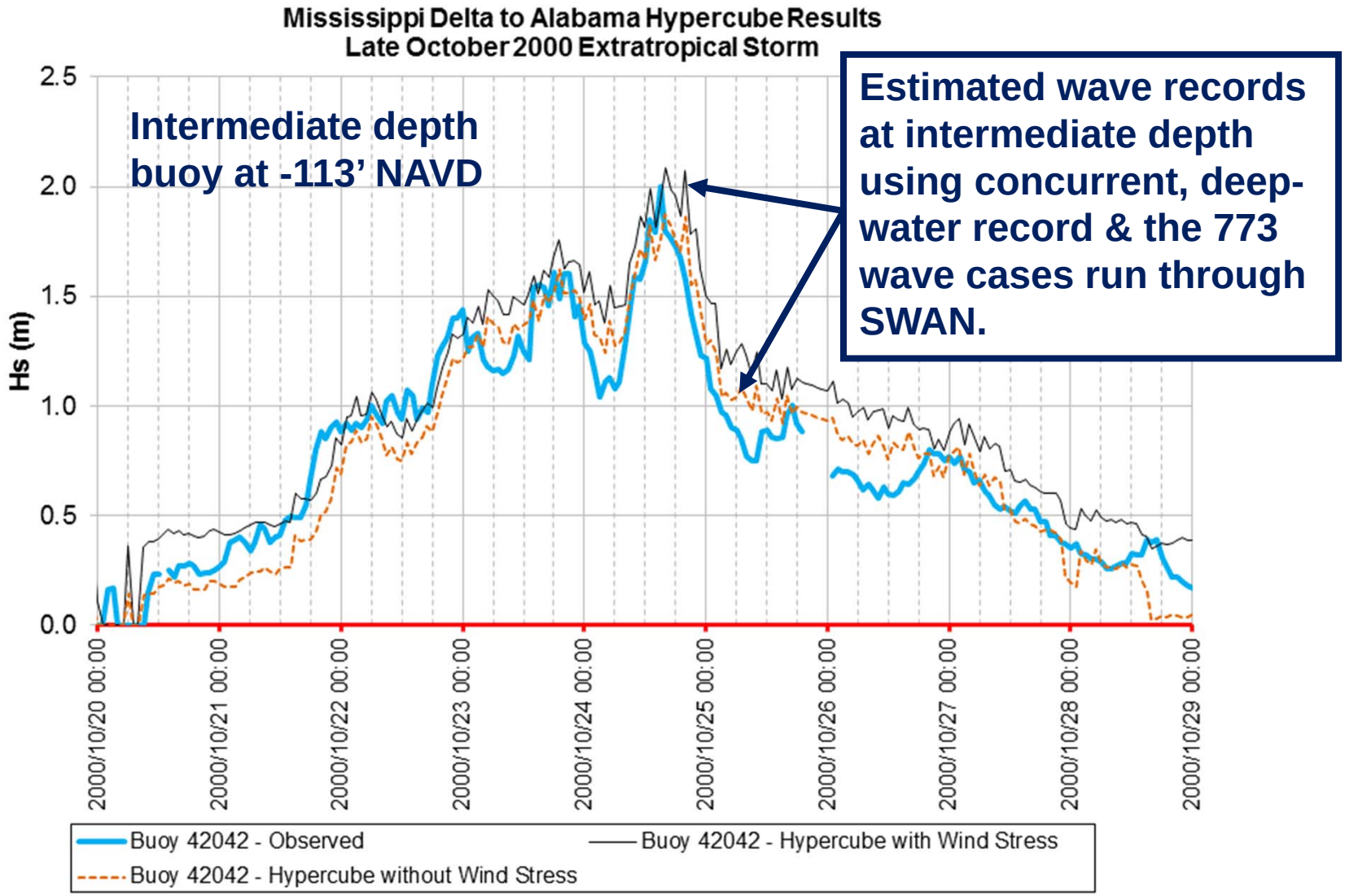


SWAN RESULTS

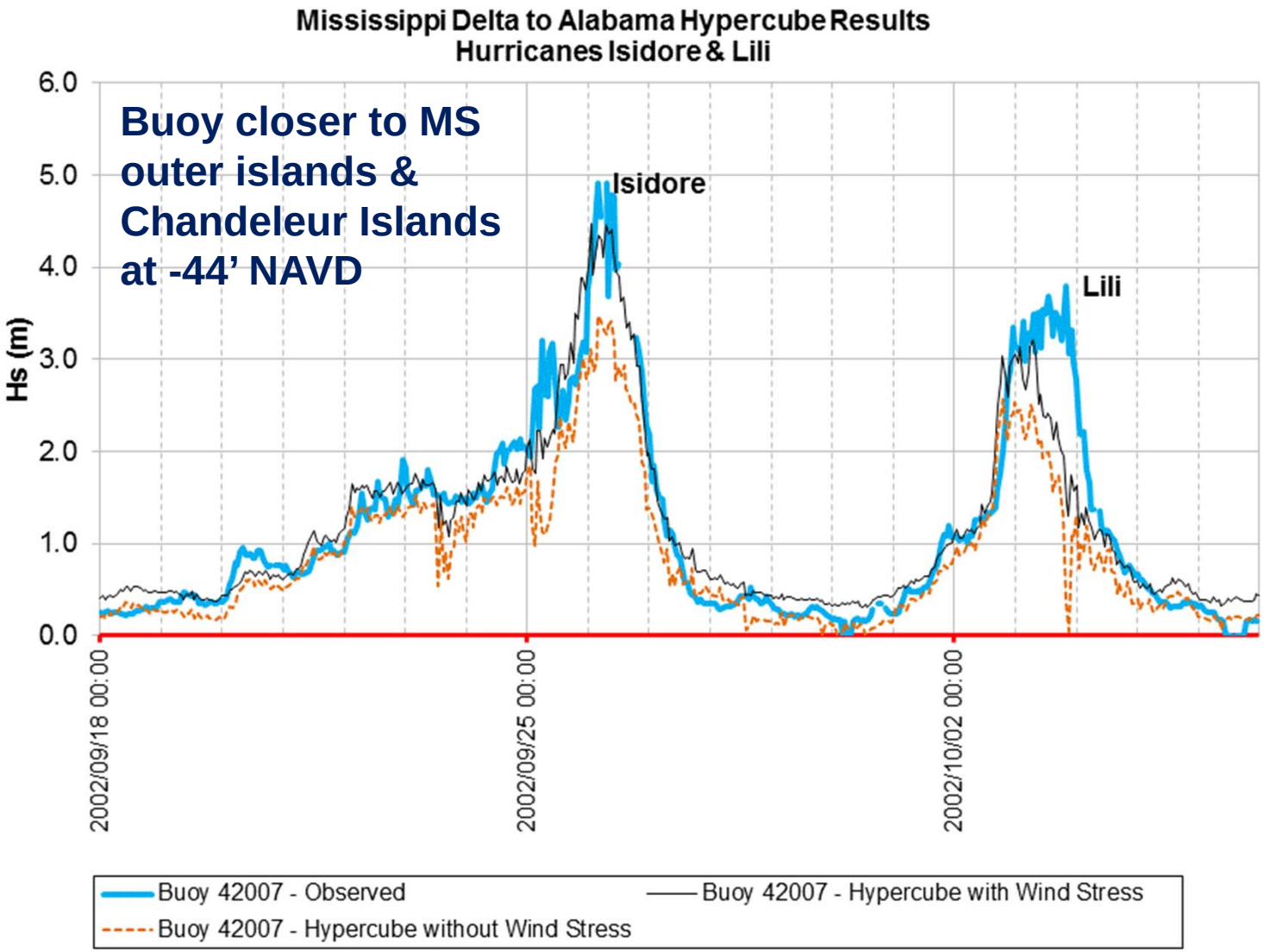
Conditions similar to Hurricane Katrina (2005)



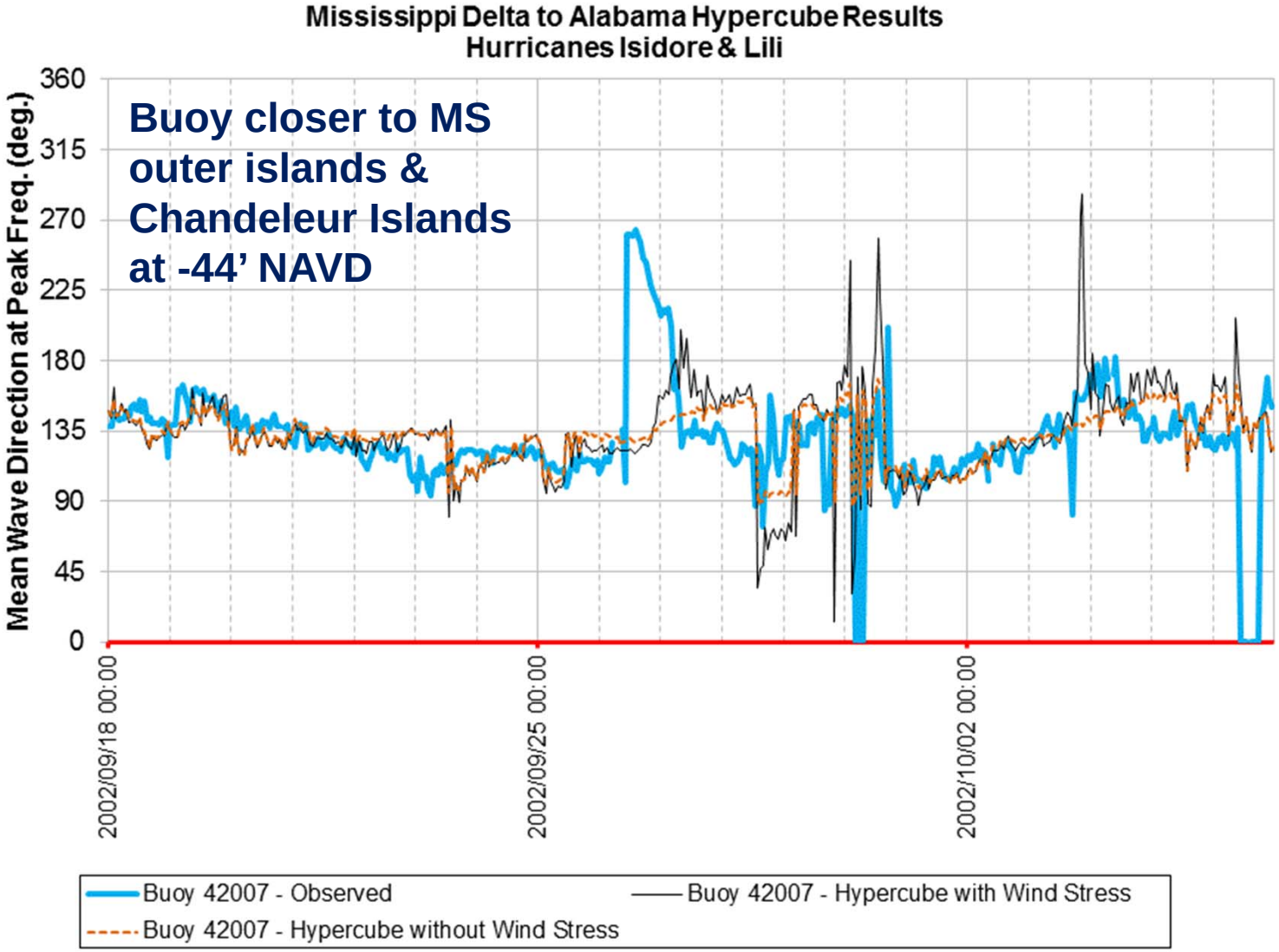
HYPERCUBE RESULTS



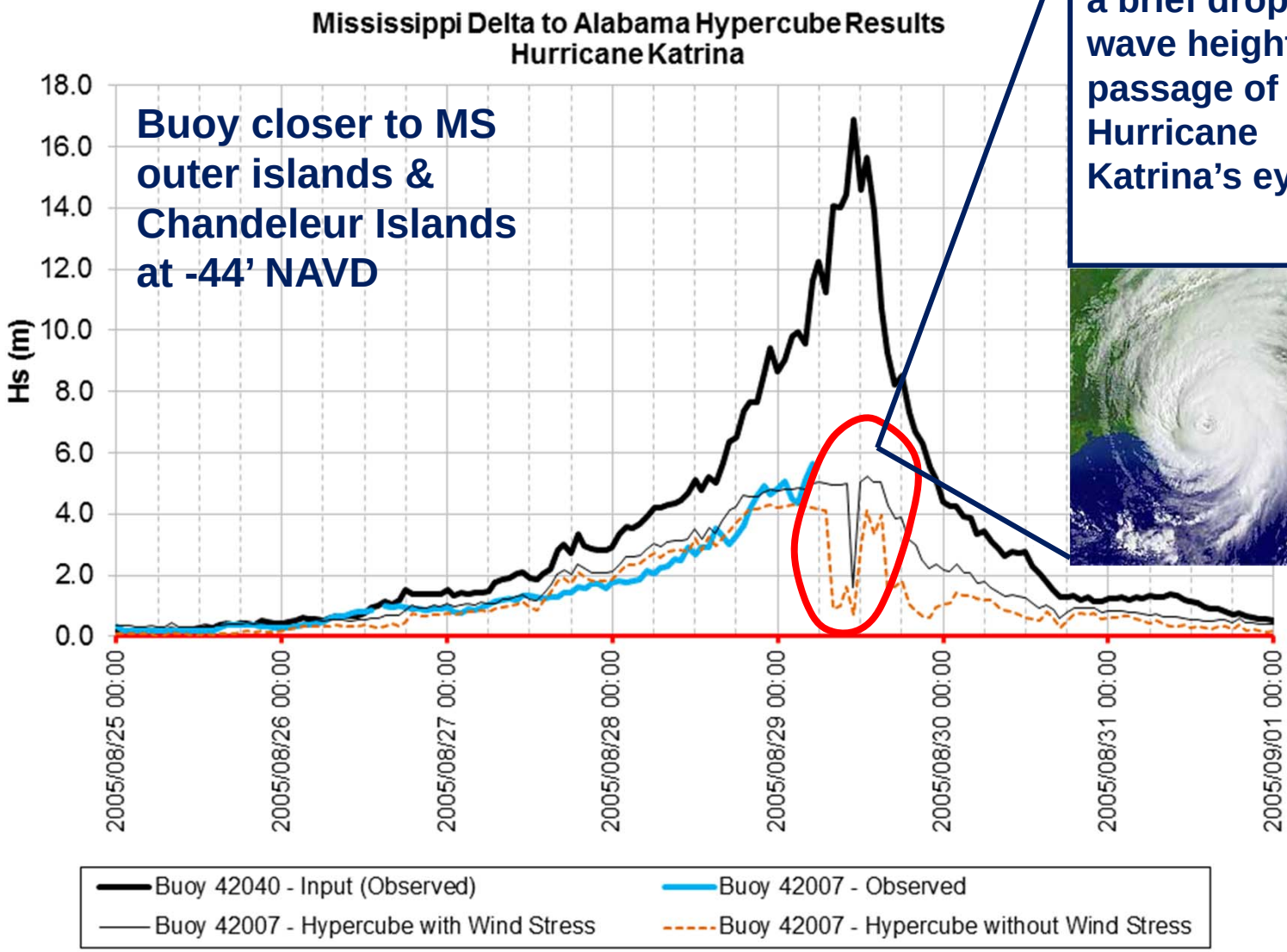
HYPERCUBE RESULTS



HYPERCUBE RESULTS

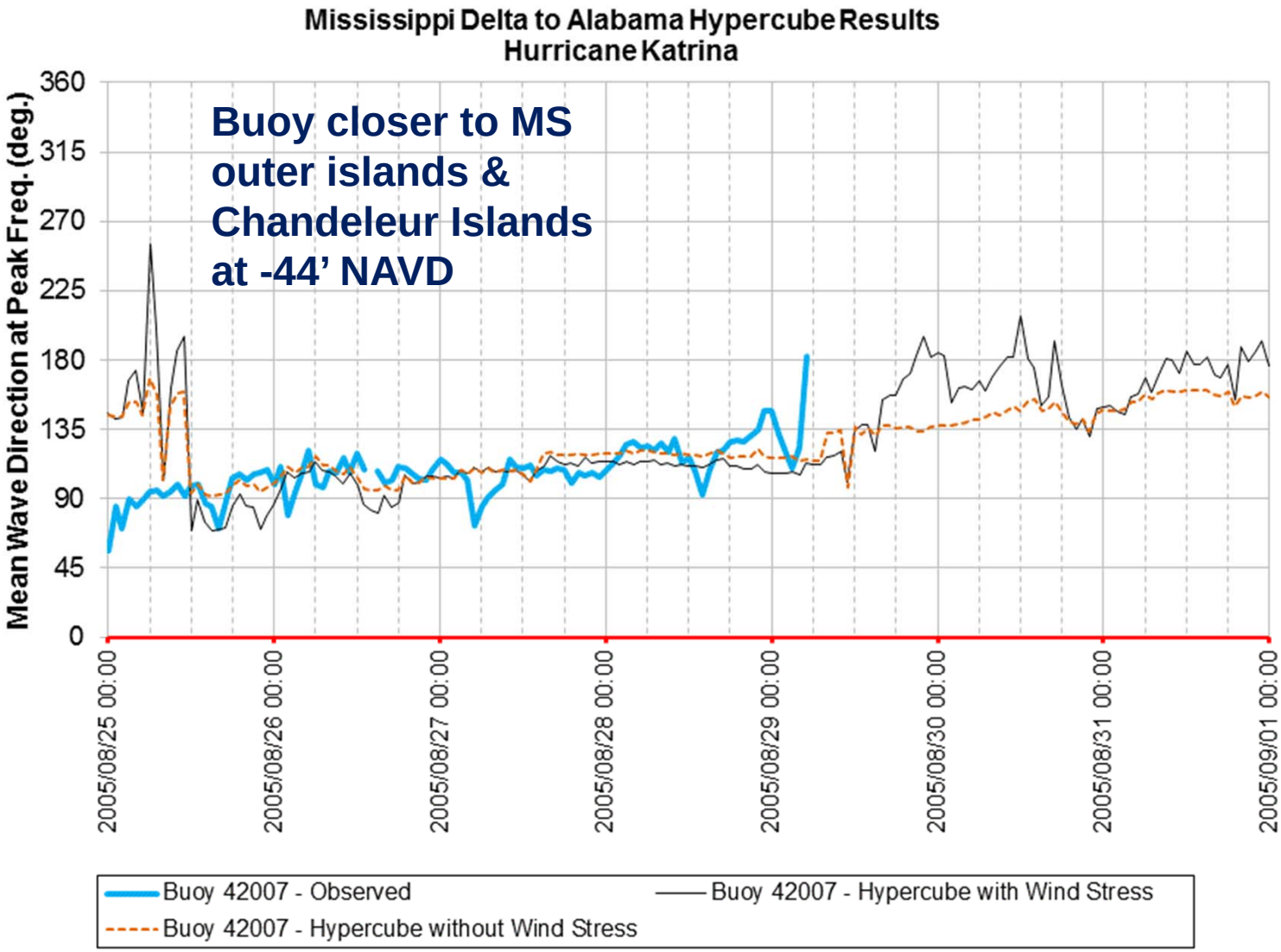


HYPERCUBE RESULTS

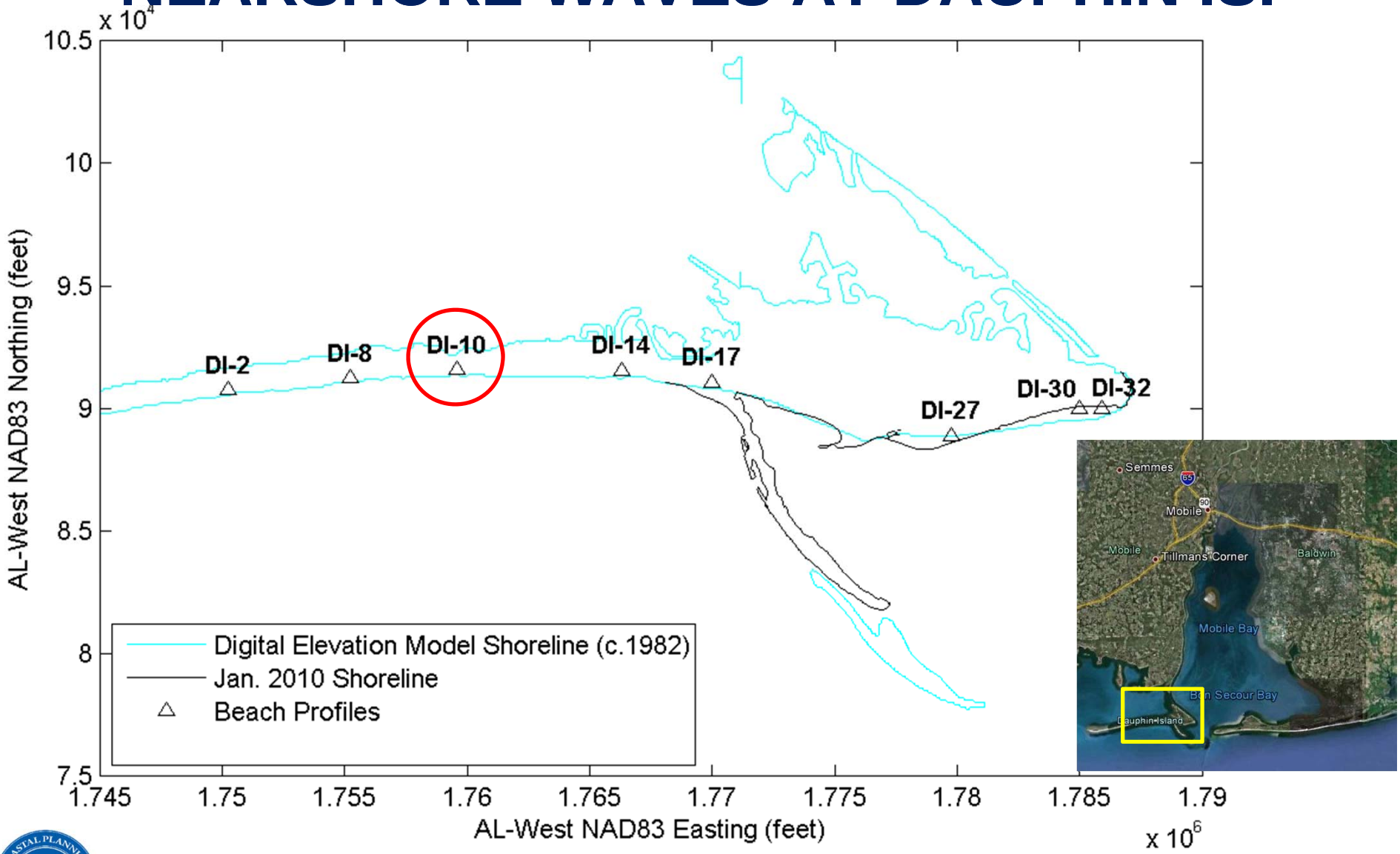


Method estimates a brief drop in wave height with passage of Hurricane Katrina's eye.

HYPERCUBE RESULTS

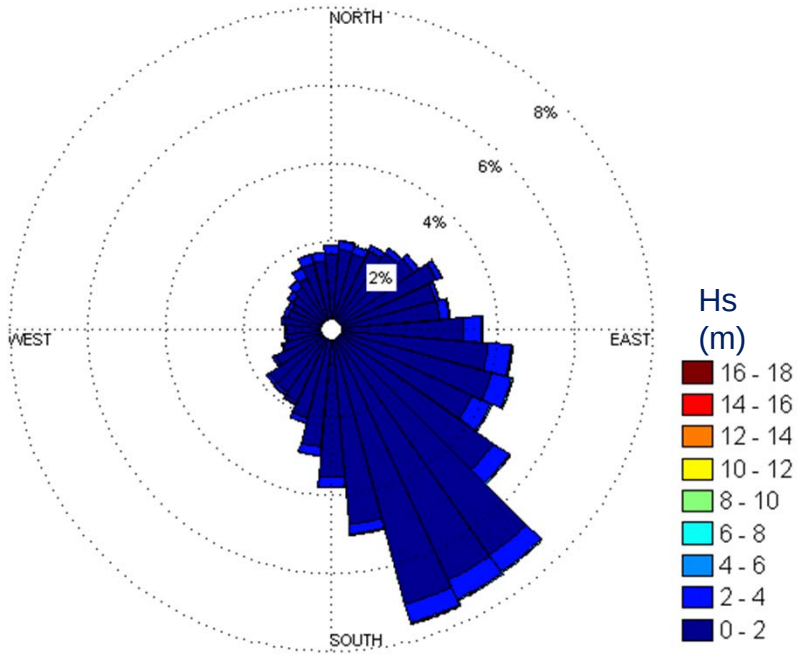


NEARSHORE WAVES AT DAUPHIN IS.



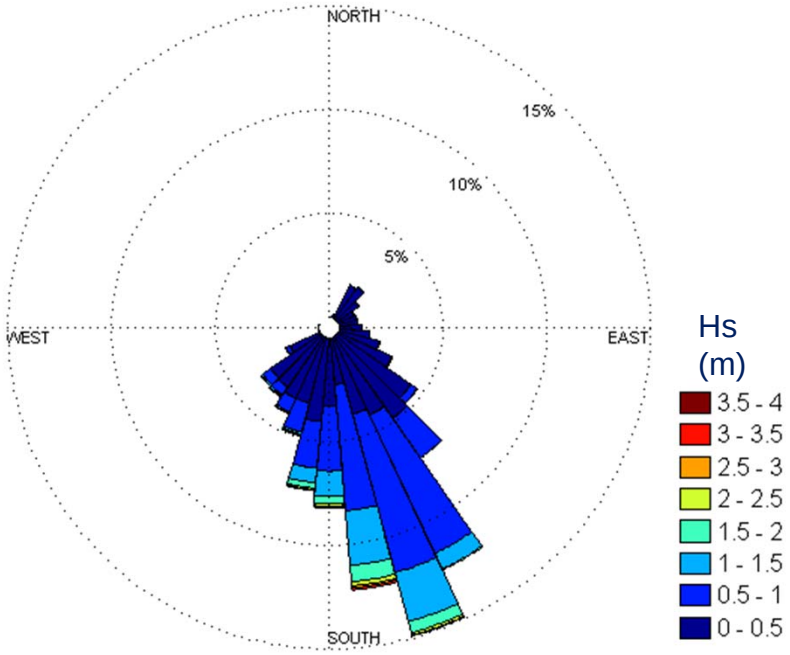
NEARSHORE WAVES AT DAUPHIN IS.

Buoy 42040, -792’ (-241 m) NAVD



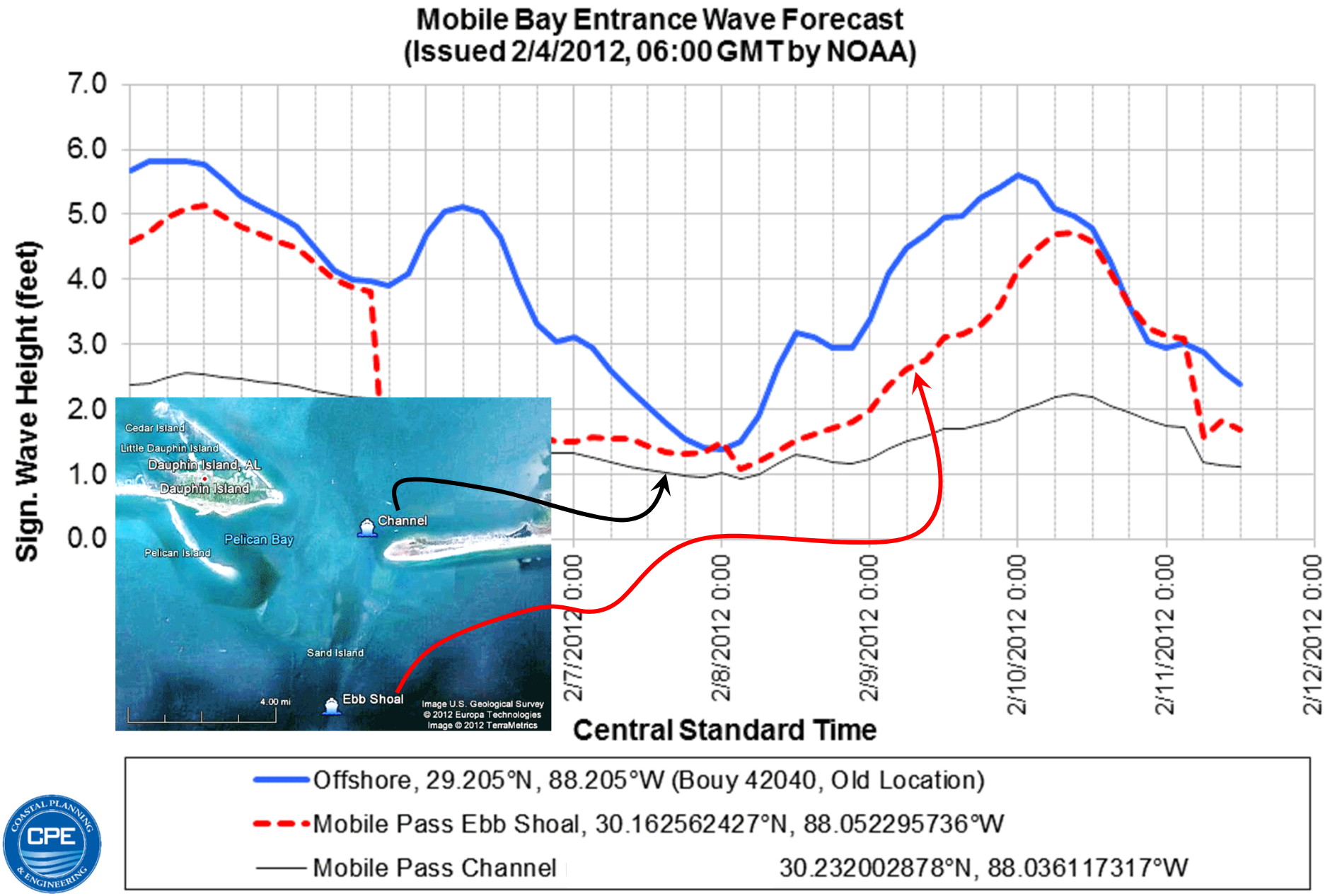
RMS Hs = 1.3 m = 4.2’
Average Tp = 5.6 s
Average Dir. = 124°

Profile DI-10, -22’ (-6.7 m) NAVD

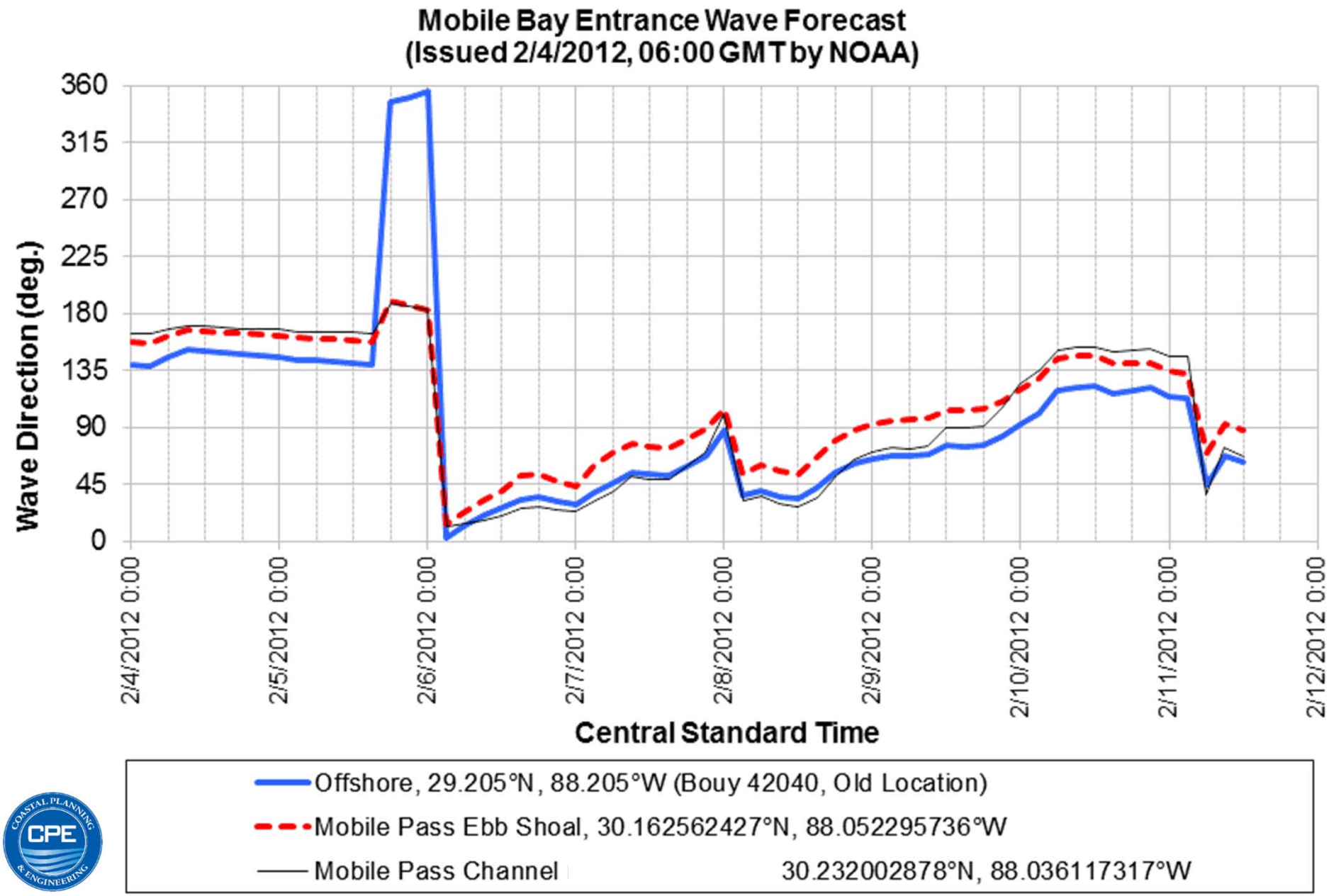


RMS Hs = 0.7 m = 2.2’
Average Tp = 5.6 s
Average Dir. = 169°
Max Hs = 3.8 m = 12.3’

NEARSHORE WAVE PREDICTION



NEARSHORE WAVE PREDICTION



CONCLUSIONS & RECOMMENDATIONS

- The Hypercube method can realistically estimate a long-term series of nearshore wave data based on a concurrent record of offshore wave data under both average and extreme conditions.
- Substantial reductions in computational time (95-99%) can be realized using the “wave case” approach in Hypercube vs. a conventional application of a non-stationary wave model.
- Assigning a wind velocity to each wave case provides for higher & more realistic wave height estimates in most cases. The variability in wind speed & direction does not excessively compromise height or direction estimates. However…
- Future research should identify a more robust means of assigning a wind velocity to each wave case. IH Cantabria's efforts are presently focusing on this aspect of the Hypercube method.

ACKNOWLEDGEMENTS

Deltares

Instituto de Hidraulica Ambiental de la Universidad de Cantabria (IH Cantabria)

National Oceanographic & Atmospheric Administration

South Coast Engineers, LLC

Town of Dauphin Island, Alabama

U.S. Army Corps of Engineers

U.S. Geological Survey

WRS Infrastructure & Environment, Inc., d/b/a WRScompass