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Risk Sciences

Storm Surge Flood Risk Modeling

SIFM Conference July 21, 2023

Agenda

Some unique aspects of flood modeling

Some history of US flood modeling at RenaissanceRe; Storm surge models hierarchy

Current state of US flood modeling

Latest developments and future steps

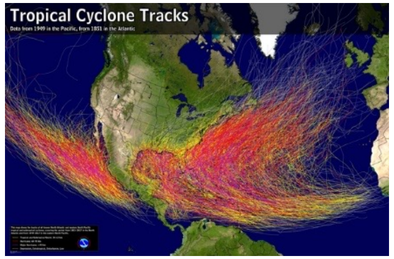
Extra topics:

Combined rain+surge effect

Climate change

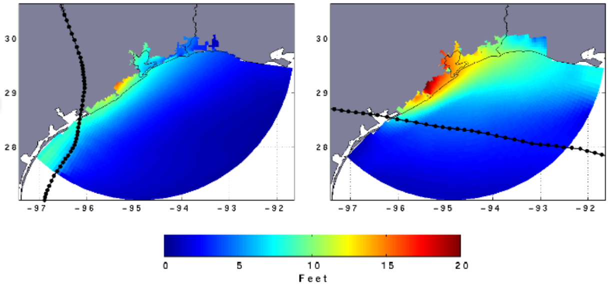
Geocoding problems

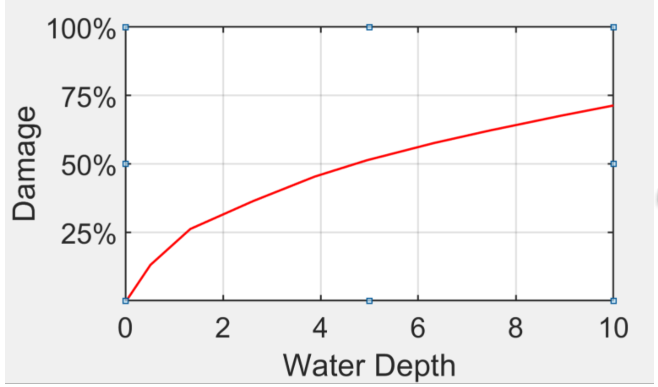
US-wide stochastic model is the tool of choice for storm surge risk analysis



Event Set

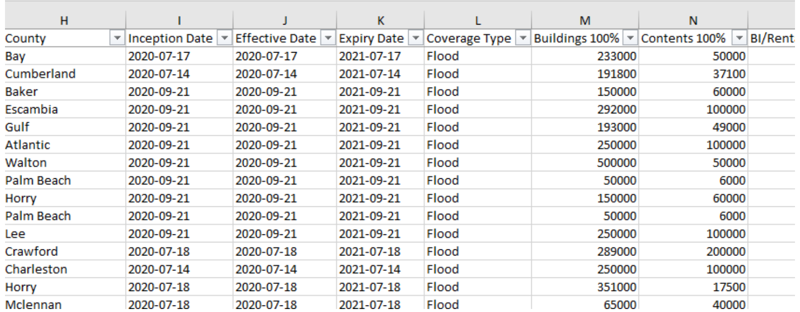
Hazard model





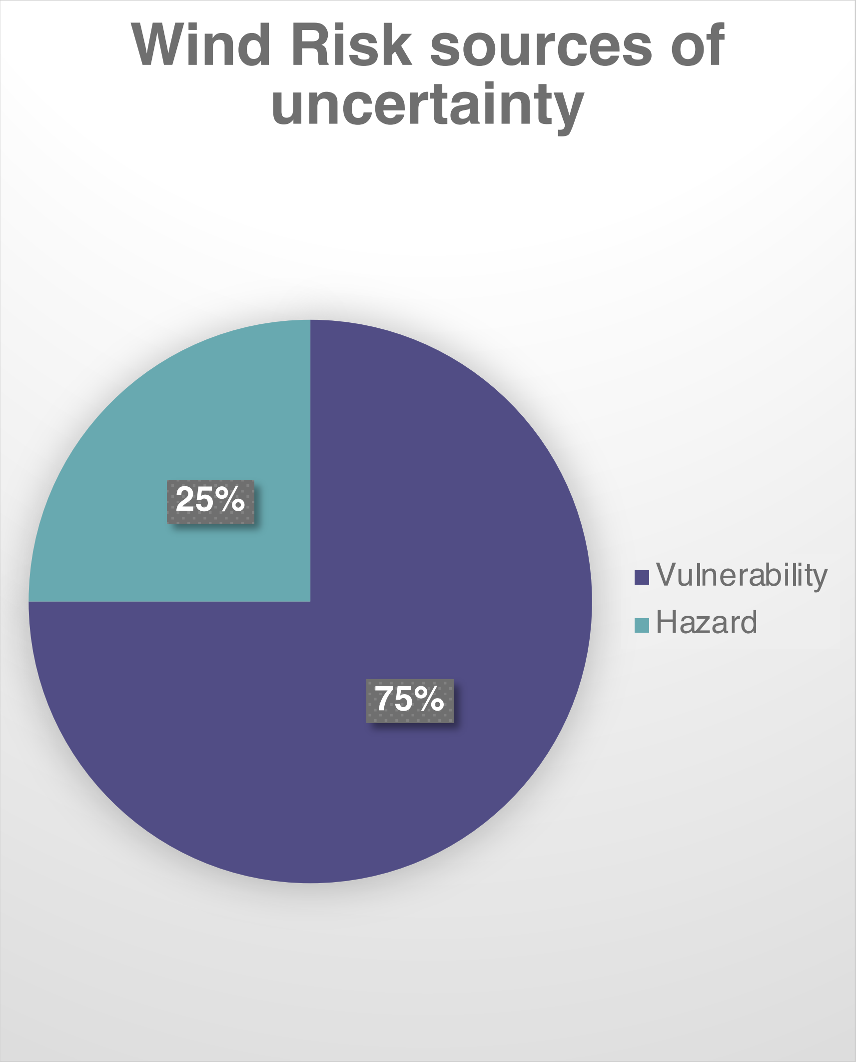
Vulnerability model

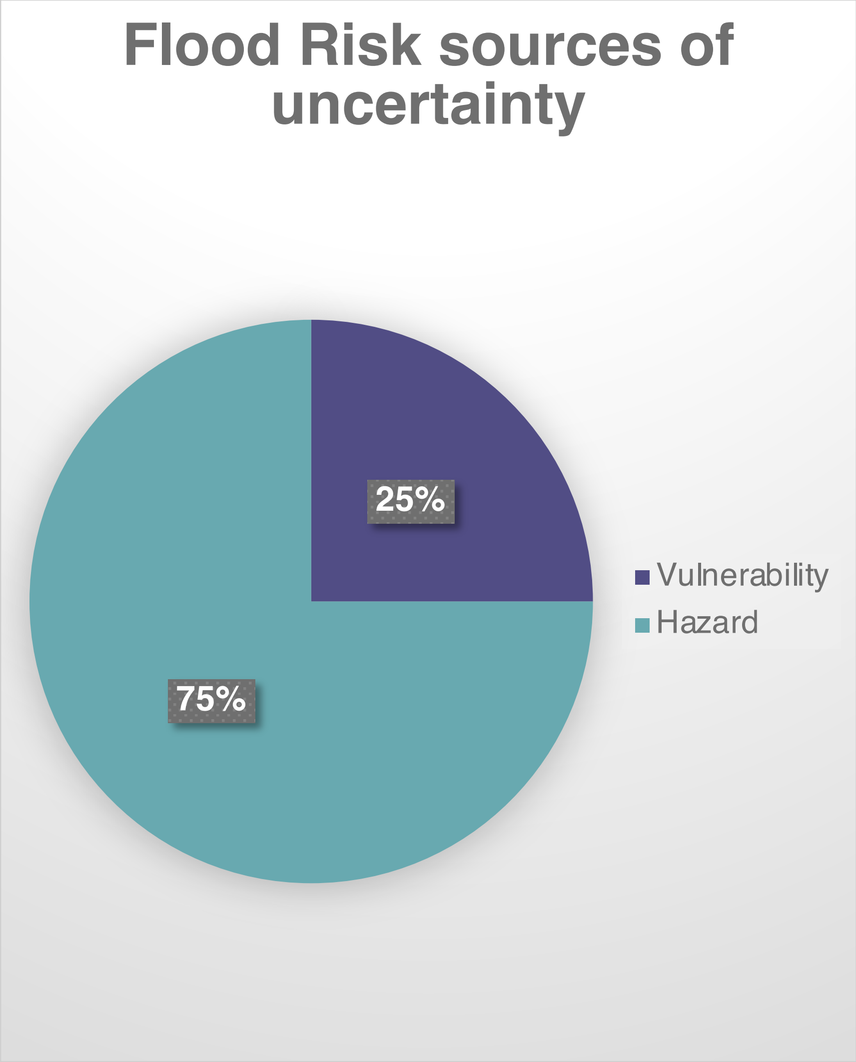
Financial model



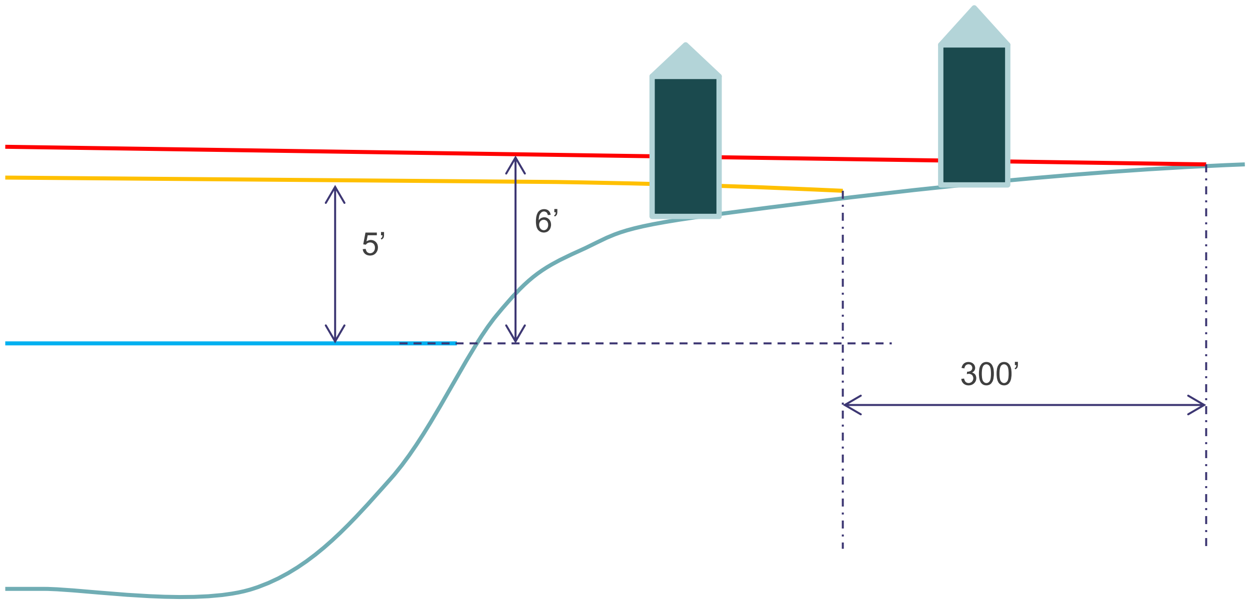
H	I	J	K	L	M	N	
County	Inception Date	Effective Date	Expiry Date	Coverage Type	Buildings 100%	Contents 100%	BI/Rent
Bay	2020-07-17	2020-07-17	2021-07-17	Flood	233000	50000	
Cumberland	2020-07-14	2020-07-14	2021-07-14	Flood	191800	37100	
Baker	2020-09-21	2020-09-21	2021-09-21	Flood	150000	60000	
Escambia	2020-09-21	2020-09-21	2021-09-21	Flood	292000	100000	
Gulf	2020-09-21	2020-09-21	2021-09-21	Flood	193000	49000	
Atlantic	2020-09-21	2020-09-21	2021-09-21	Flood	250000	100000	
Walton	2020-09-21	2020-09-21	2021-09-21	Flood	500000	50000	
Palm Beach	2020-09-21	2020-09-21	2021-09-21	Flood	50000	6000	
Horry	2020-09-21	2020-09-21	2021-09-21	Flood	150000	60000	
Palm Beach	2020-09-21	2020-09-21	2021-09-21	Flood	50000	6000	
Lee	2020-09-21	2020-09-21	2021-09-21	Flood	250000	100000	
Crawford	2020-07-18	2020-07-18	2021-07-18	Flood	289000	200000	
Charleston	2020-07-14	2020-07-14	2021-07-14	Flood	250000	100000	
Horry	2020-07-18	2020-07-18	2021-07-18	Flood	351000	17500	
Mclennan	2020-07-18	2020-07-18	2021-07-18	Flood	65000	40000	

Hazard versus Vulnerability





Level of precision required in flood hazard modeling



20% error in modeling the flood depth typically leads to 100% error in resulting losses

US storm surge modeling history at RenaissanceRe

Katrina (2005) highlighted the need for better understanding of the storm surge risk in the US
- First (internal) storm surge risk assessment tool was developed (parametric-style approach was used)

2008 – first stochastic surge model based on SLOSH (local dynamical surge model)

2011 – transitioned to ADCIRC (basin-wide dynamical surge model)

2012 – added wave setup model

2012 – Sandy happened
- 2012-2015 – transitioned to LIDAR-informed ADCIRC configurations

2016 – started using in-house flood models for primary underwriting
- Location-level precision requirement
- Detailed claims data

2023 – wave runup module, fine resolution flow over terrain module, combined rain+surge module

Storm surge model hierarchy (evolution)

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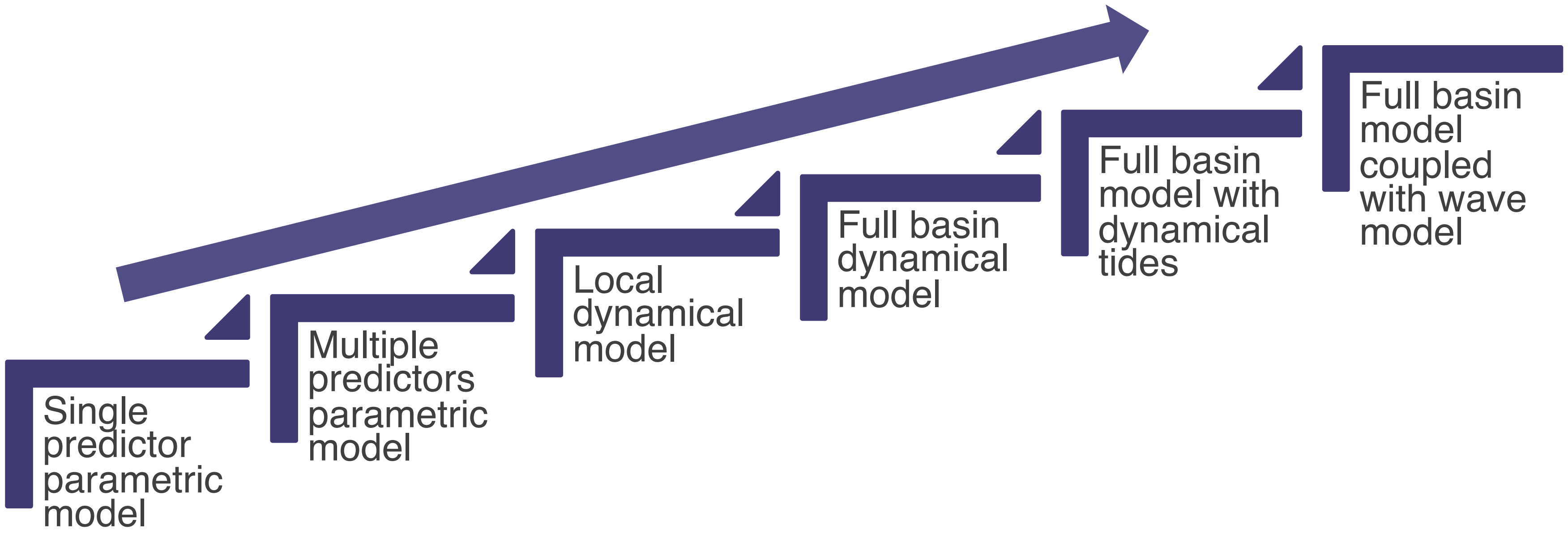


Single predictor parametric model

Multiple predictors parametric model

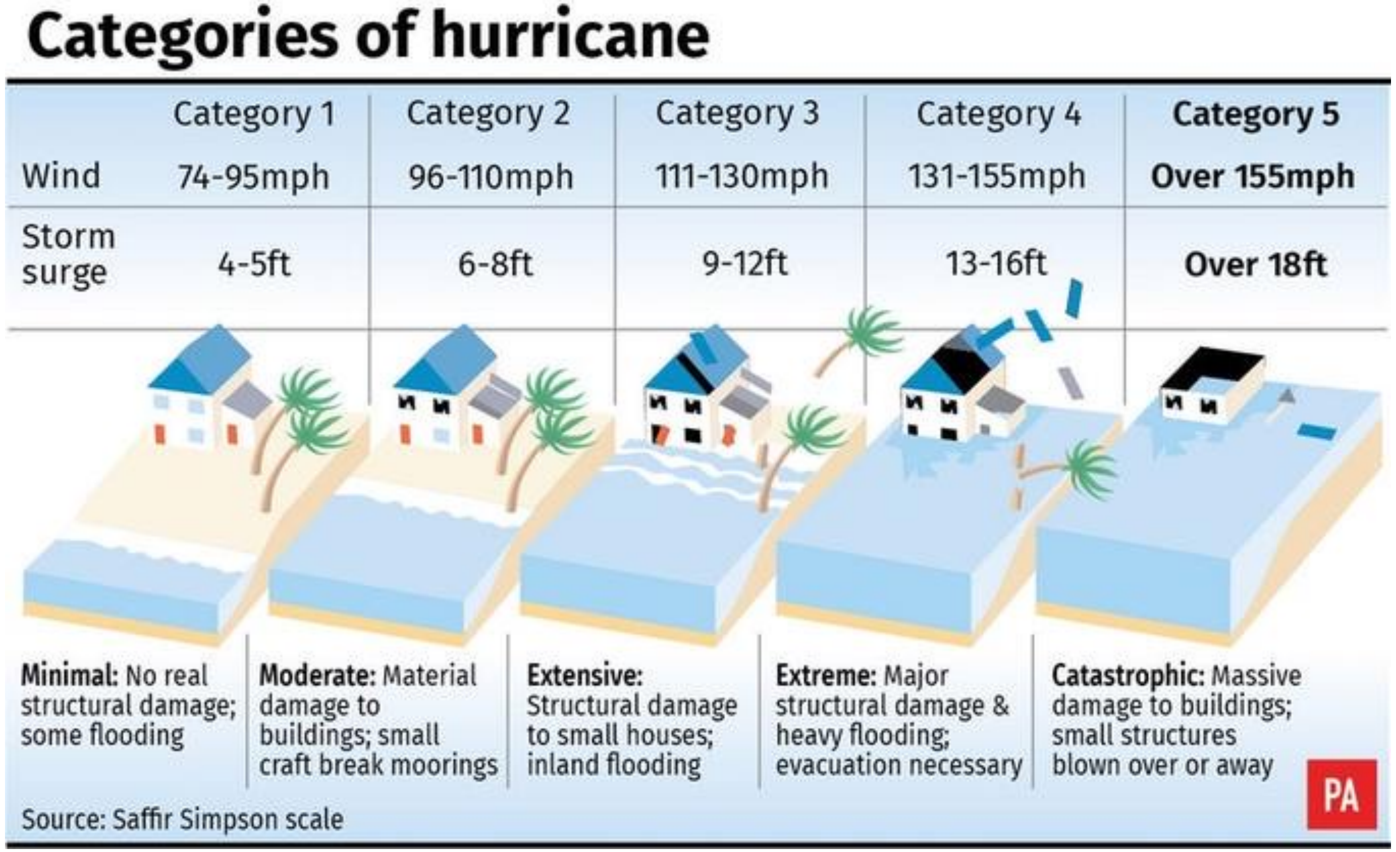
Local dynamical model

Full basin dynamical model

Full basin model with dynamical tides

Full basin model coupled with wave model

Simplest storm surge model



Categories of hurricane

	Category 1	Category 2	Category 3	Category 4	**Category 5**
Wind	74-95mph	96-110mph	111-130mph	131-155mph	**Over 155mph**
Storm surge	4-5ft	6-8ft	9-12ft	13-16ft	**Over 18ft**
	Minimal: No real structural damage; some flooding	**Moderate:** Material damage to buildings; small craft break moorings	**Extensive:** Structural damage to small houses; inland flooding	**Extreme:** Major structural damage & heavy flooding; evacuation necessary	**Catastrophic:** Massive damage to buildings; small structures blown over or away

Source: Saffir Simpson scale

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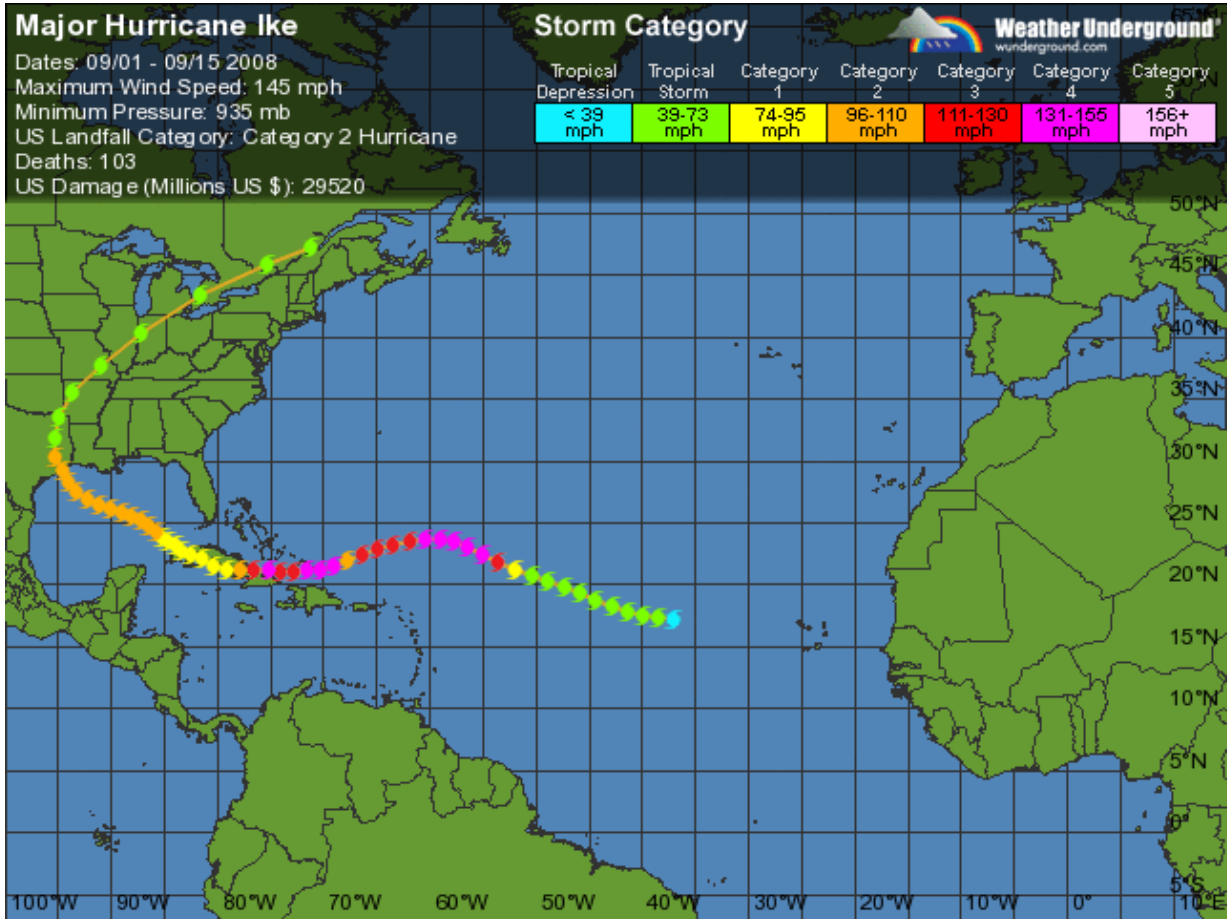
In this simplest approach the wind speed (storm category) is the single predictor of the storm surge

This is a single parameter “parametric” surge model

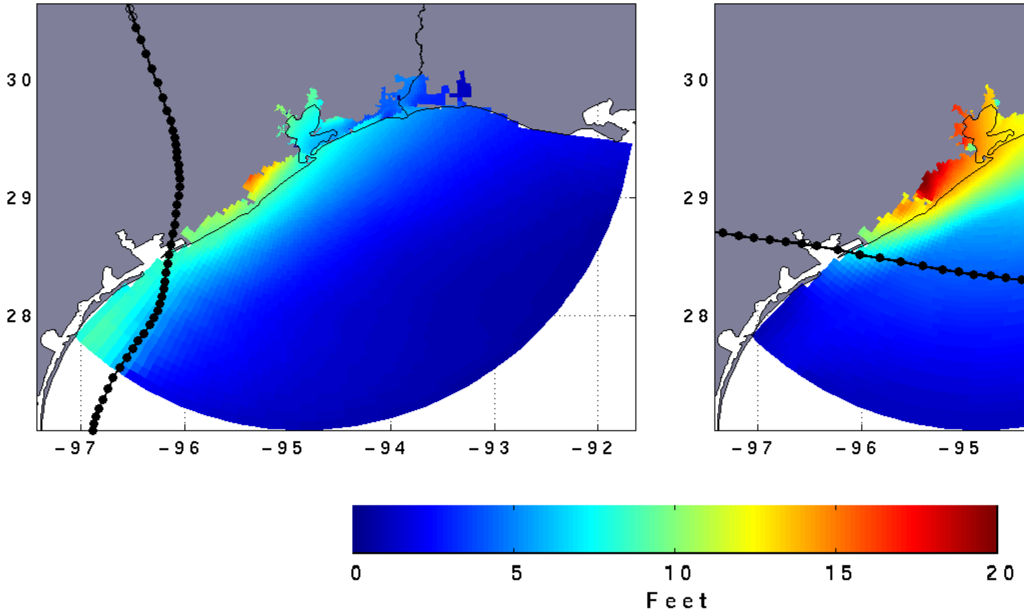
Hurricane Ike (2008) – decisive case against single parameter storm surge models



The next level storm surge model is a multiparameter parametric model

- While making landfall only as category 2 hurricane Ike generated storm surge characteristic of a category 5 hurricane
- The reason is the size of the storm
- Ike is a clear case showing that at least two predictors (intensity and size) should be used by a parametric storm surge model
- In reality, other parameters, e.g., propagation speed, are also important

Storm surge phenomenon is too complex to be adequately described with a parametric model



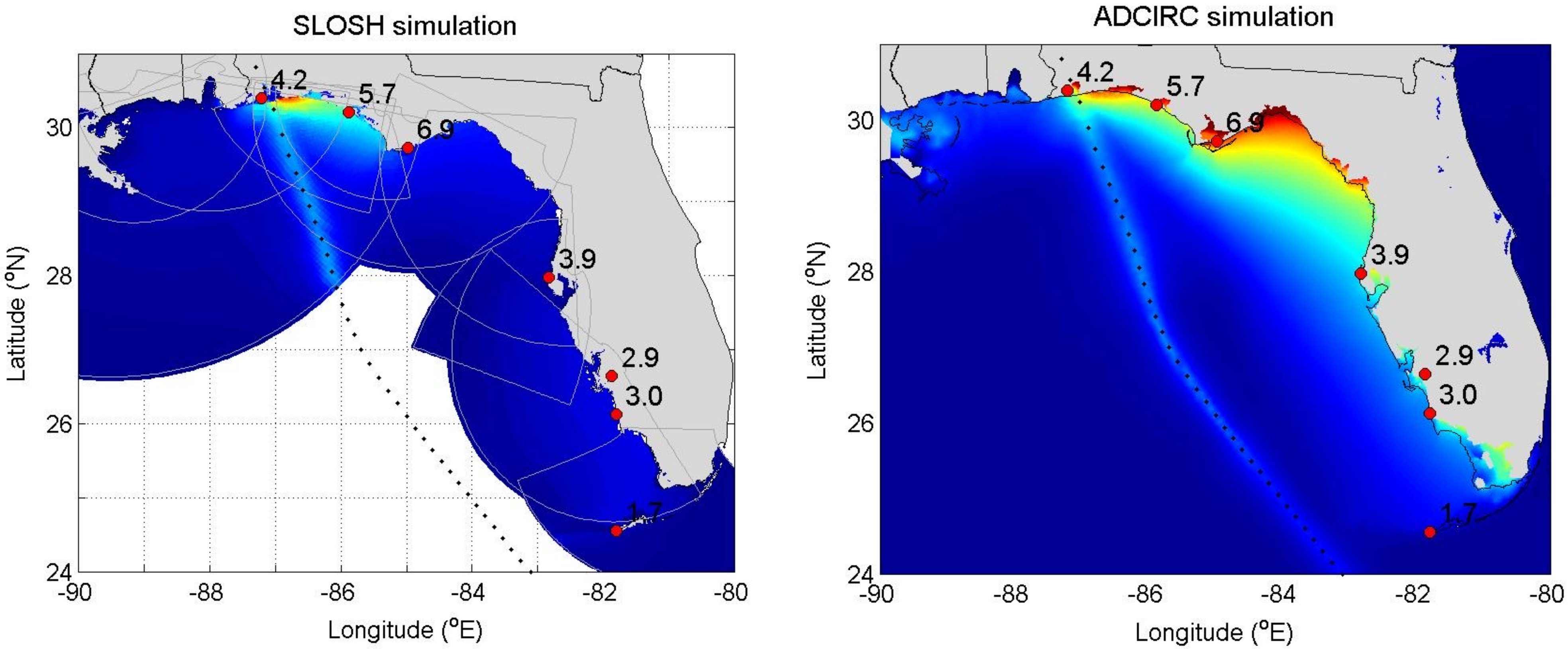
Storm surge for two hypothetical category 4 hurricanes of similar size making landfall at the same location but approaching the coast at different angles

The next level storm surge model is a **local dynamical** model (SLOSH)

Dynamical models compute storm surge by solving a system of differential equations describing the water movement in the ocean

Storm surge is not a local phenomenon

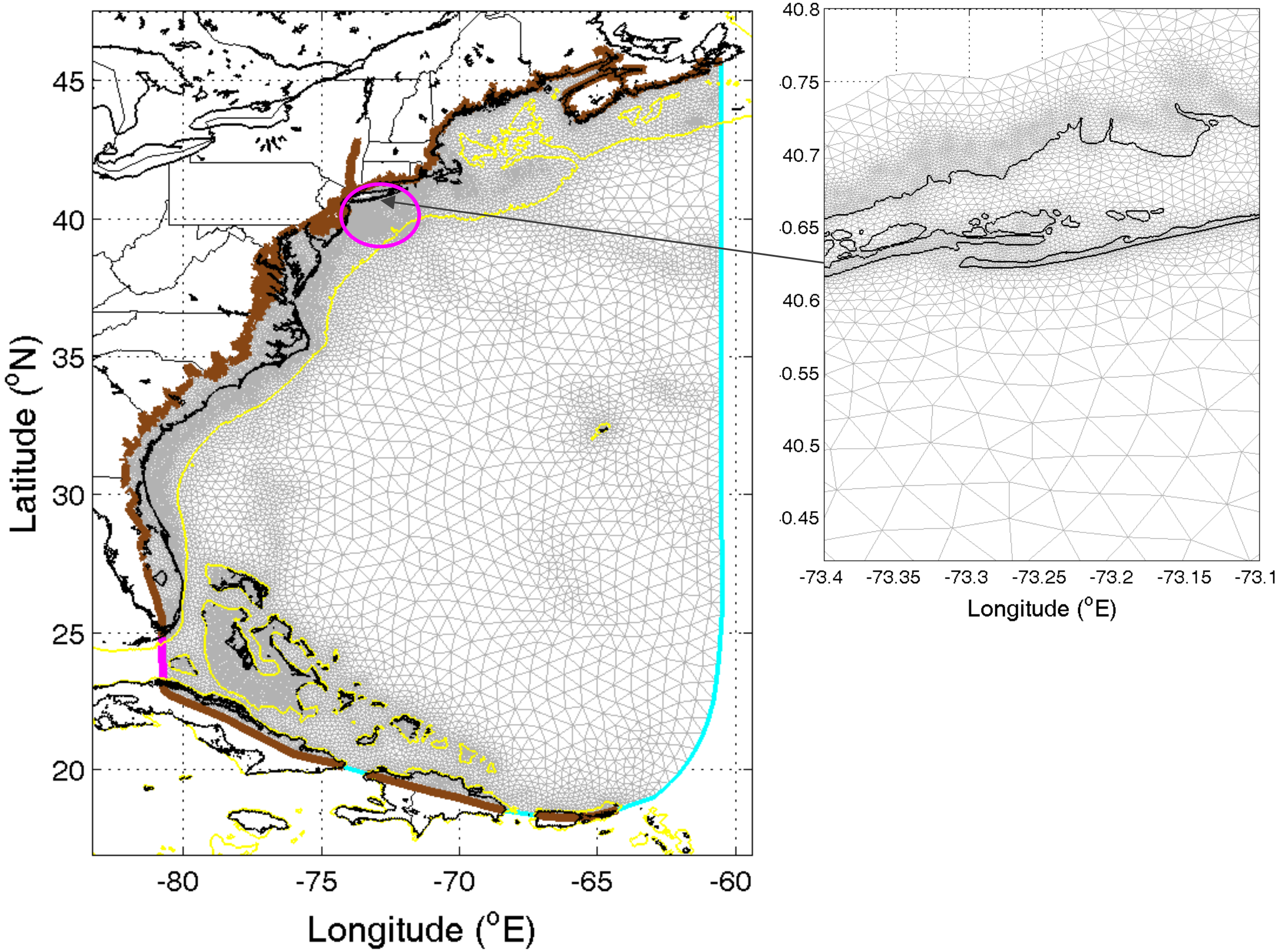
Hurricane Dennis (2005) storm surge envelope



The next level storm surge model is a **full basin dynamical** model

A full basin model computes the ocean's response over the entire storm path (not just the landfall location) capturing important integral effects, e.g. coastal wave.

ADCIRC advantage



ADCIRC allows for full-basin coverage while preserving high resolution needed in coastal areas

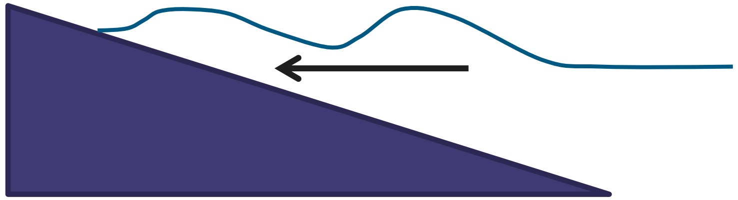
Storm surge is affected by other ocean phenomena, e.g. wave setup

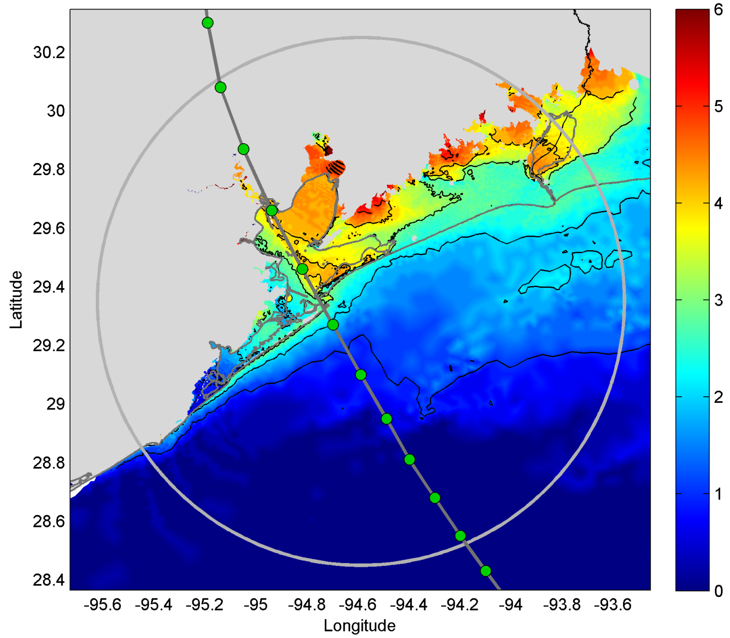
Wave setup is a physical phenomenon when waves push water onshore

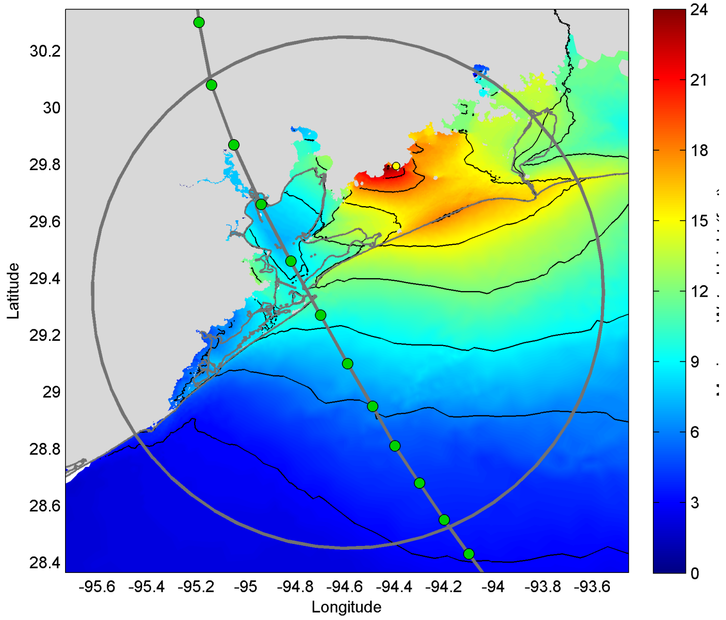
Wave setup systematically acts to increase the surge anywhere from 5 to 30%

Wave setup is very much location specific

Wave setup must be modeled explicitly (separate model)




Simulated wave setup height (in feet) during hurricane Ike


Simulated SS height (in feet) during hurricane Ike

Storm surge is affected by other ocean phenomena, e.g. tides

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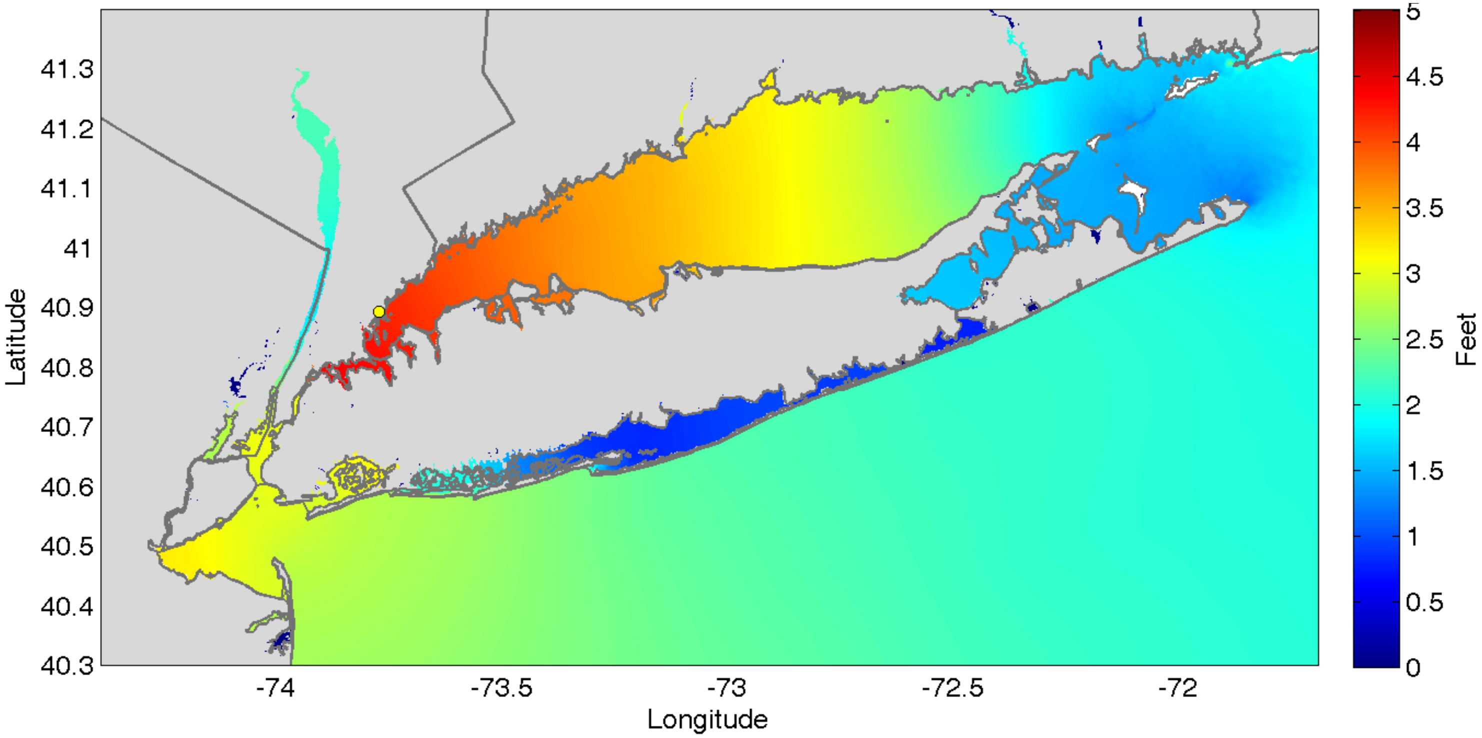
Tides need to be simulated **dynamically** (as opposed to uniform water level shifts) simultaneously with the surge within the same full basin dynamical model



ADCIRC is capable of simulating realistic tides

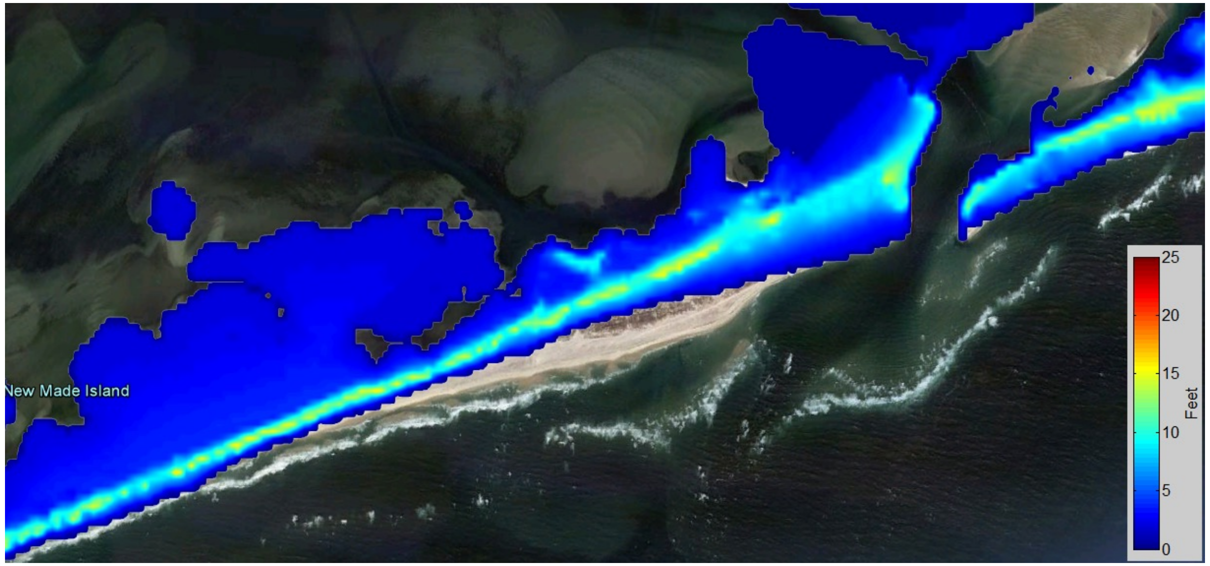
We include realistic tides into simulation of all events

Synthetic events are simulated with random tidal phases; we have shown that with sufficiently large event set this methodology works well

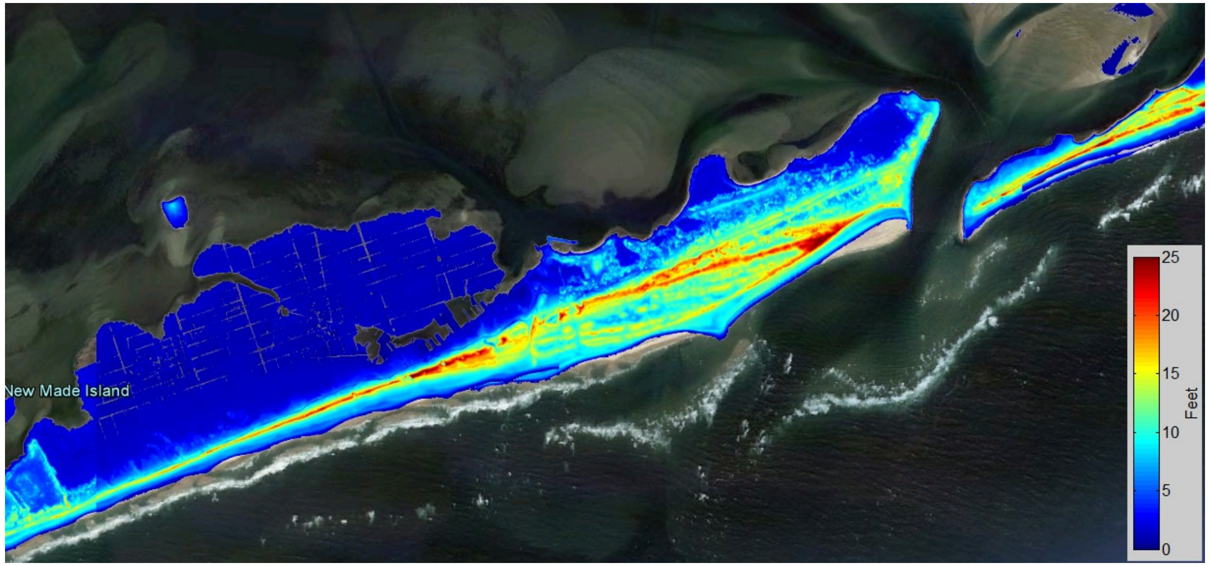
High-resolution ground elevation data are critical

USGS 10/30 meter elevation data vs. LiDAR-derived data

USGS



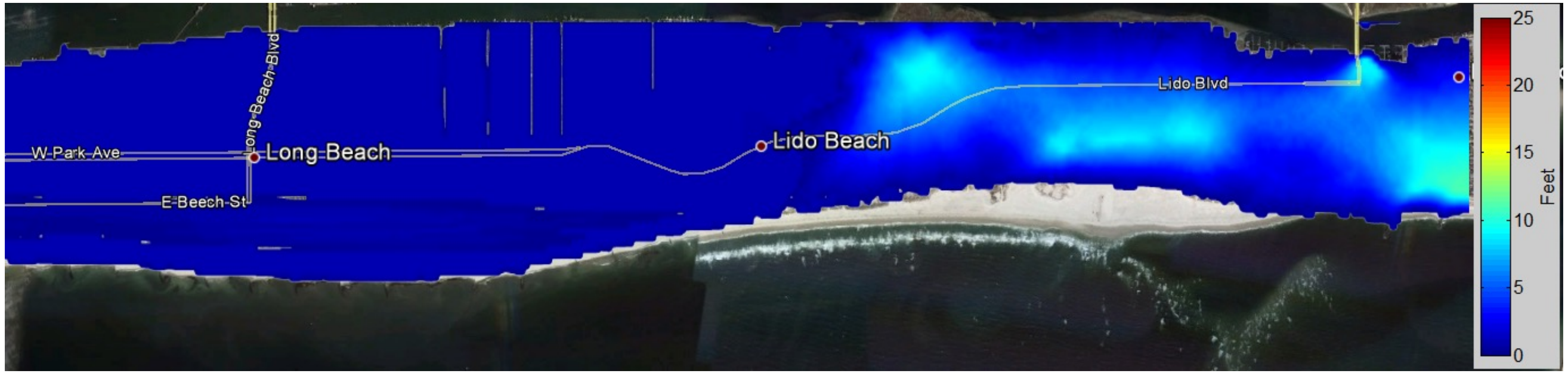
LIDAR



High-resolution ground elevation data are critical

USGS 10/30 meter elevation data vs. LiDAR-derived data

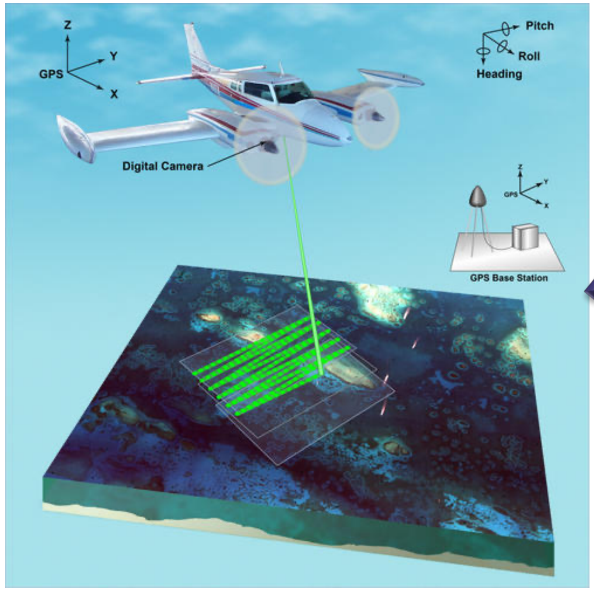
USGS

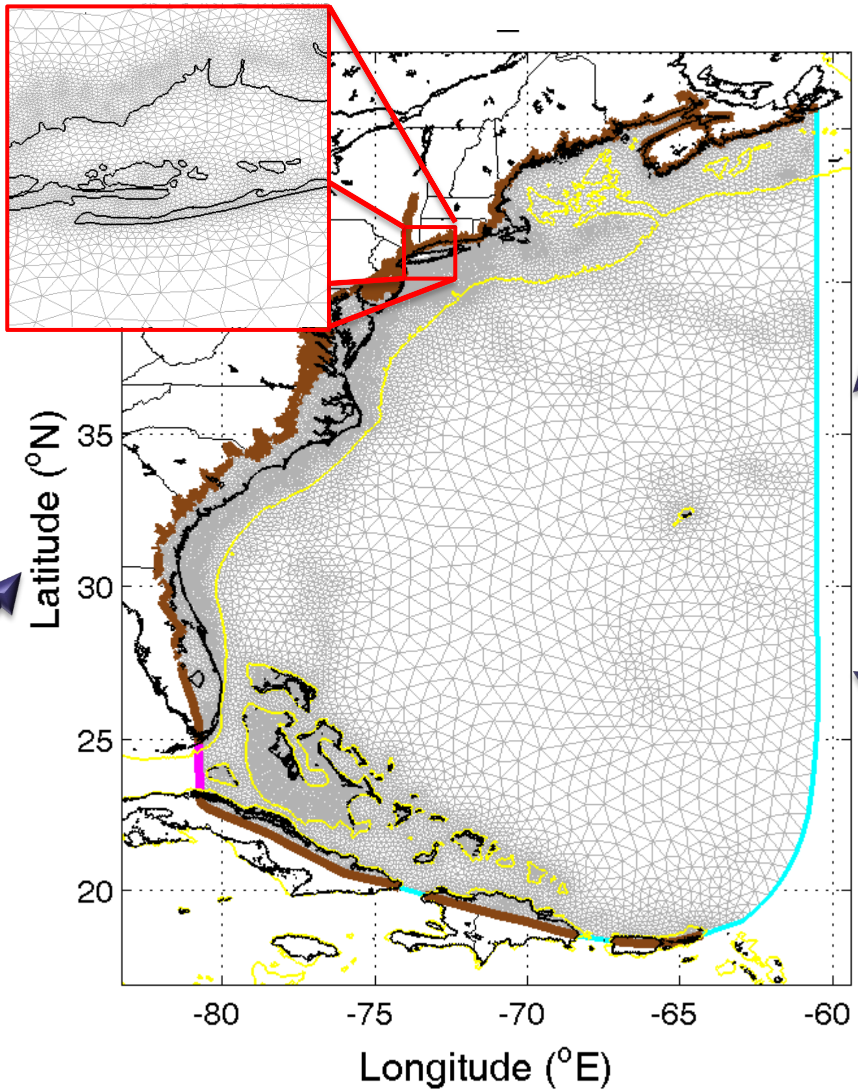


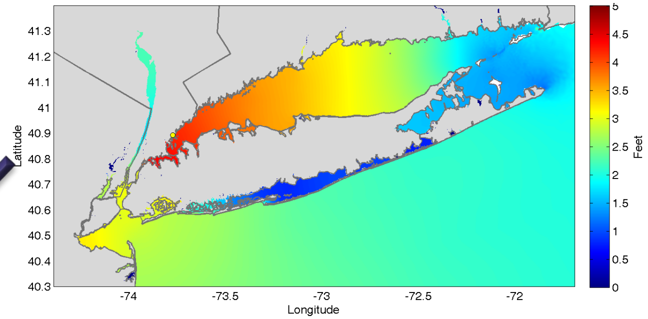
LIDAR

State-of-the-art Storm Surge Hazard model

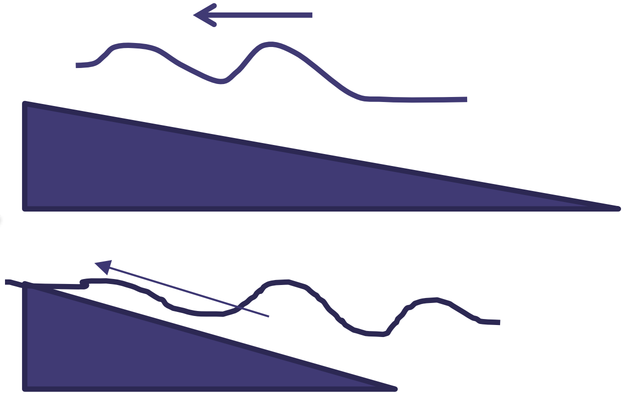
LIDAR elevation data





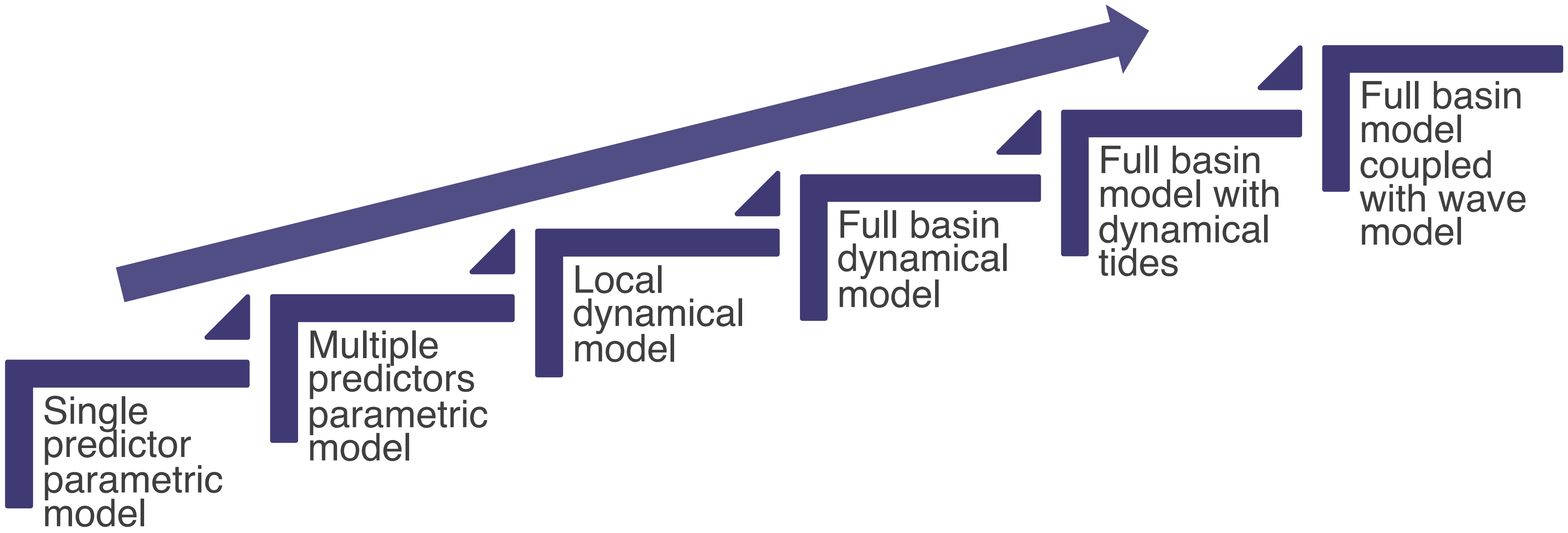


Tides model



Wave model (setup and runup)

Storm surge model hierarchy (evolution)



Single predictor parametric model

Multiple predictors parametric model

Local dynamical model

Full basin dynamical model

Full basin model with dynamical tides

Full basin model coupled with wave model

What next?

Lessons learned after using the model for primary underwriting

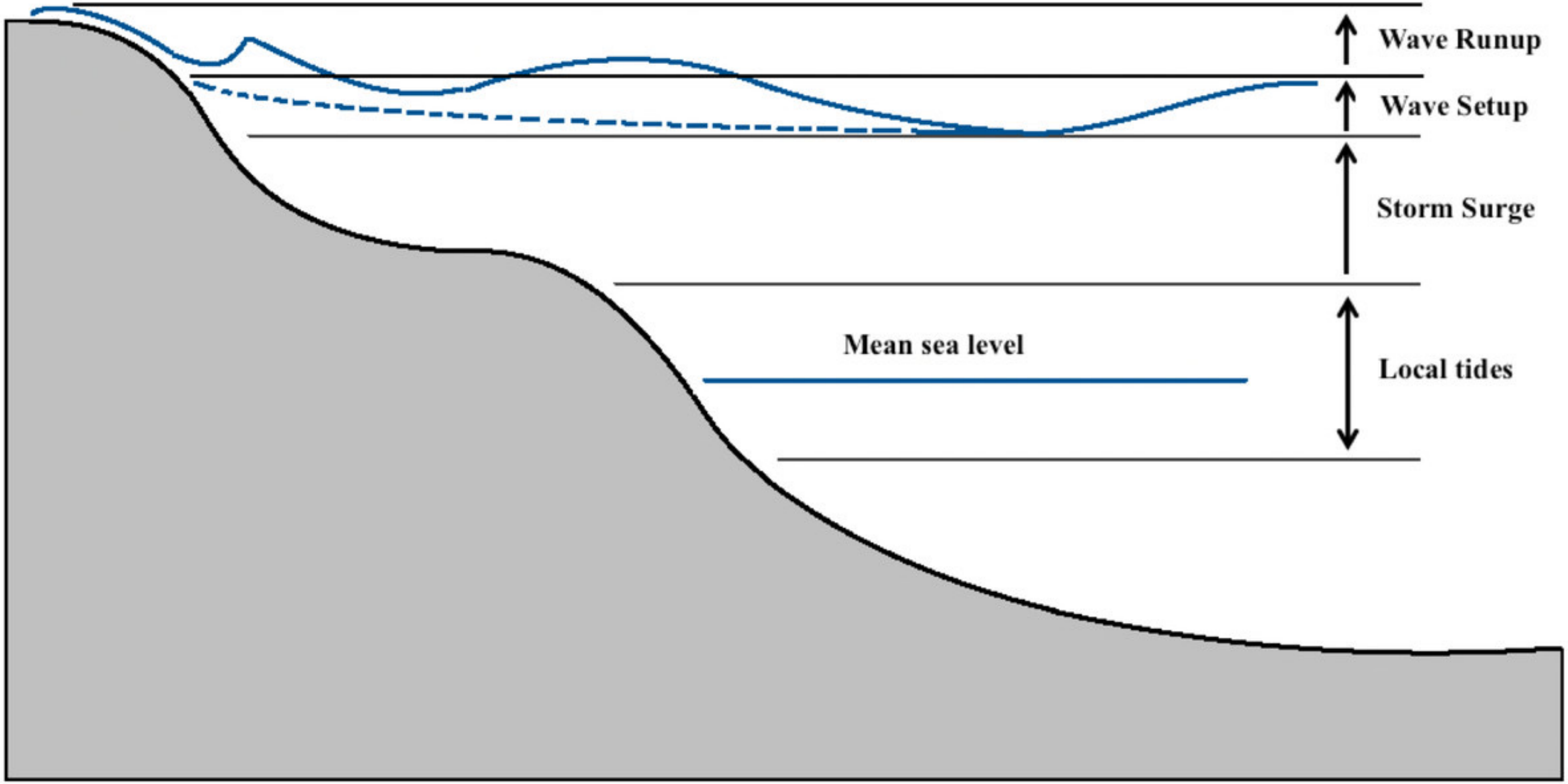
2016 – started using in-house flood models for primary underwriting in Florida

- Location-level precision requirement
- Detailed claims data; experience in 3 major events (Irma (2017), Michael (2018), Ian (2022))

Emphasis on location-level modeling revealed subtle problems with the model that were missed at the portfolio level

- The model was found to underrepresent the flood risk at V-zone ocean front locations; the problem was traced to the **wave runup effect**
- Storm surge risk at some inland locations was also found underrepresented; the problem was tracked to two physical effects:
  - Surge water **flow via small-scale channels**
  - Combined rain+surge flooding effect

Wave Runup Effect



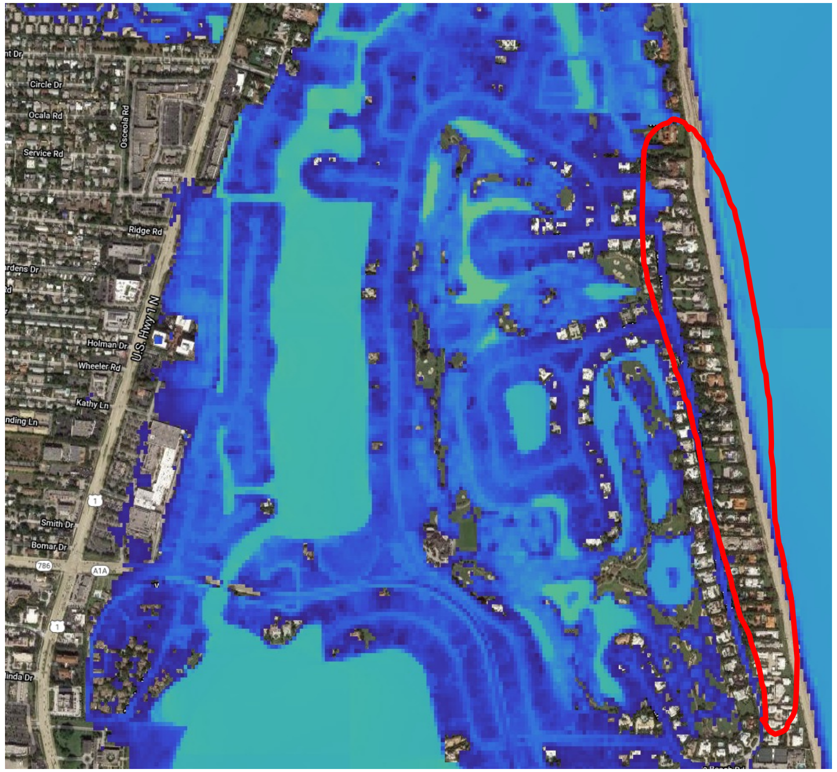
Wave Runup: Impact on Storm Surge Risk

100-year **still** (no waves) surge level modeled by RRRS is comparable to FEMA SHA in this region except for the narrow strip of properties right along the beach line (circled in red); this is due to FEMA accounting for the **wave runup** effect

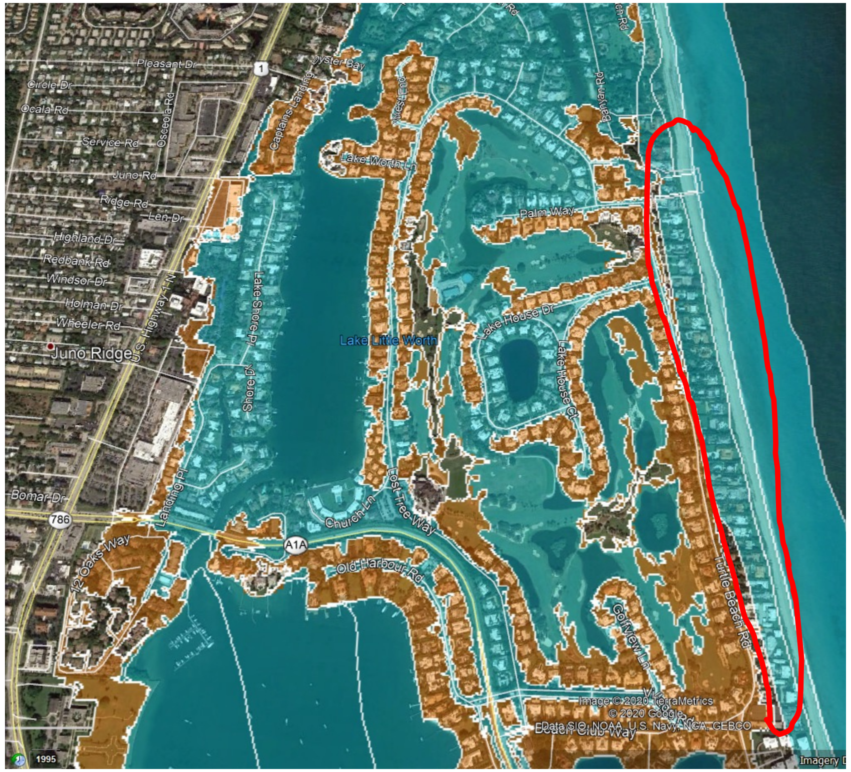
The problem is confined to a relatively small area, why does it matter?

1. This is the area with (extremely) high value homes
2. It matters a lot if the model is used for risk selection

100-year inundation depth modeled with RRRS storm surge model (segment of FL east coast)



100-year (green) and 500-year (brown) inundation extent defined by FEMA



Small-scale Topographic Features: Impact on Storm Surge Risk

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Elevated roads (circled in back) act as barriers to storm surge

Narrow passages or dips in elevation (circled in red) can channel surge further inland inundating large areas

If these small-scale features are not resolved by the storm surge model, the modeled inundation extent would look something like the blue line

Storm surge risk in area circled with green will be severely underestimated

Observed (FEMA) storm surge inundation in Sandy (2011)

LIDAR-derived ground elevation

Modeling Wave Runup (FEMA approach)

- FEMA is modeling wave runup by manually analyzing individual 1-d cross-sections perpendicular to the coastline
- The analysis is based on results of engineering studies like the one shown in figure
- This approach is impractical within a stochastic model context

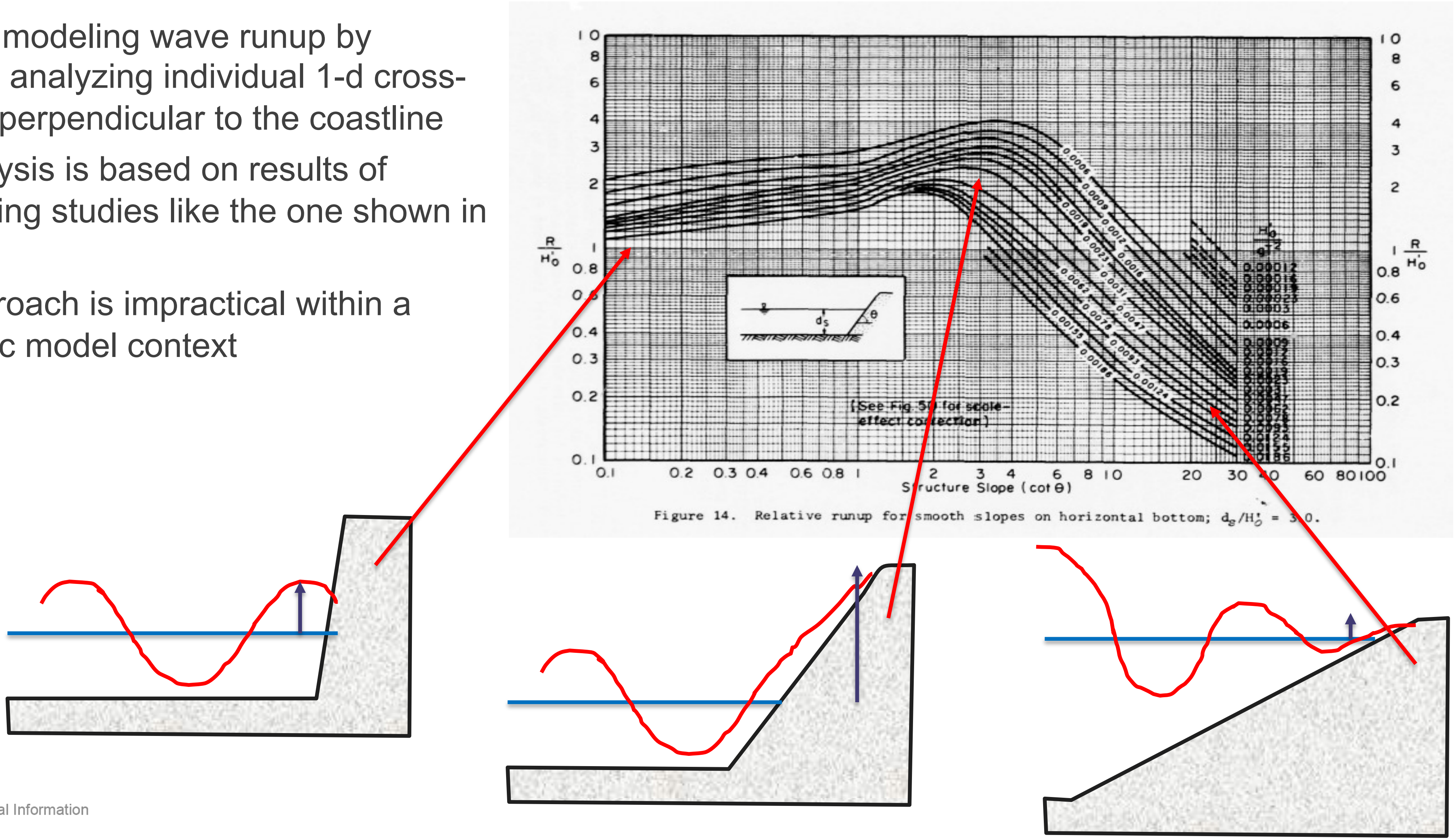
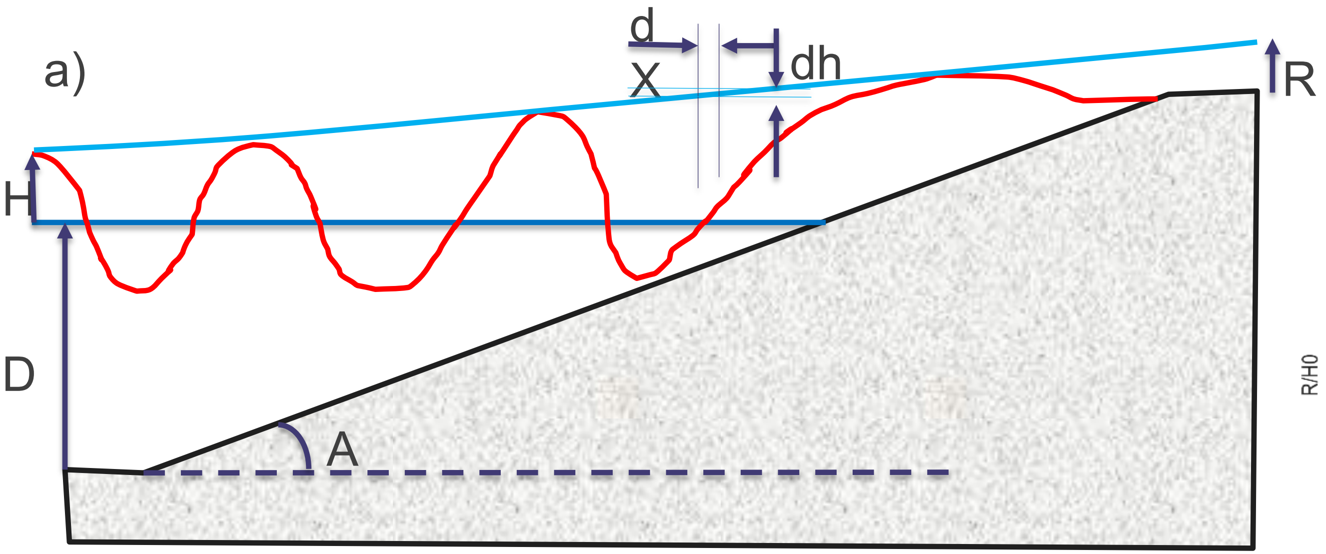
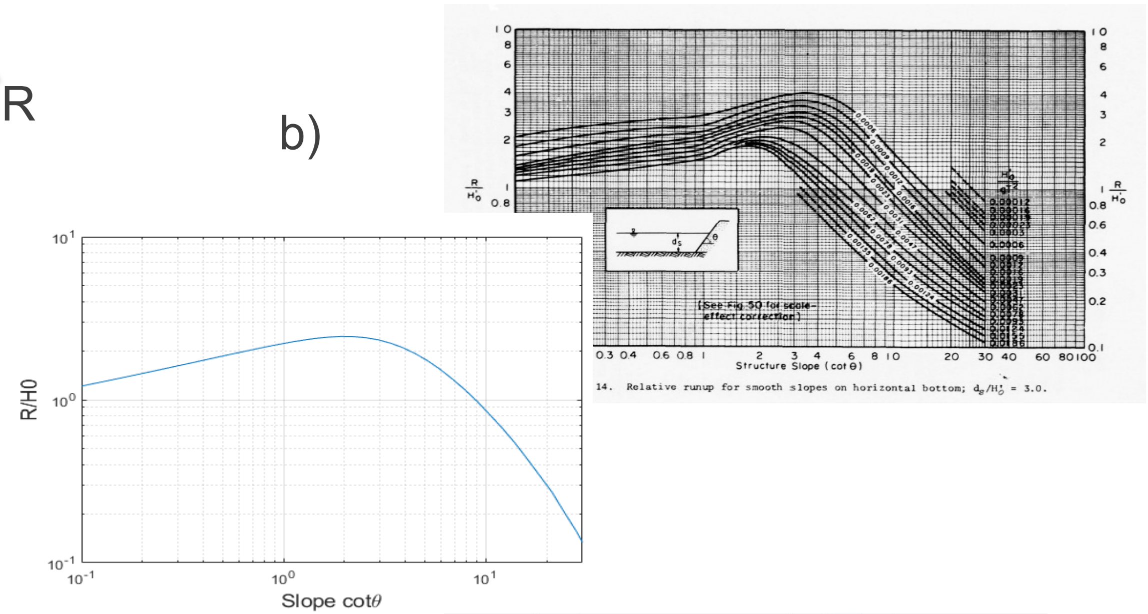
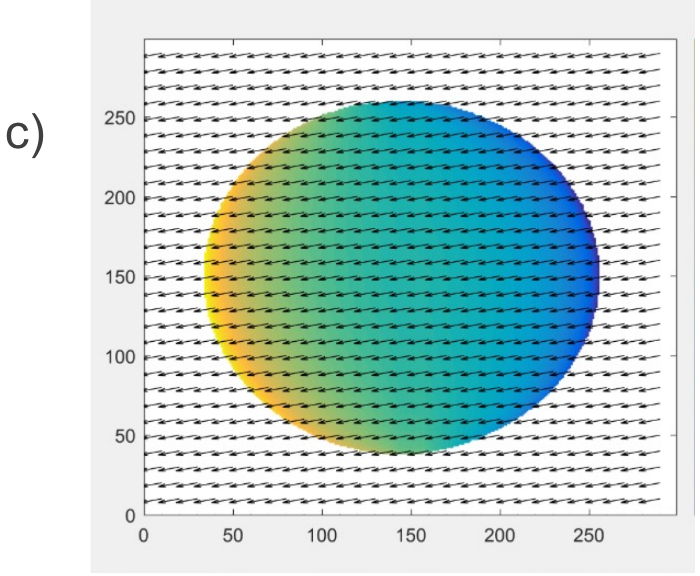


Figure 14. Relative runup for smooth slopes on horizontal bottom; $d_s/H'_0 = 3.0$.

Finite Difference Implementation of Wave Runup Calculation







$$R=f(D,H,A) \Longrightarrow dh=F(D,H,A)*dX$$

RRRS designed a finite differencing scheme solved efficiently using image matrix convolution methods at 10-meter horizontal resolution (panel a)

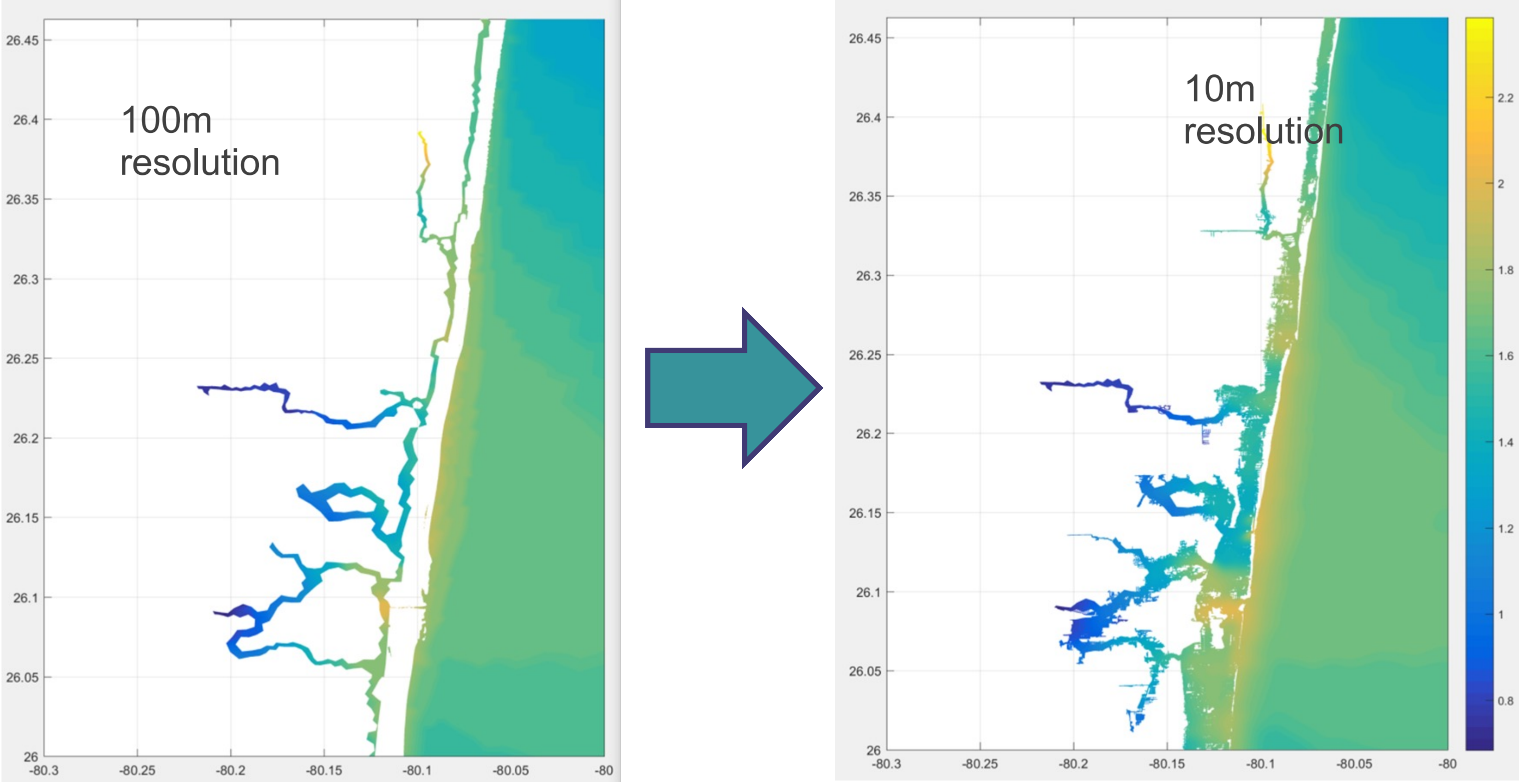
The scheme is designed to match engineering study results used by FEMA in 1-d case (panel b)

The scheme can be naturally extended to 2-d cases; lower panels show results of idealized experiments with wave runup modeled over conical bottom (panel c; arrows indicate wave direction)

Enhancing Footprints With High Resolution Simulation of Inland Surge Propagation

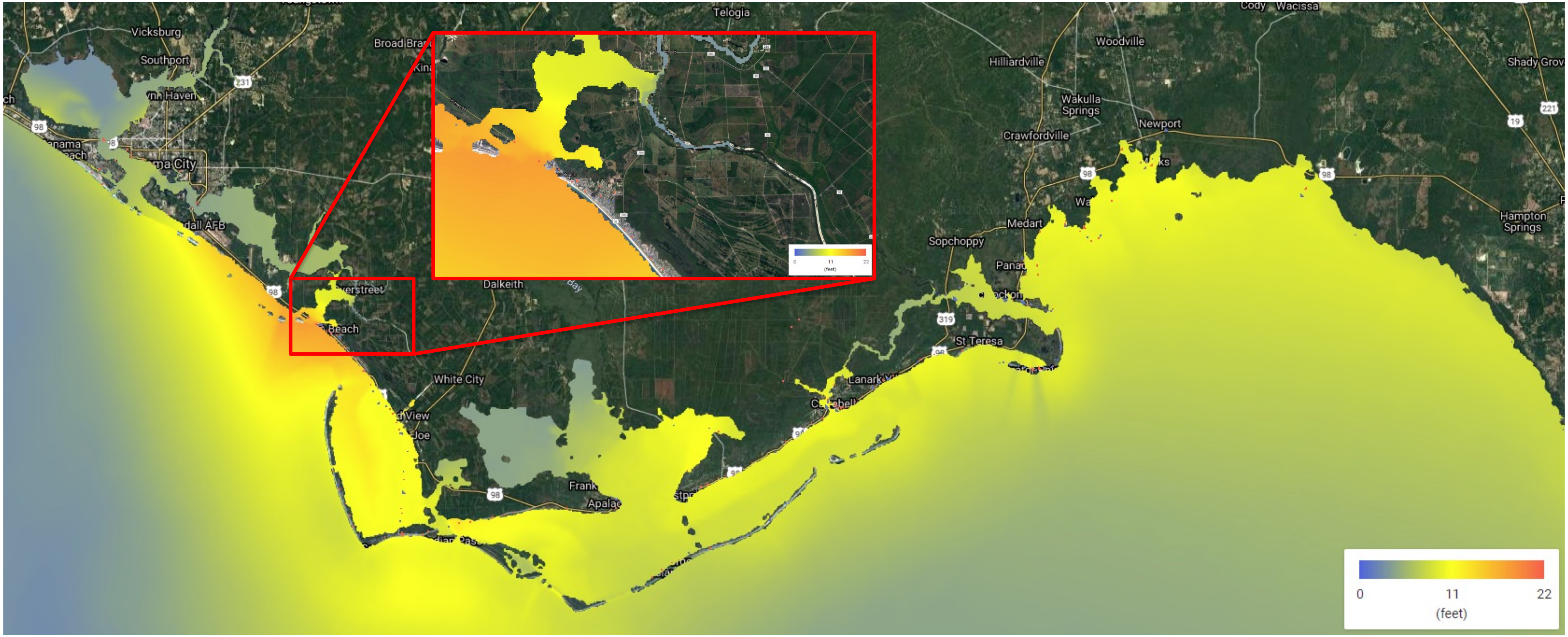
Treat the original 100m-resolution footprints as initial condition

Utilize simple (and efficient) flow over terrain model to simulate surge propagation further inland over 10-meter terrain



New RRRS Storm Surge Model: Hurricane Michael (2018) illustration

Hurricane Michael (2018) footprint as simulated with the original version of the RRRS storm surge model



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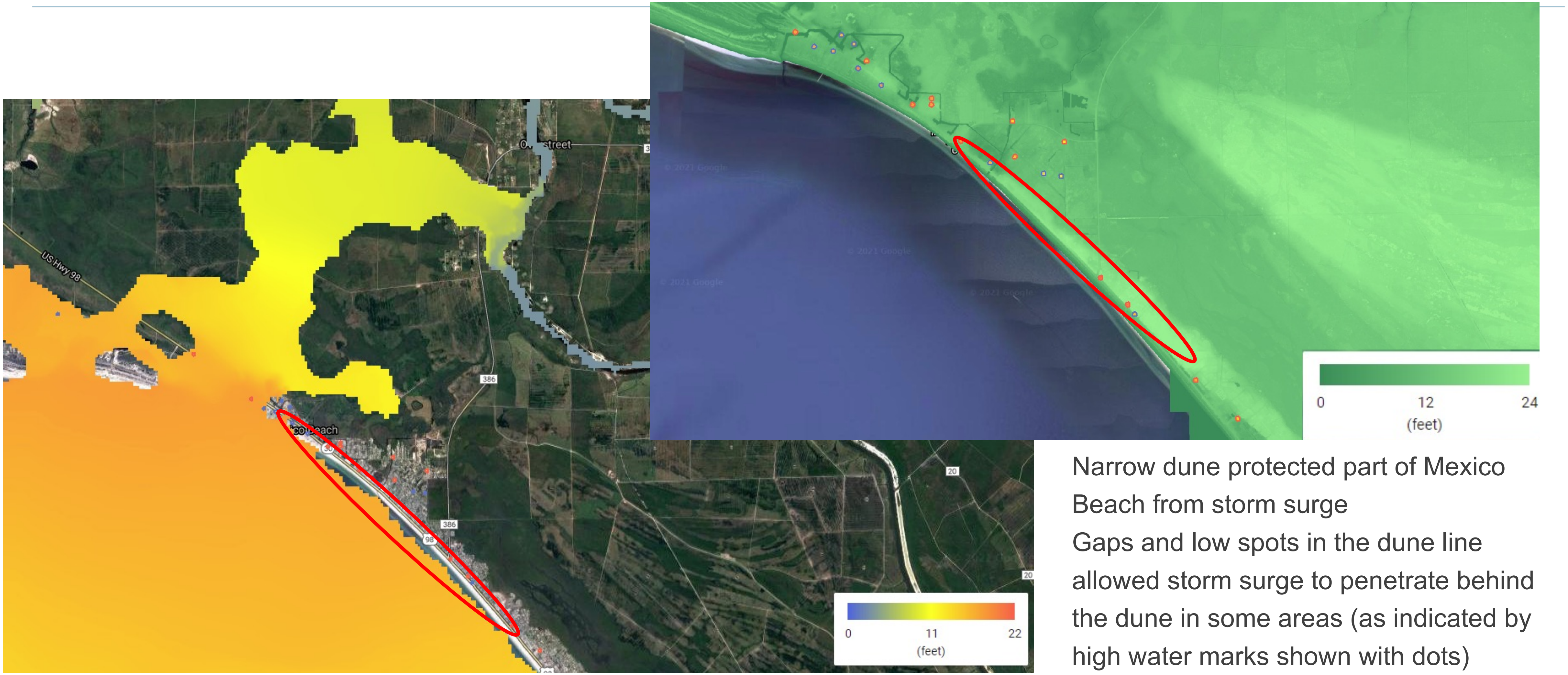

Narrow dune protected part of Mexico Beach from storm surge

Gaps and low spots in the dune line allowed storm surge to penetrate behind the dune in some areas (as indicated by high water marks shown with dots)

These gaps are not resolved by the 100m model simulation

New RRRS Storm Surge Model: Hurricane Michael (2018) illustration

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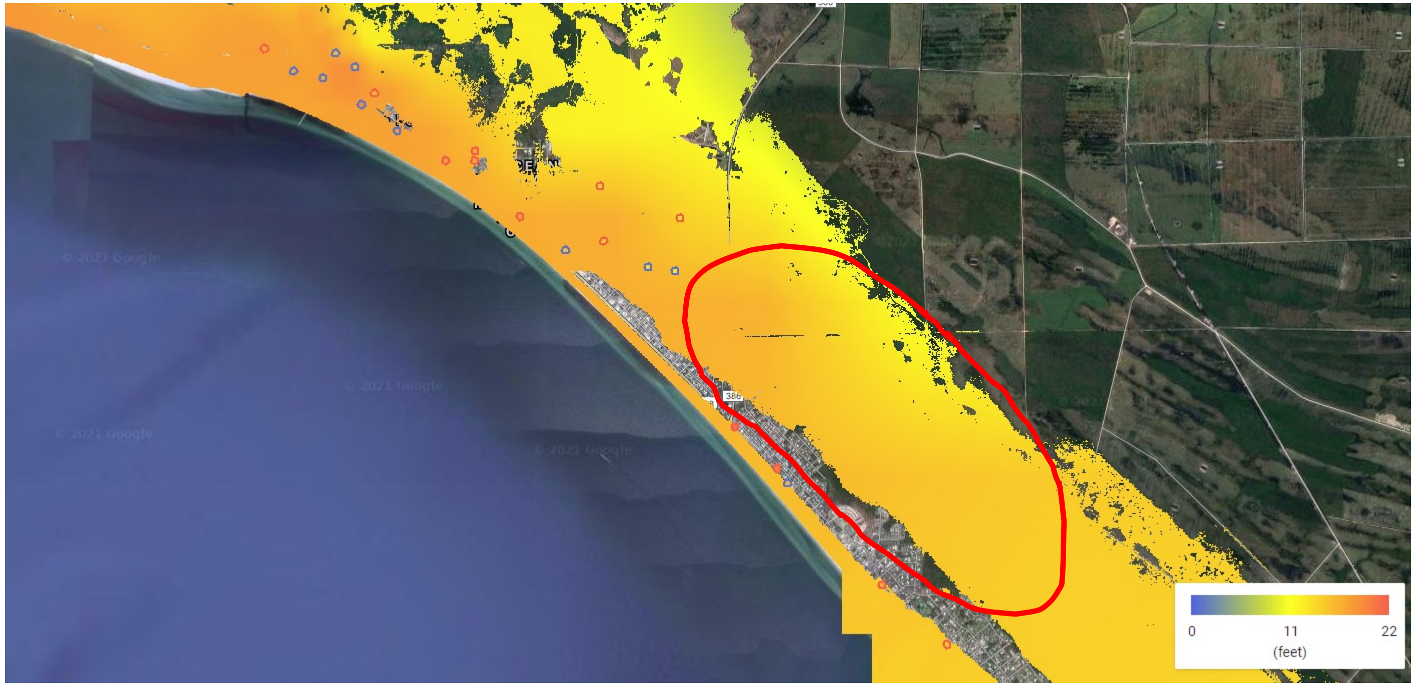
This is another simulation of Michael storm surge; the model resolution is the same (~100m), but the coarse resolution (100m) ground elevation was not adjusted to represent coastal barriers like it was in the previous version

The model does not “see” the dune line and inundates everything behind it

Observations indicate that area circled with red was not inundated; so, this simulation is also inaccurate

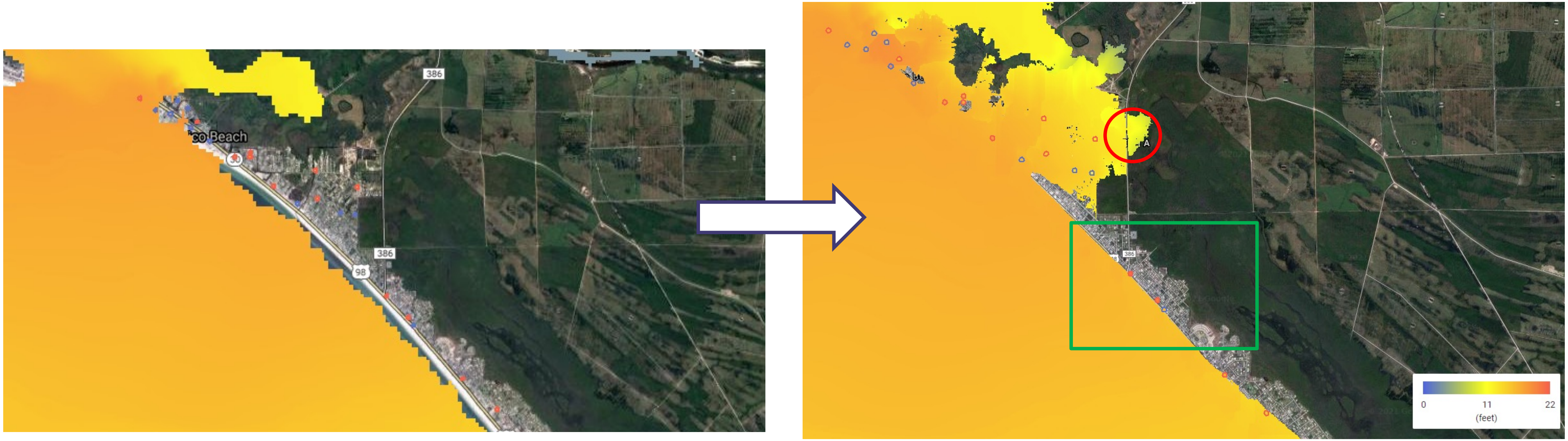
Water flow over small-scale terrain features must be resoled to get to correct solution



New RRRS Storm Surge Model: Hurricane Michael (2018) illustration

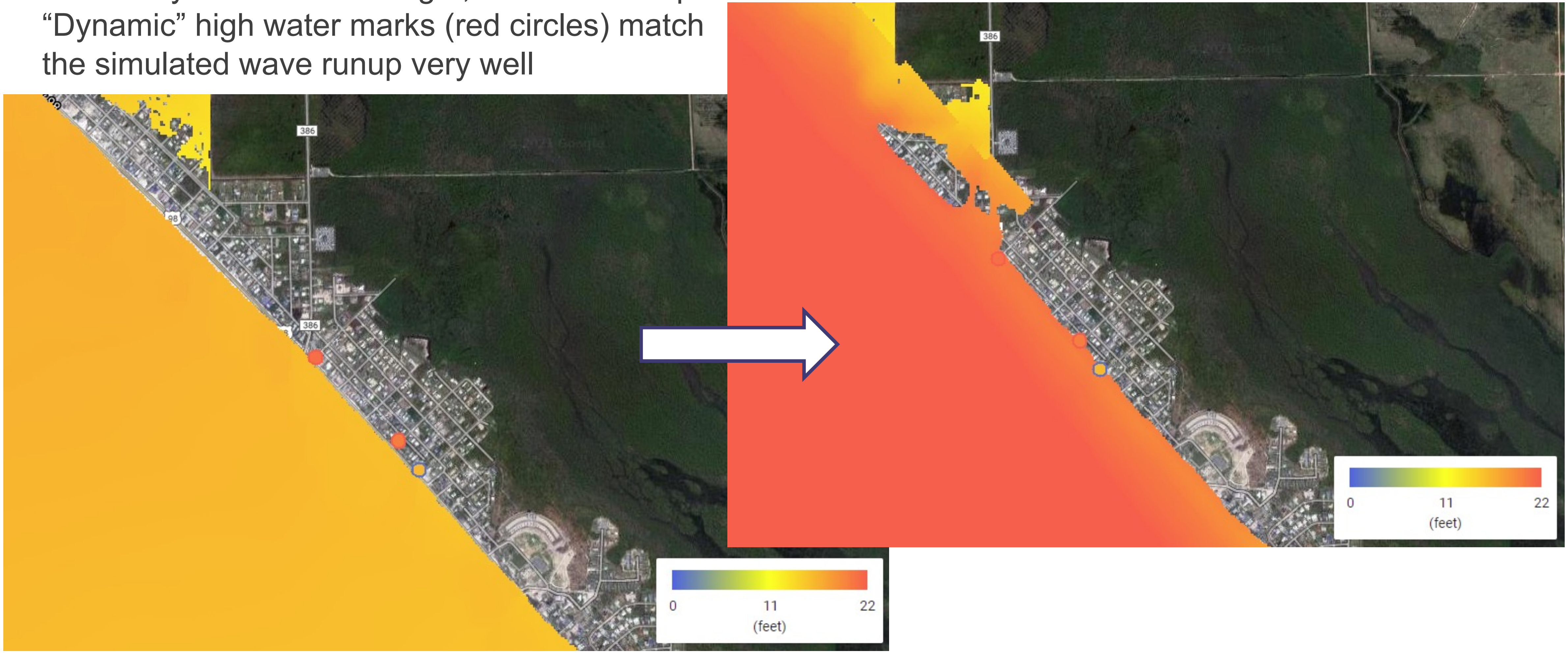
Water flow over terrain is simulated with 10m resolution resolving such fine scale features as flow over elevated road (circled with red)

The resulting storm surge footprint inundates parts of town of Mexico Beach leaving other parts dry consistent with observations



New RRRS Storm Surge Model: Hurricane Michael (2018) illustration

Added “dynamic” water height, i.e. wave runup
“Dynamic” high water marks (red circles) match the simulated wave runup very well



Key takeaways

Storm surge (flood risk in general) presents some unique challenges
  - Intuition built on working with wind risk catastrophe models is not always applicable to surge (flood) models

Hazard component of a storm surge model is the most challenging (and complex) one
  - Storm surge models vary greatly in terms of precision of their hazard component
  - One should be very careful when selecting a storm surge risk model for a particular task

Primary underwriting (risk selection) is the most demanding task in terms of modeling precision requirements
  - Further model development is needed to close all the gaps cased by inadequate representation of “secondary” physical phenomena involved in the storm surge hazard

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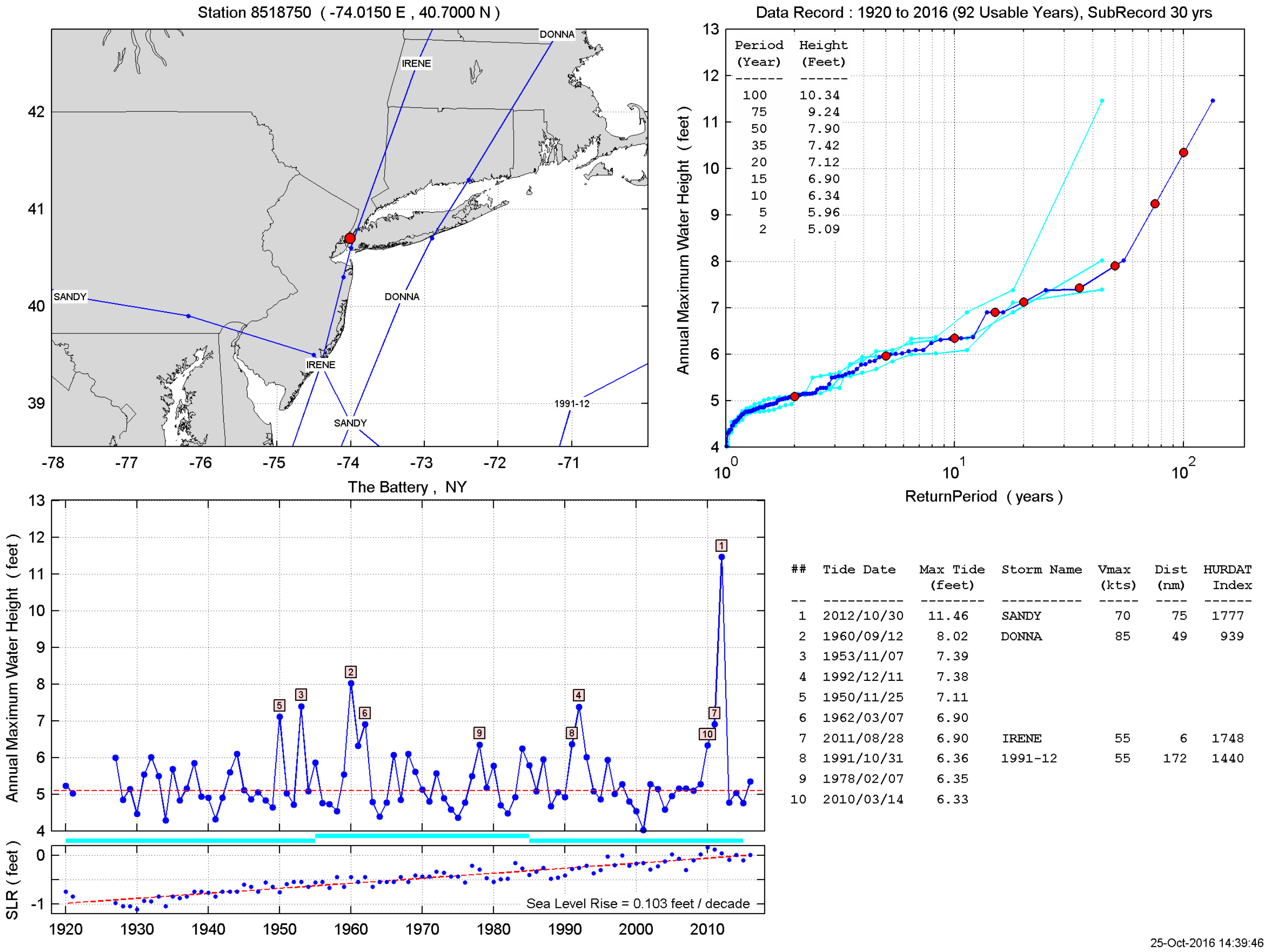
Extra Topics

Climate change: Analyzing long-term tidal records

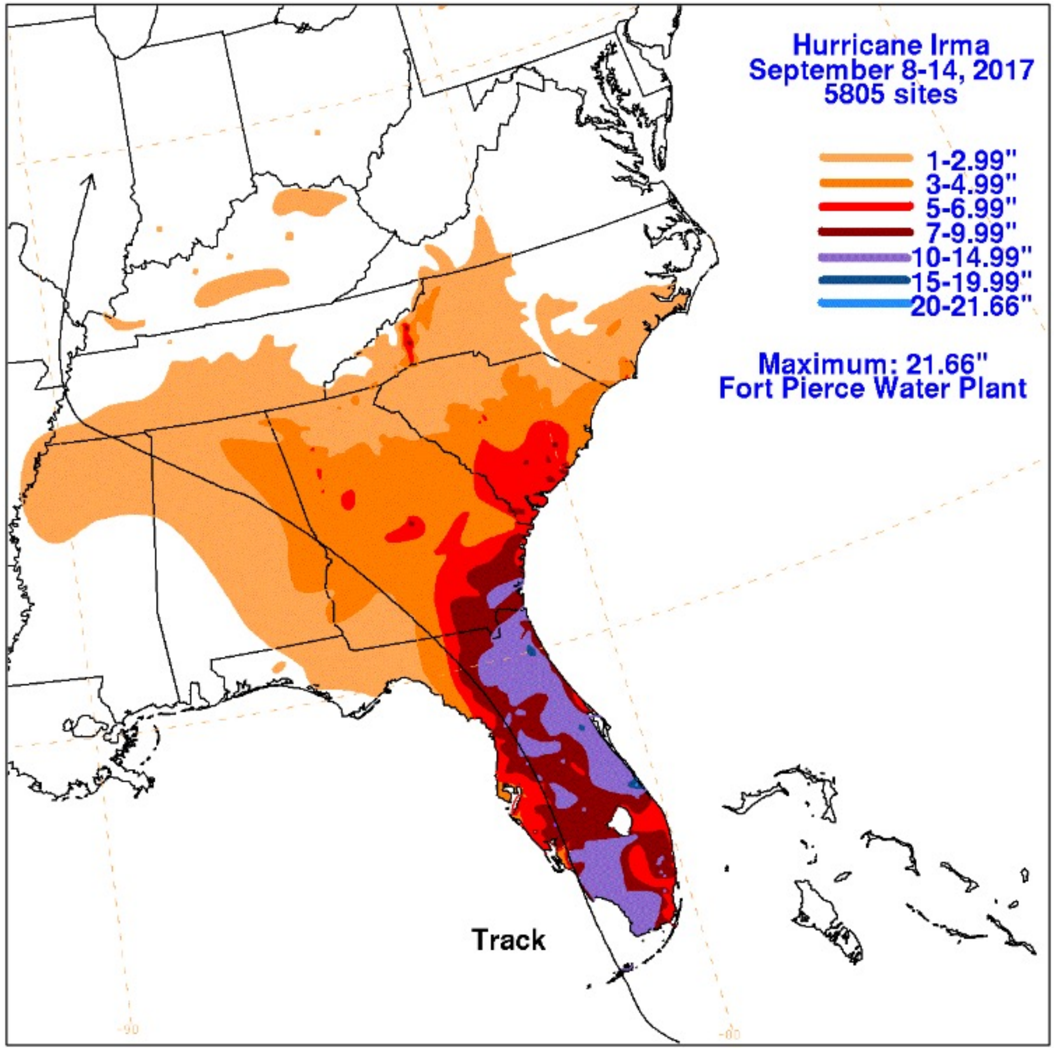


Period (Year)	Height (Feet)
100	10.34
75	9.24
50	7.90
35	7.42
20	7.12
15	6.90
10	6.34
5	5.96
2	5.09

##	Tide Date	Max Tide (feet)	Storm Name	Vmax (kts)	Dist (nm)	HURDAT Index
1	2012/10/30	11.46	SANDY	70	75	1777
2	1960/09/12	8.02	DONNA	85	49	939
3	1953/11/07	7.39				
4	1992/12/11	7.38				
5	1950/11/25	7.11				
6	1962/03/07	6.90				
7	2011/08/28	6.90	IRENE	55	6	1748
8	1991/10/31	6.36	1991-12	55	172	1440
9	1978/02/07	6.35				
10	2010/03/14	6.33				

Surge levels for older events are corrected (amplified) to account for the sea level rise

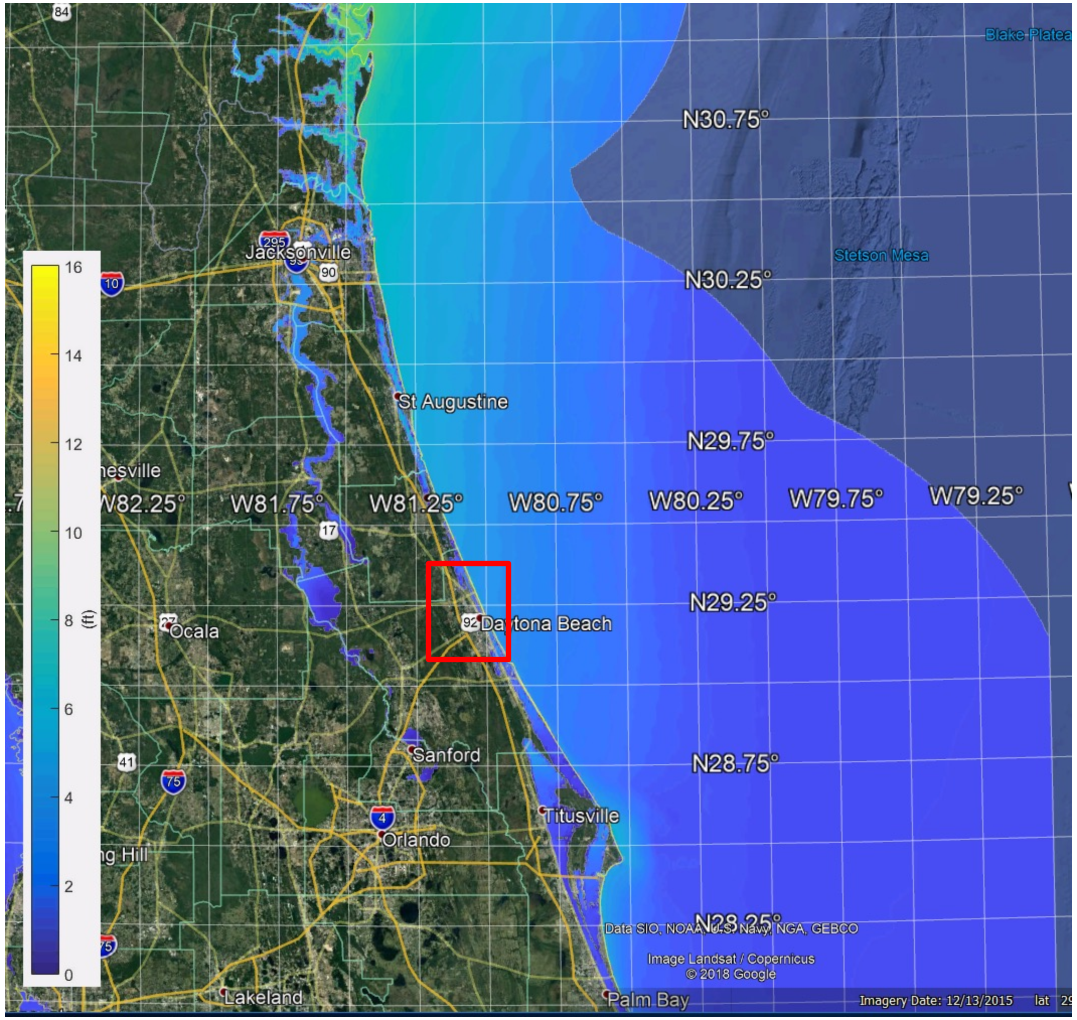
Hurricane Irma (2017) – a significant rain and surge event



Observed rainfall (inches) from Hurricane Irma over the southeastern United States. Courtesy of David Roth from NOAA's Weather Prediction Center.

Irma had a very unusual wind and rain structure stretching over most of Florida

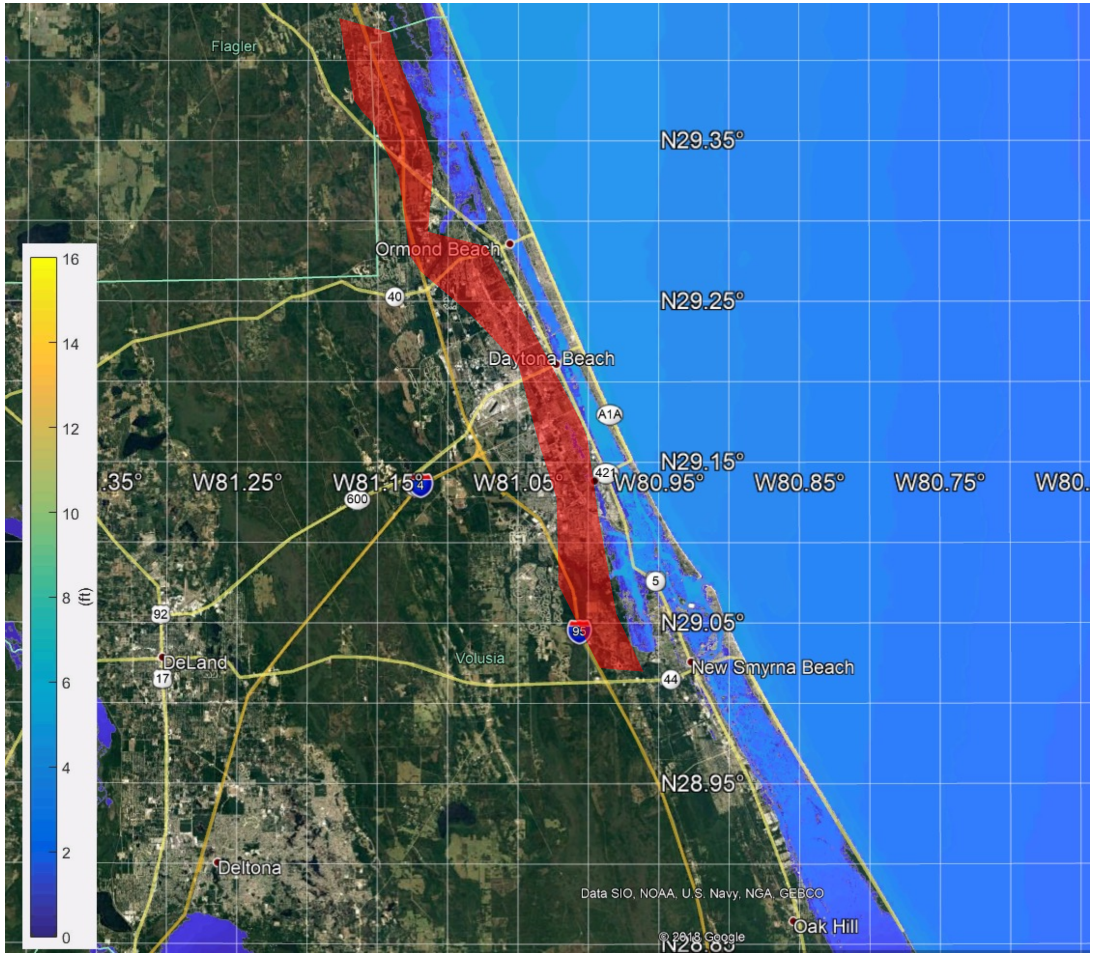
Hurricane Irma (2017) – surge footprint



Florida East coast segment of the surge footprint generated with the RRRS storm surge model (full basin dynamical model with dynamical tides and coupled with a wave model)

The footprint was extensively validated against tidal gages (including mobile gages deployed behind barrier islands and within estuaries) and high water marks

Hurricane Irma (2017) – surge footprint

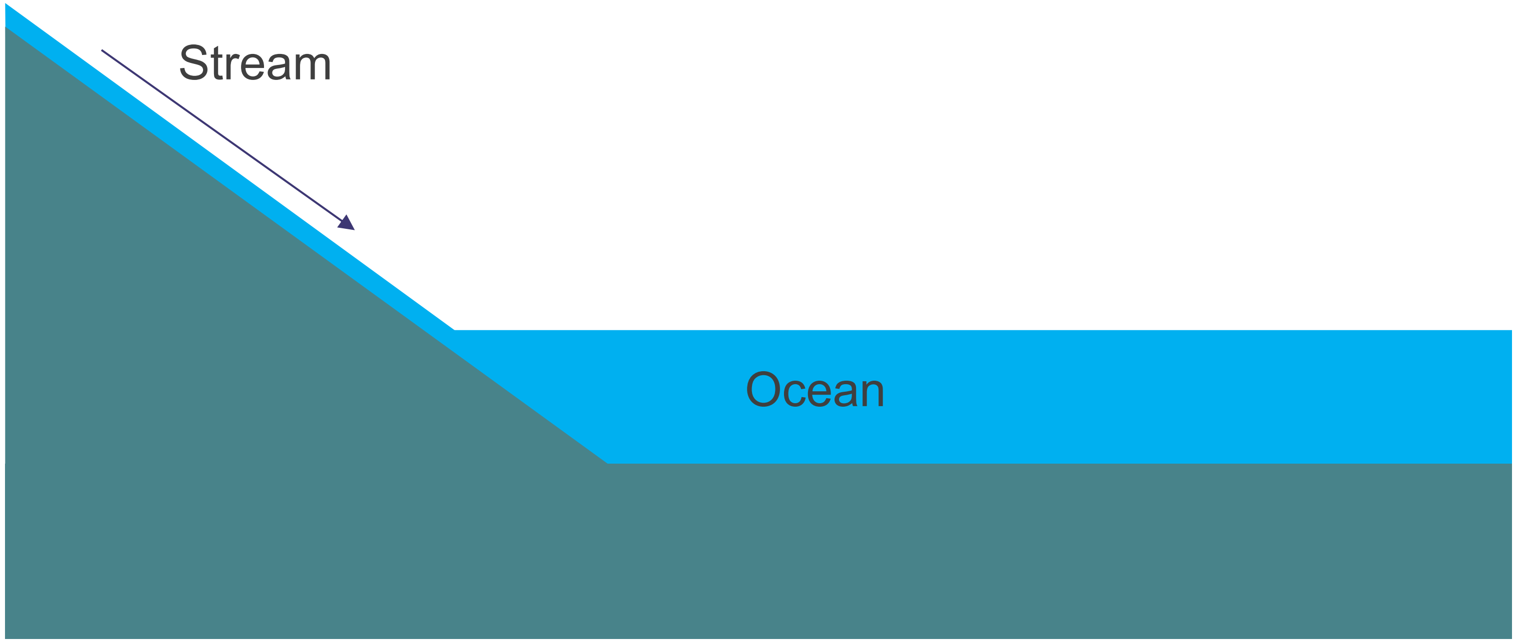


Storm surge along the East Coast of Florida is significant enough to create inundation over some areas behind the barrier islands

Detailed flood claim analysis revealed a significant number of claims in areas adjacent to the surge footprint without modeled inundation from either surge or rain footprints (the area shown is for demonstration purposes only, it may or may not contain actual claims)

Coastal watershed schematic

A schematic depiction of a “normal” (preflood) state for a typical estuary

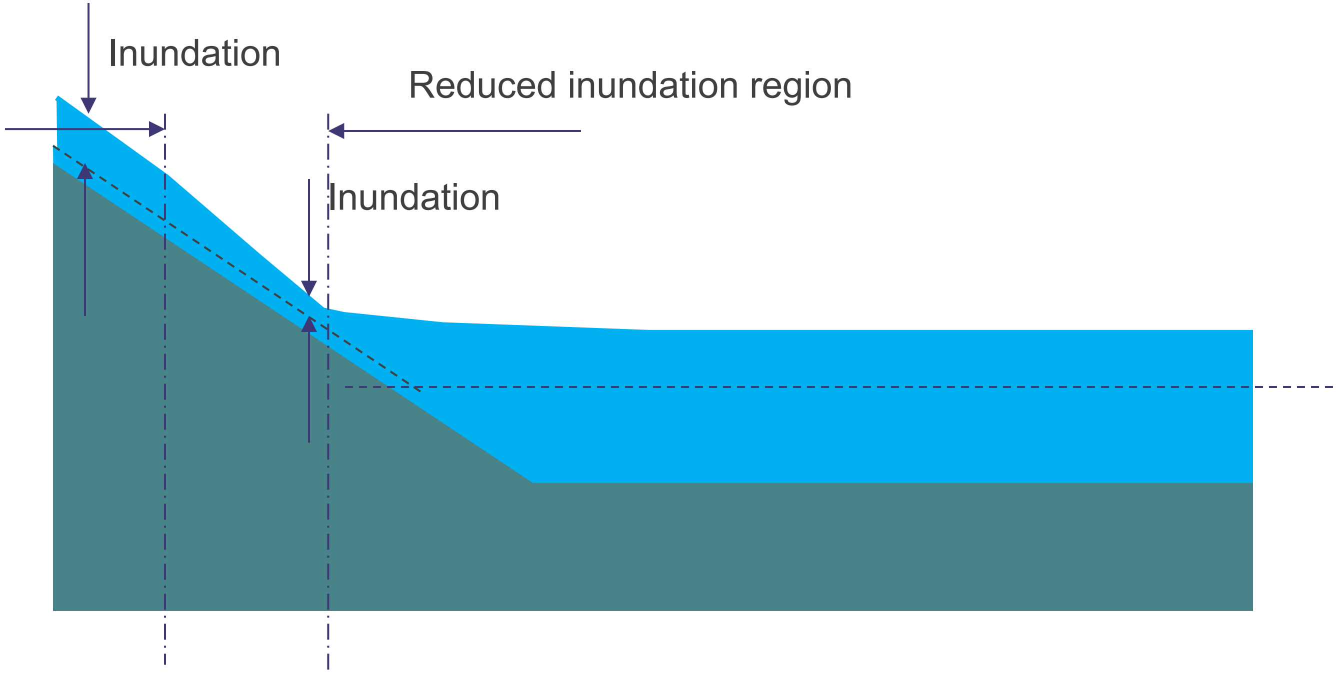


Rain-induced flooding

Schematic depiction of a typical rain-induced flood event without surge; inundation levels decrease at the mouth of the estuary due to large drainage capacity typical for these areas

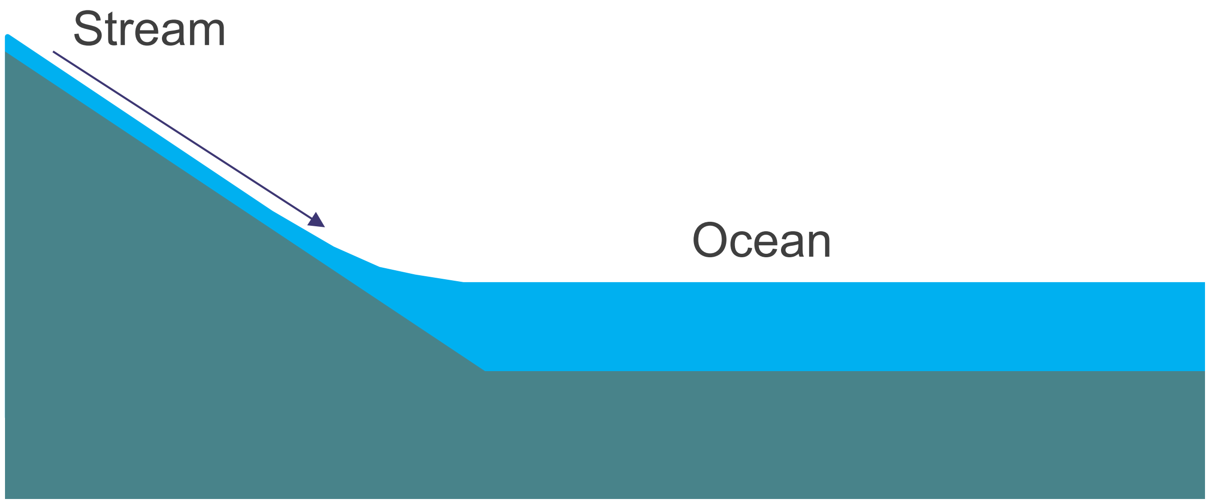
Rain-induced and storm surge flooding

Schematic depiction of rain-induced and surge flood simulated separately (no dynamic interaction)



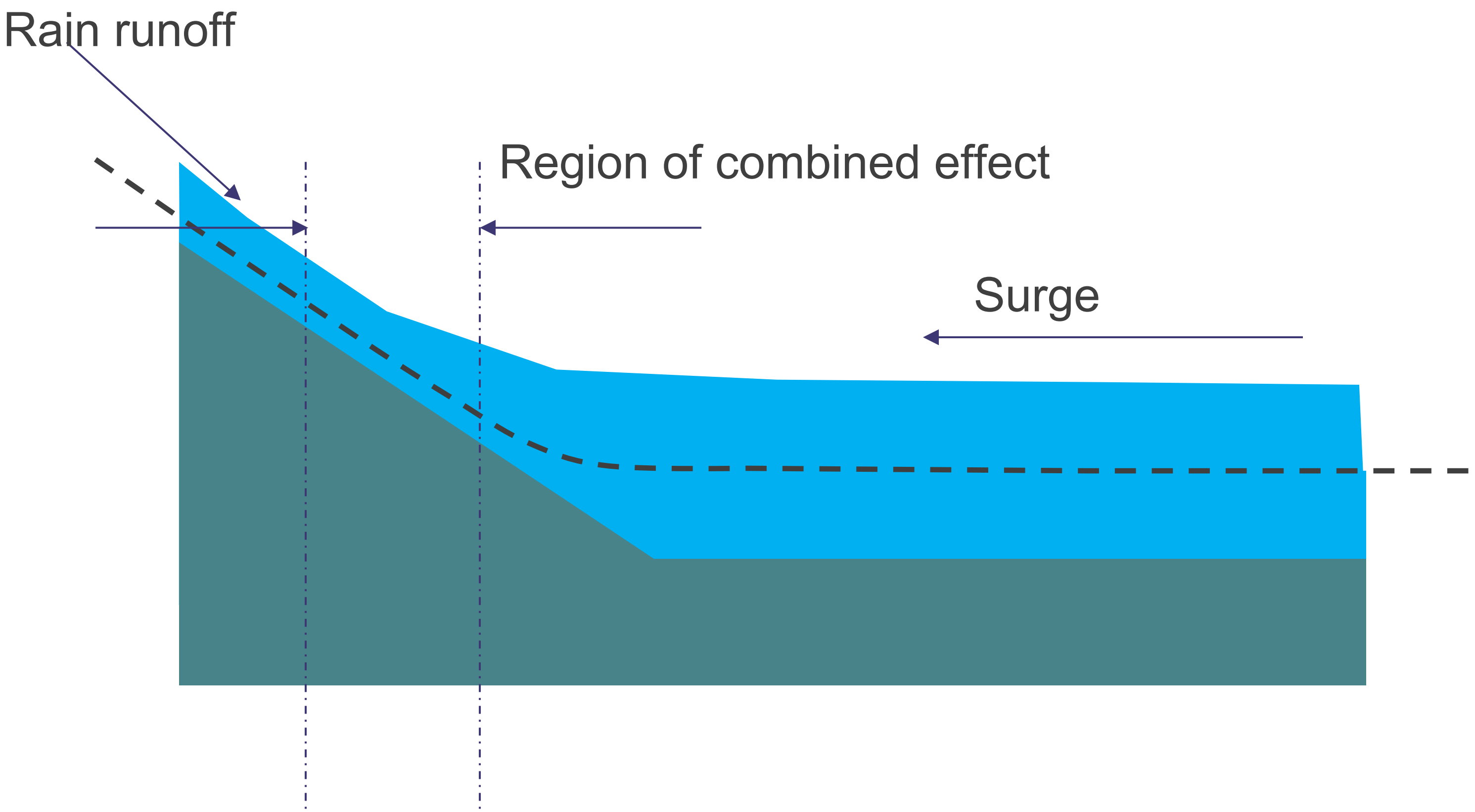
Dynamically correct coastal watershed schematic

A schematic depiction of a "normal" (preflood) state for a typical estuary with a dynamical transition between river channel flow and open ocean properly simulated



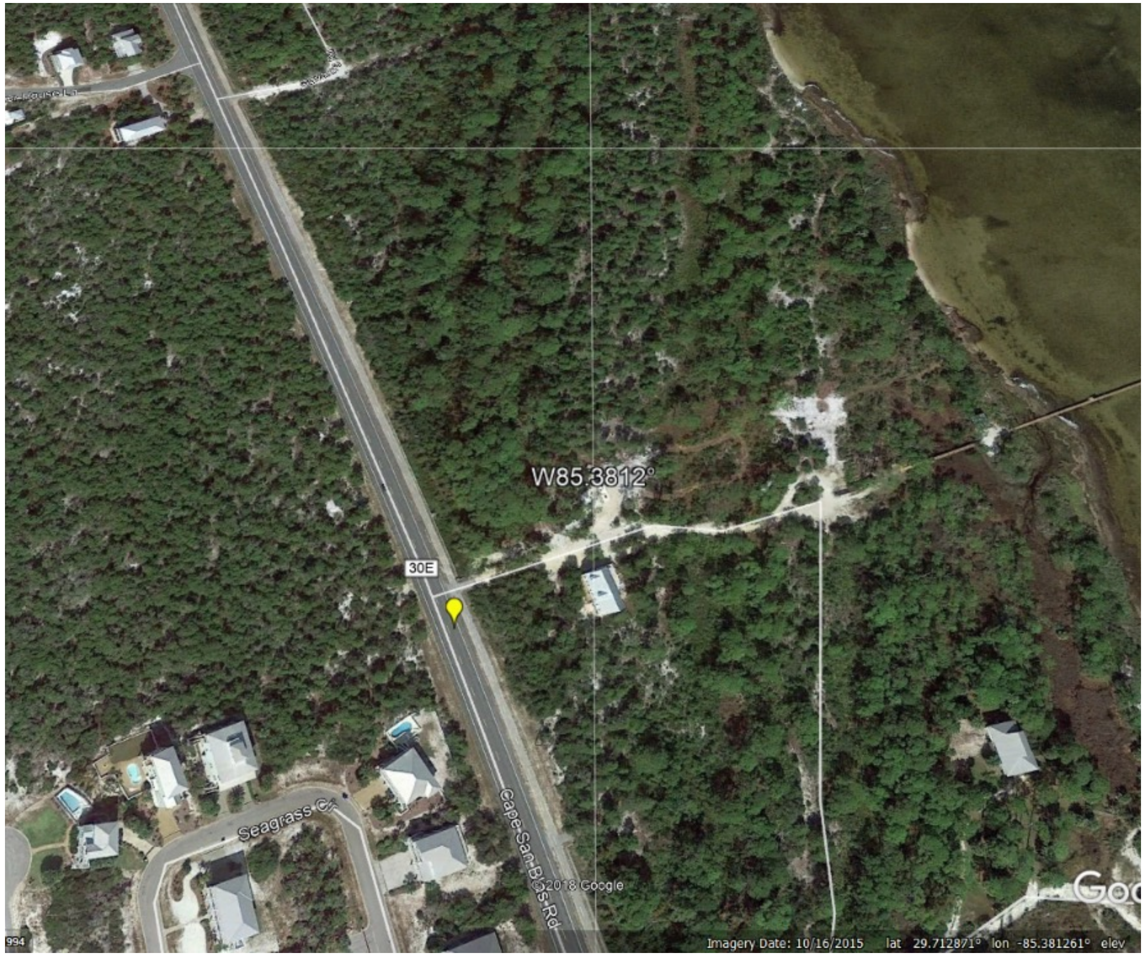
Dynamically correct rain-induced + storm surge flooding

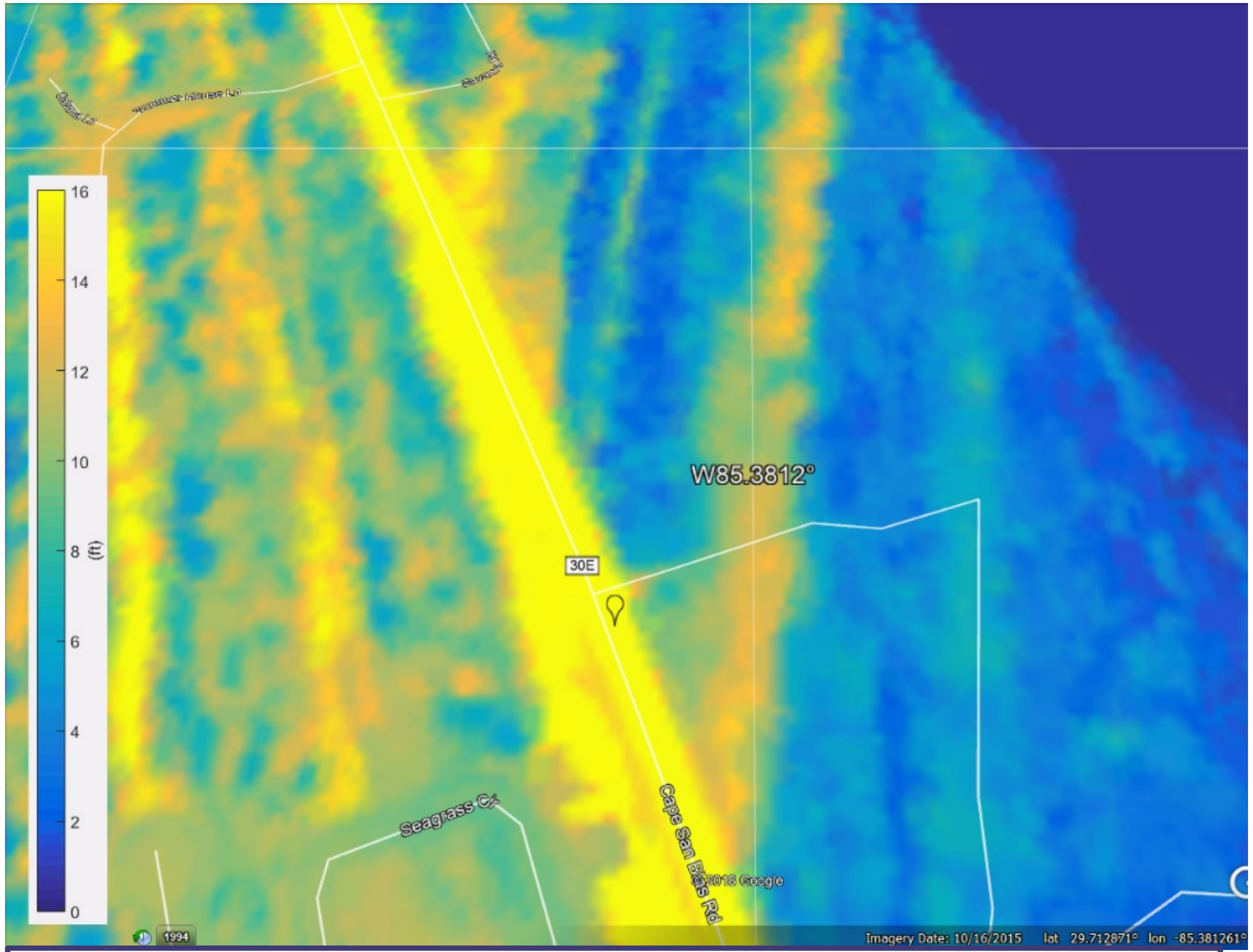
The transitional (between river channel flow and open ocean) region moves further upstream when surge and rain-induced flood are simulated together (as a single dynamically linked system) creating regions of increased inundation



Geocoding Issues

An example of bad geocoding: this location was geocoded to the nearby highway; corresponding ground elevation is much higher than that at the actual structure





LIDAR-informed ground elevation in feet

Geocoding Issues

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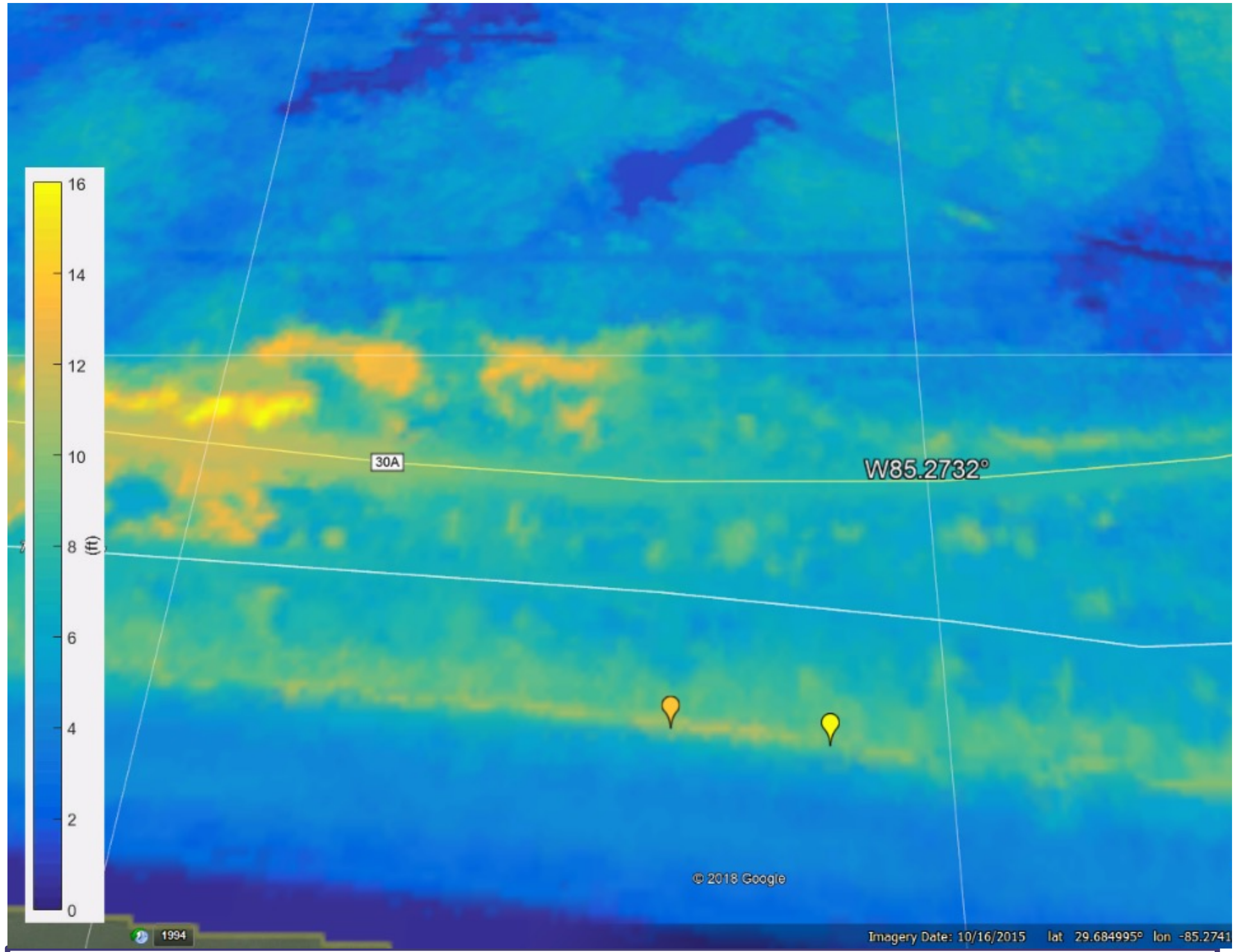
Another type of geocoding problem. Structures are being geocoded to nearby dunes - dunes are substantially higher than surrounding areas resulting in 0 modeled loss at these locations



LIDAR-informed ground elevation in feet