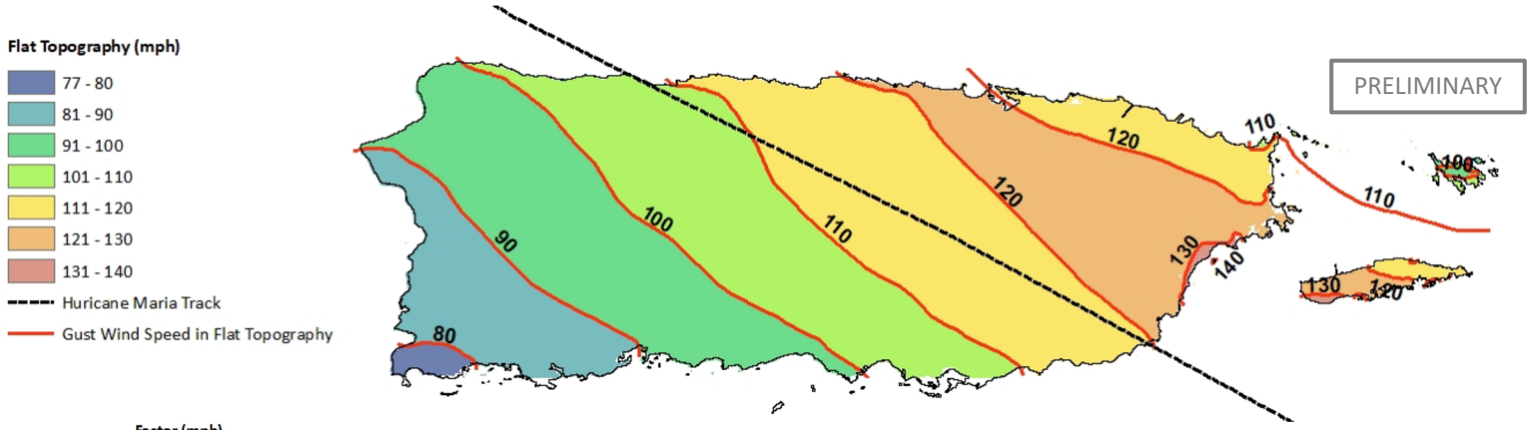
NCST Technical Investigation of Hurricane Maria (Puerto Rico)

Hazard Characterization Project

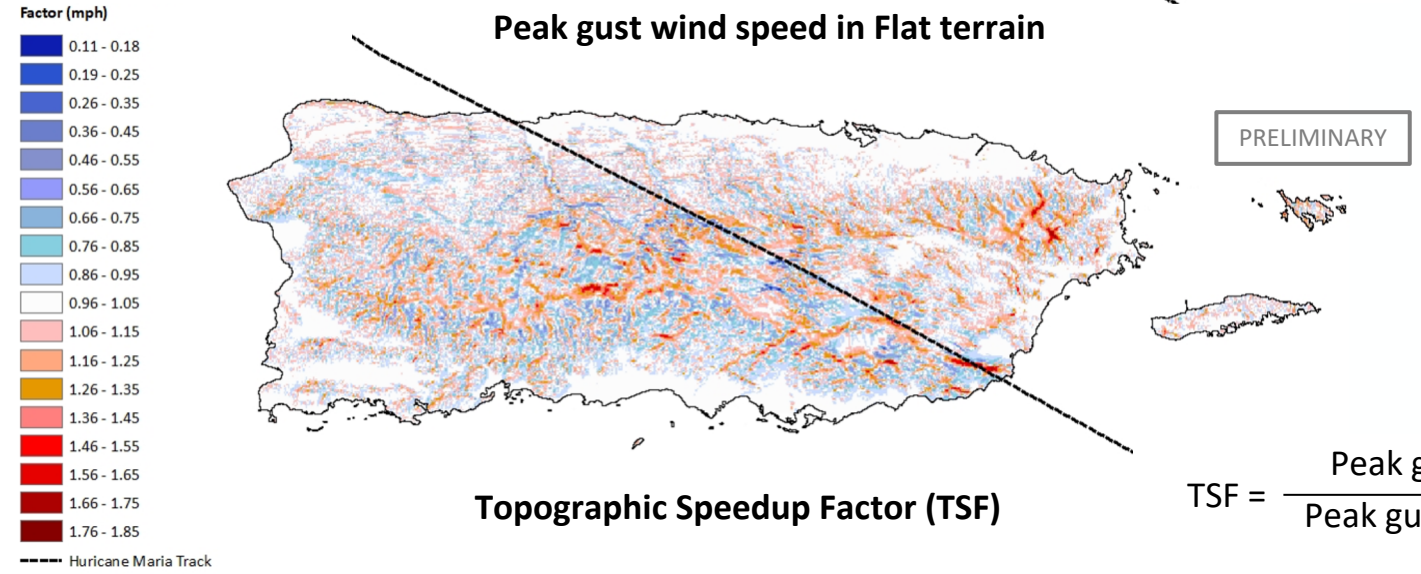
Project Leaders: DongHun Yeo and Scott Weaver

Objective: To characterize the wind environment associated with Hurricane Maria's impact on Puerto Rico, using measurements and modeling of the time-dependent hurricane wind-field in conjunction with wind tunnel studies of topographic effects, and to document other hazards associated with the hurricane, including storm surge, rainfall, flooding, and landslides

Background: Wind Hazard from Hurricane Maria



Peak gust wind speed in Flat terrain



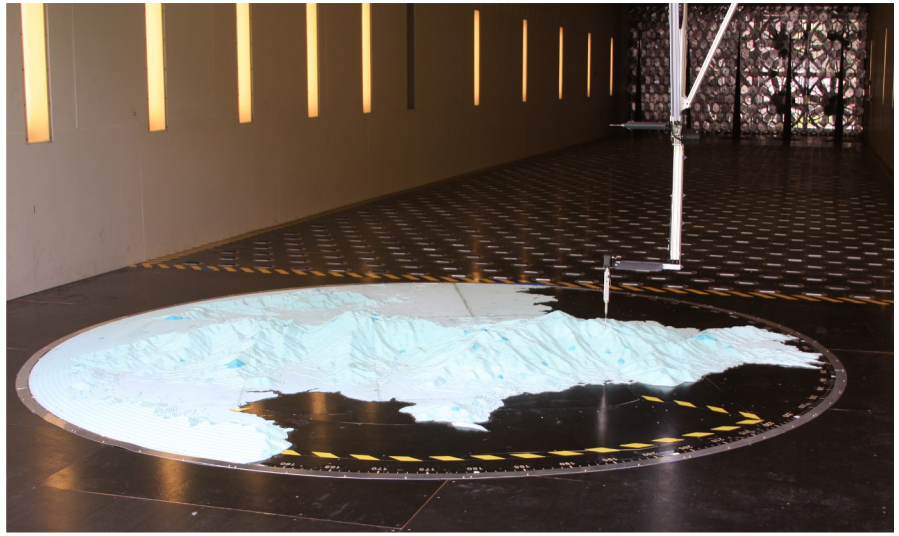
Topographic Speedup Factor (TSF)

$$\text{TSF} = \frac{\text{Peak gust speed with topo. corrections}}{\text{Peak gust speed without topo. corrections}}$$

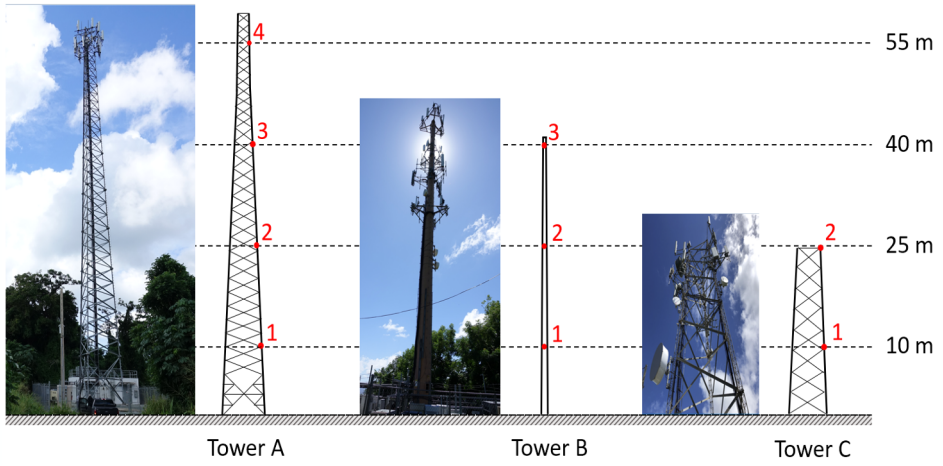
Hurricane Maria in Puerto Rico (Cat. IV storm at landfall):

- Peak gusts in flat terrain exceeded 140 mph
- Preliminary analysis shows topography increased peak gusts by up to ~ 80 % (especially in mountainous areas)

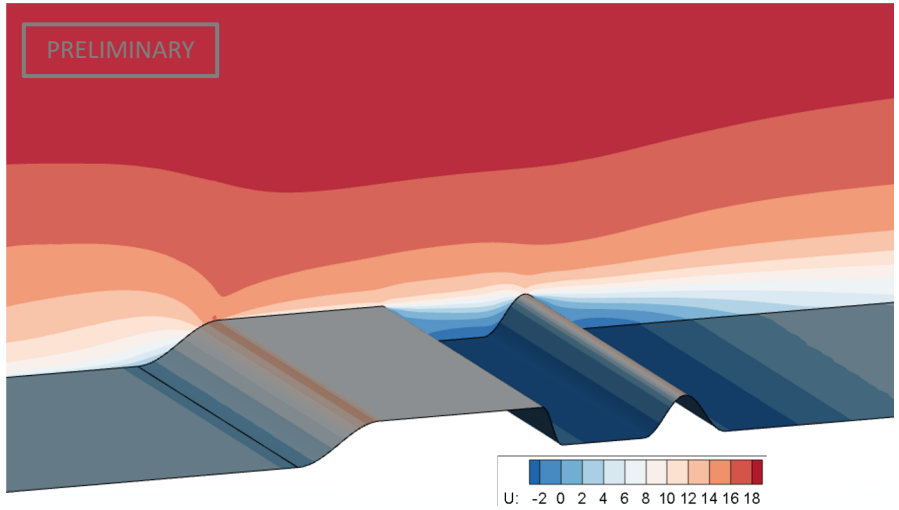
Wind Hazard: Project Plans



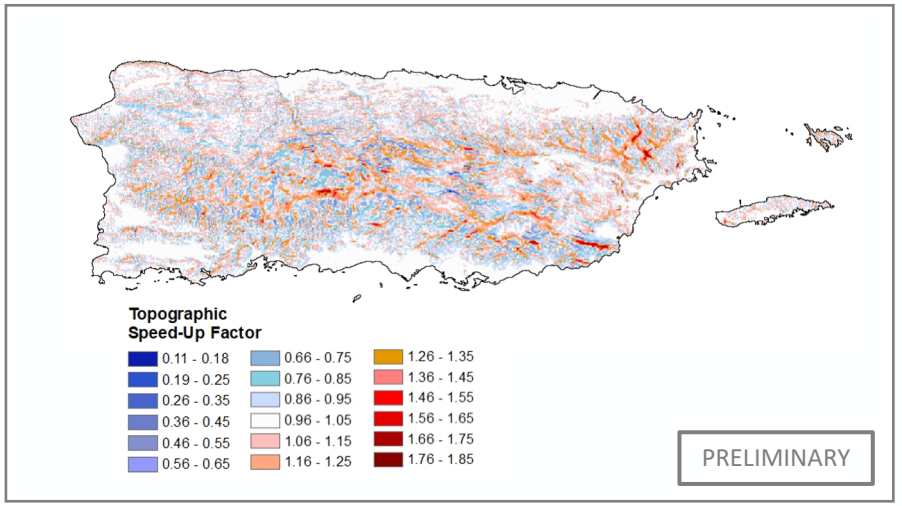
Wind Tunnel Testing



Field Measurements



Numerical Simulation



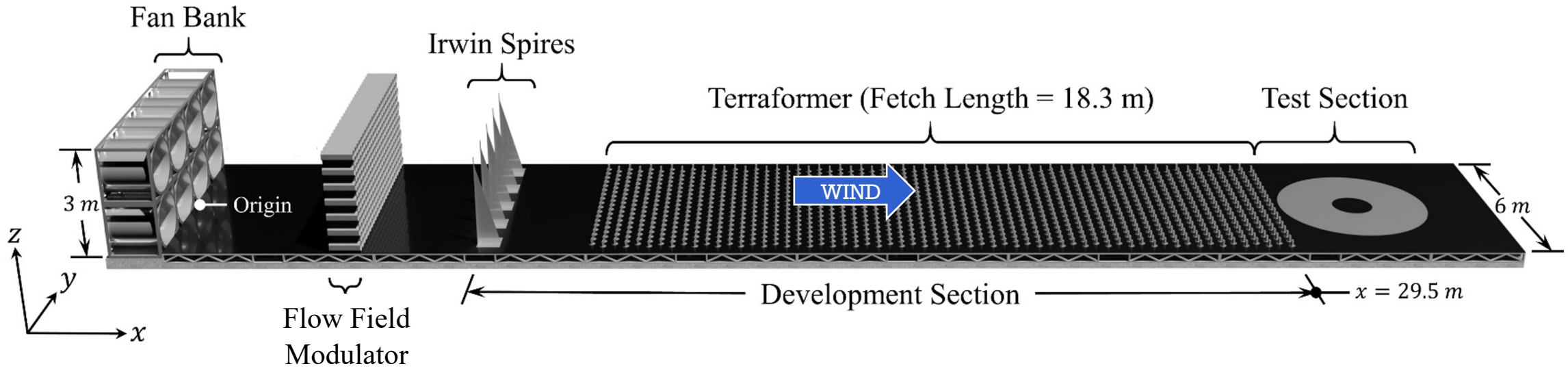
Wind Field Modeling

Wind Hazard: Recent Progress (Wind Tunnel Testing)

Purpose: Obtain flow-field measurements from wind tunnel testing of topographic features to provide experimental data with quantified uncertainties for characterization of topographic speedup effects and for validation of numerical models

Contract with University of Florida to support wind tunnel testing tasks:

- Fabrication and wind tunnel testing of topographic models
- Fabrication and wind tunnel testing of building models (supports Critical Buildings Project)



Wind Hazard: Recent Progress (Wind Tunnel Testing)

Testing of generic topographic models:

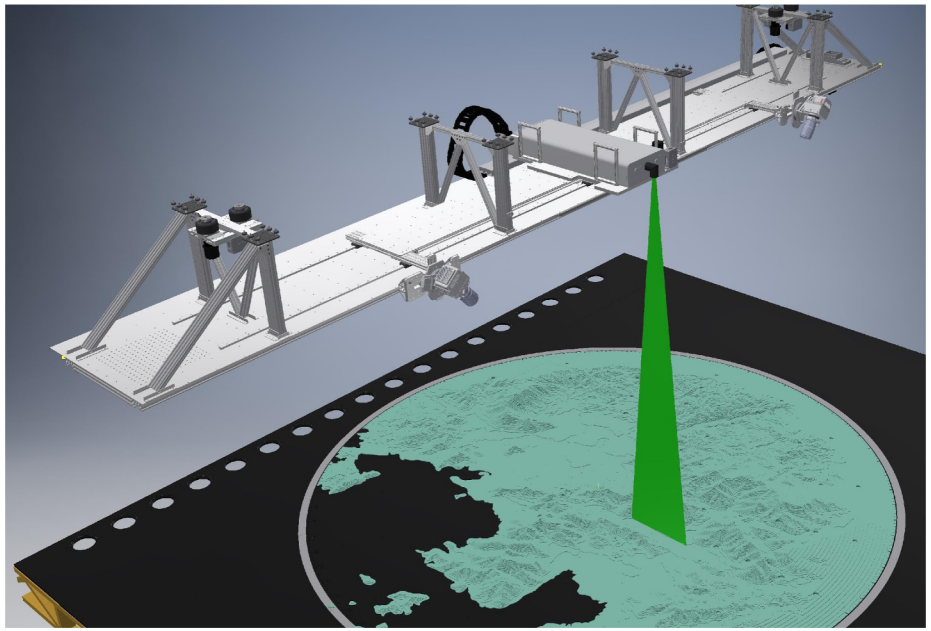
For validating numerical results and quantifying uncertainties in wind tunnel testing results

Measurement of flow velocities around and pressure on models (PIV, pressure scanner)

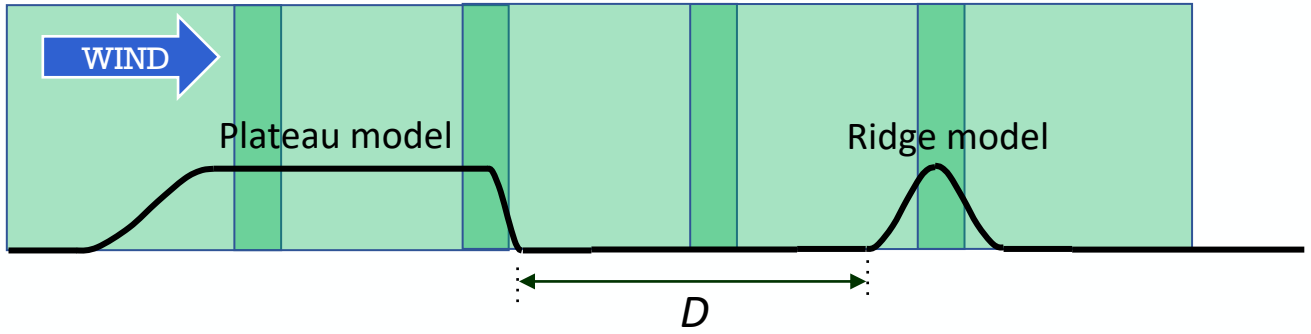
Configurations of 2-D ridge and plateau models (Net distances: $D = 2H$, $5H$, $10H$ where H = model height)

Surface roughness modeling (smooth, rough, terraced surface)

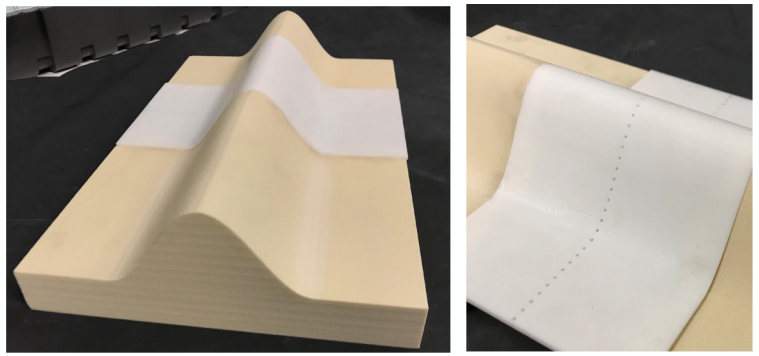
Approach flow (Exposures C [open terrain] and D [open water])



Particle Image Velocimetry (PIV)



Terraced surface



Smooth surface

Wind Hazard: Recent Progress (Wind Tunnel Testing)

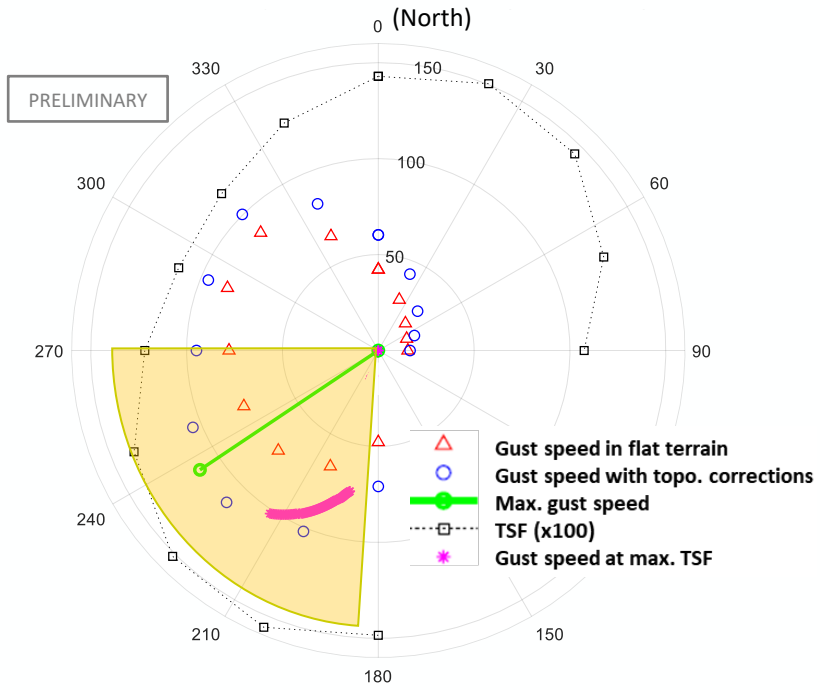
Testing of Puerto Rico topographic model: Mayaguez

Wind directions (180°- 360°) during Hurricane Maria: max. TSF (~210°), max. gust speed (~230°)

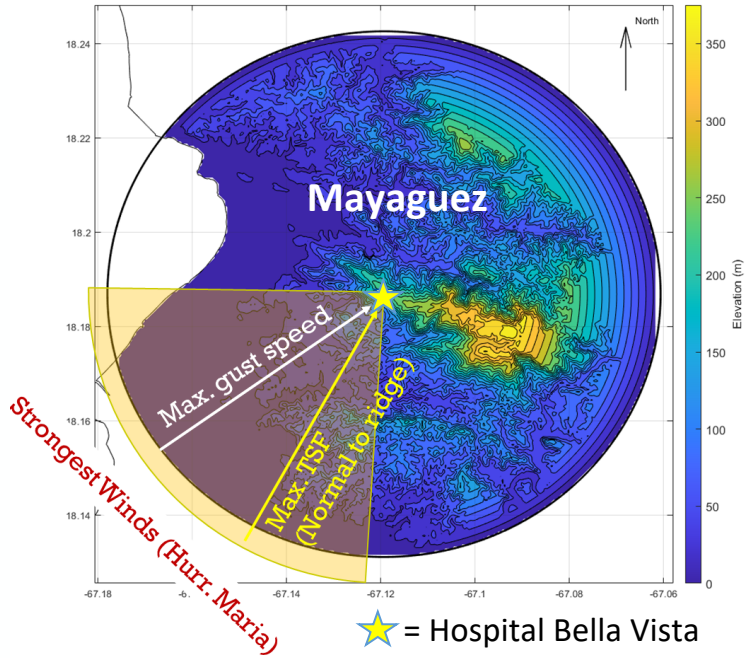
PIV: 2 twelve-plane tests (210°, 230°), 17 one-plane tests (180°- 360°)

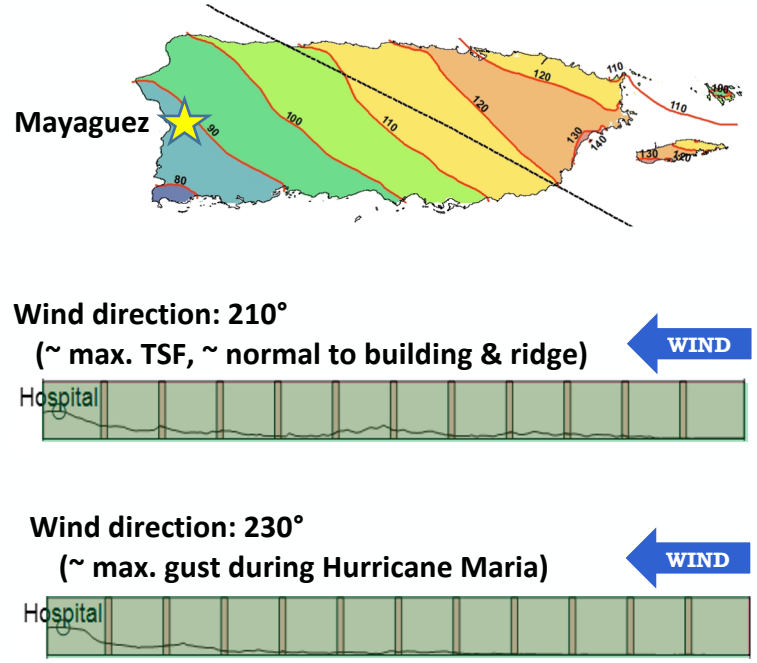
Cobra probes: 14 positions & 8 heights each (210°, 230°), 8 heights at hospital site (180°- 360°)

Testing data will be also used for generating approach flow in building/area model tests



Wind speed and direction during Hurricane Maria

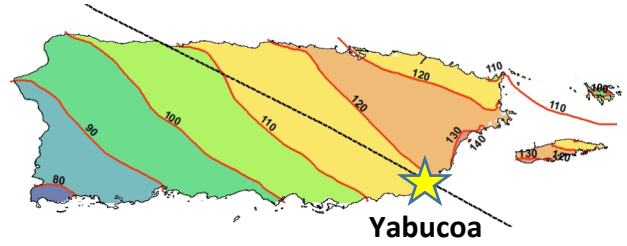




PIV testing planes

Wind Hazard: Recent Progress (Wind Tunnel Testing)

Testing of Puerto Rico topographic model: Yabucoa

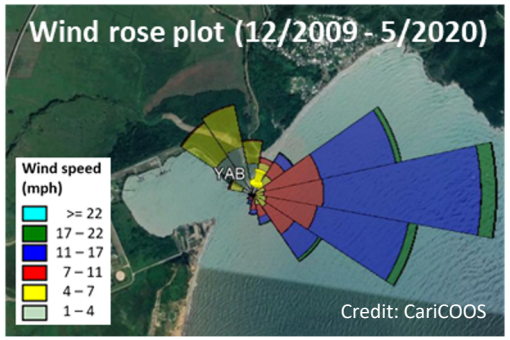


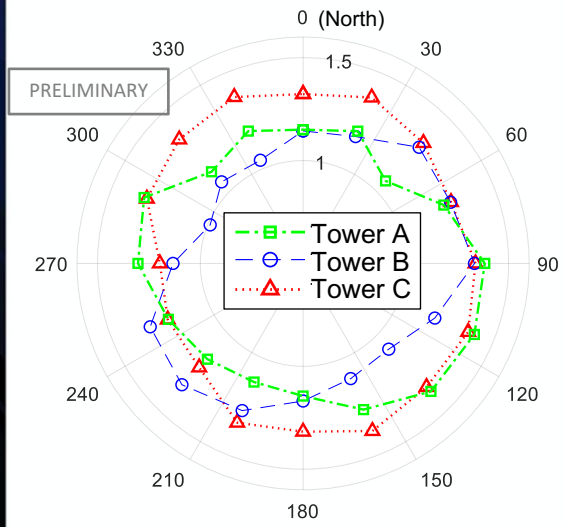
Testing is planned for comparison with data from field measurements and CFD sim.

Directions of prevailing wind and high TSF at towers: ~ East/Southeast

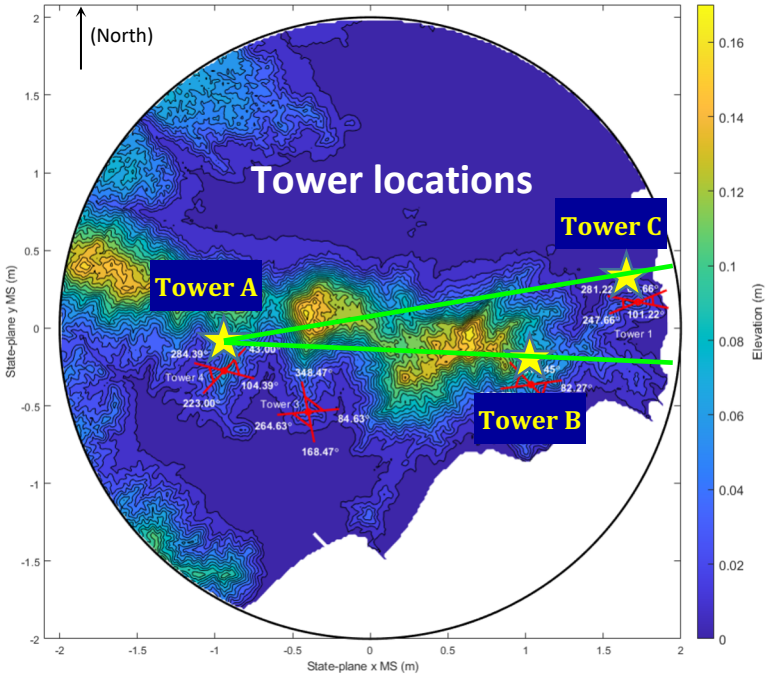
PIV, cobra Probes: Tower C to Tower A (80.6°), Tower B to Tower A (92.6°), Tower C (92.6°)

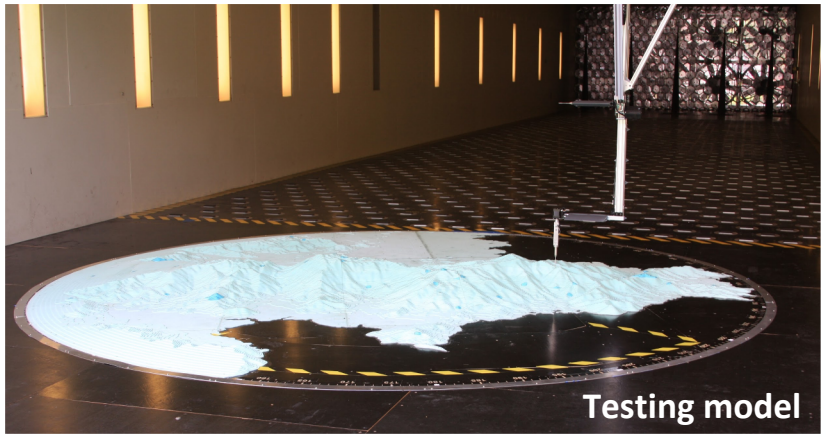
Cobra probes: 8 heights at Towers (mostly from East, in 22.5° increment)

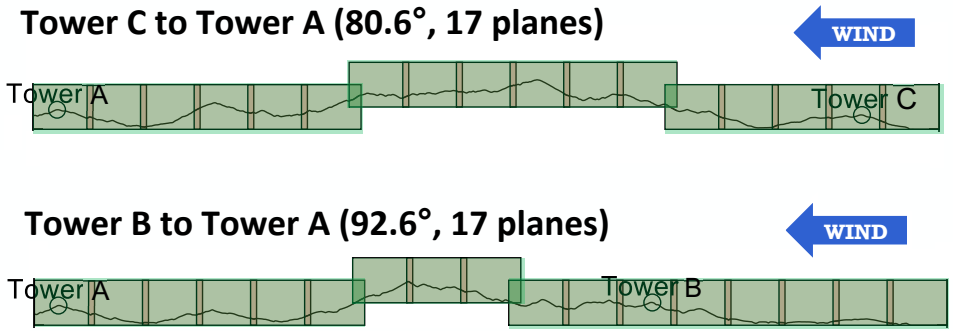




TSFs at towers







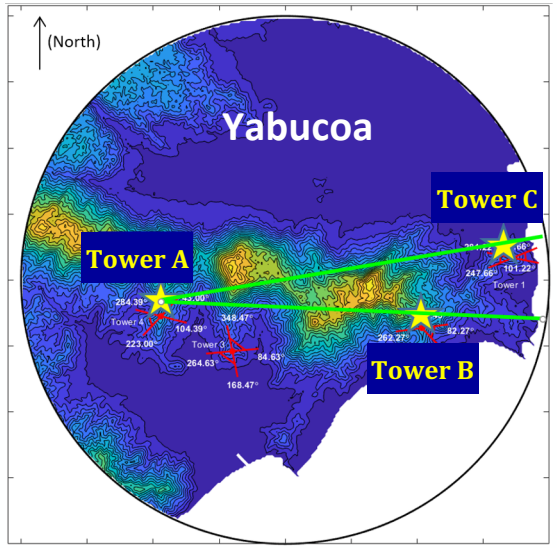
PIV testing planes

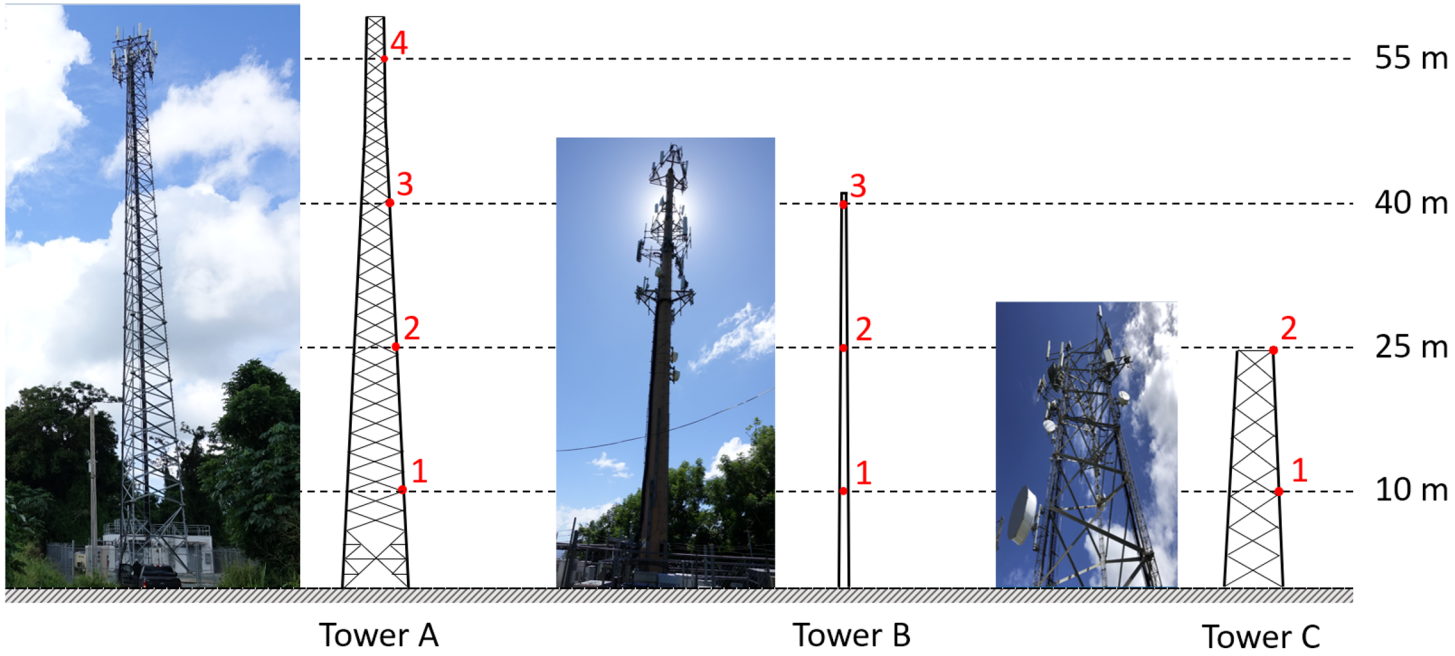
Wind Hazard: Recent Progress (Field Measurement in PR)

Purpose: Obtain full-scale measurements of winds in regions of topographic interest in Puerto Rico, to provide information for validation of wind tunnel test results and numerical models

Contract awarded to University of Florida (subcontractor: WeatherFlow)

- Selected three communication towers in the Yabucoa region for measurement of topographic effects on winds, along with installation heights for deployment of anemometers
  (in coordination with American Tower Corp.)

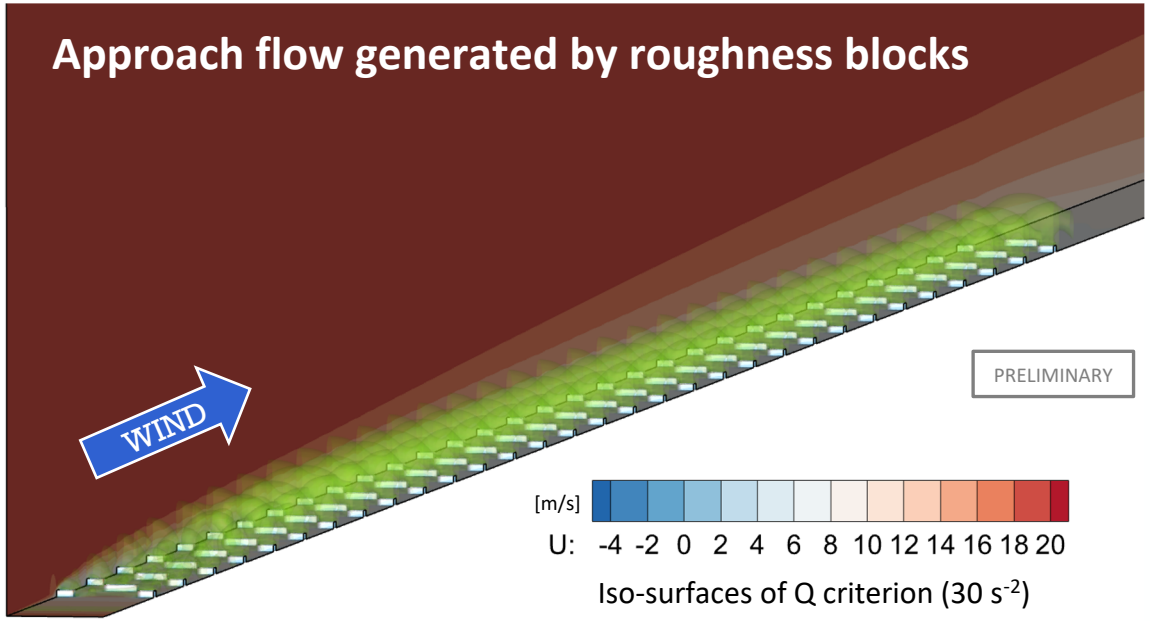


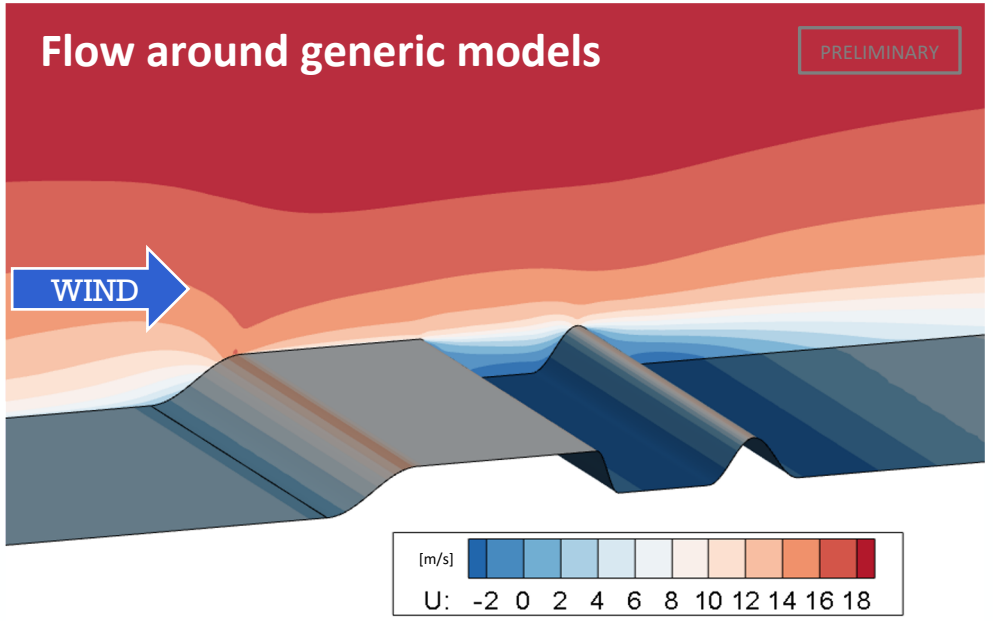


Wind Hazard: Recent Progress (Numerical Simulation)

Purpose: Develop computational fluid dynamics (CFD) models for topographic effects on winds, verify CFD simulations, validate CFD results against wind tunnel and field measurement data, and use the validated CFD models to evaluate and characterize topographic speedup effects in Puerto Rico

- Developed numerical approaches for modeling of approach flow and terrain surface:
  - Roughness blocks
  - Canopy model
  - Wall function
- Simulates flow over generic models (in progress)





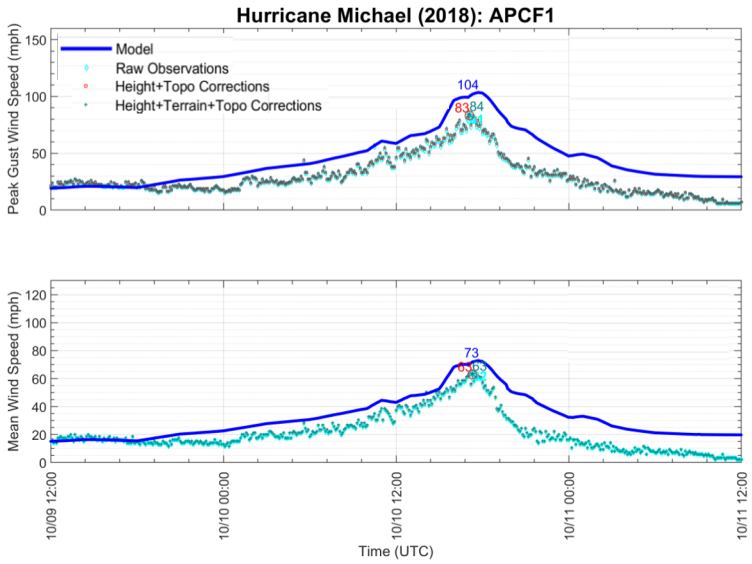
Wind Hazard: Recent Progress (Wind Field Modeling)

Purpose: Develop a time-dependent wind-field model of Hurricane Maria's impact on Puerto Rico that optimally matches available measured data

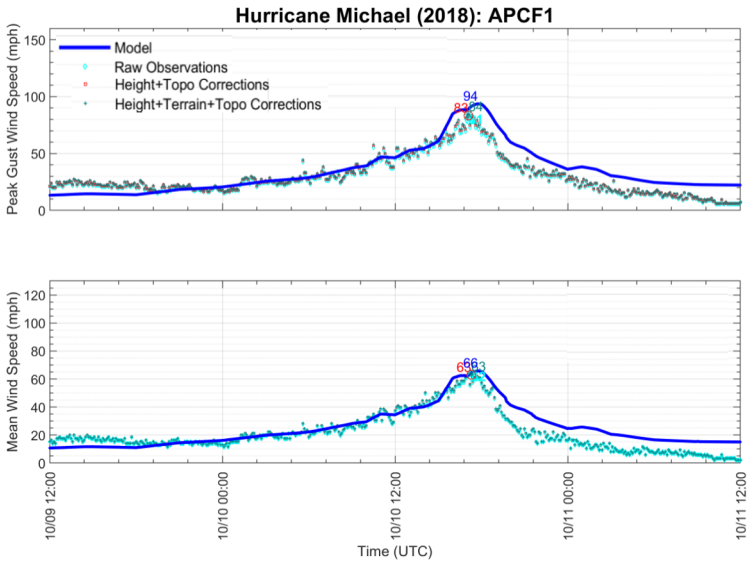
Contract with Applied Research Associates to support wind field modeling tasks:

- Completed methodology for adaptation of model to better handle strongly asymmetric wind fields
- Completed methodology for optimization of model fitting to observed data, including assessment of goodness of fit and quantification of uncertainty
- Testing of these methodologies is currently underway using Hurricanes Irma (Puerto Rico), Irma (CONUS), and Michael

Without Peak Factor



With Peak Factor



A new Peak Factor was developed to improve the hurricane model fit to account for asymmetries in the wind field.

The plots at left show example comparisons of modeled to observed data with and without the Peak factor in Hurricane Michael (2018) for Buoy Station APCF1 - 8728690 located in Apalachicola, Florida.

Wind Hazard: Next Steps

Wind tunnel testing:

- Fabricate the Mayaguez topographic model
- Perform tests of generic and PR topographic models

Field measurement:

- Install weather stations on 3 existing towers, with anemometers at multiple heights on each tower
- Collect wind data at three weather stations for one year

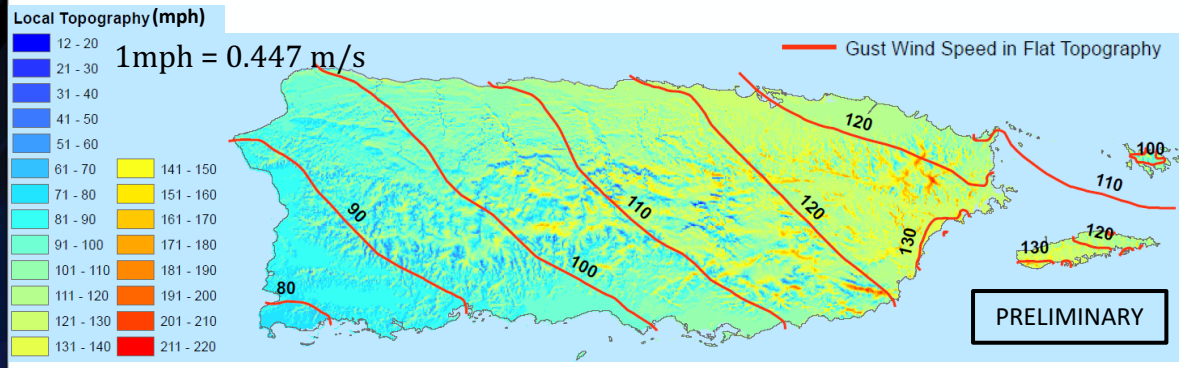
Numerical simulation:

- Complete simulations of generic and topographic models
- Validate numerical topographic simulation modeling with wind tunnel data

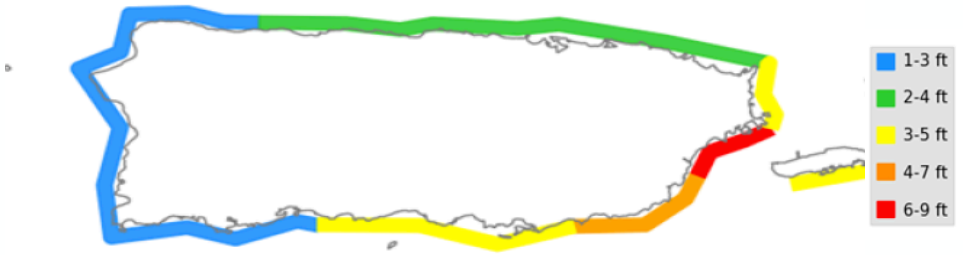
Wind field modeling:

- Complete testing of methodologies and finalize the wind field model improvements for asymmetric wind fields and optimization of fit
- Complete the final wind field model of Hurricane Maria based on modeling improvement and updated consideration of topographic speedup effects, once the experimental topographic speedup data has been obtained and analyzed

Initial Observations: Multiple Hazards from Hurricane Maria

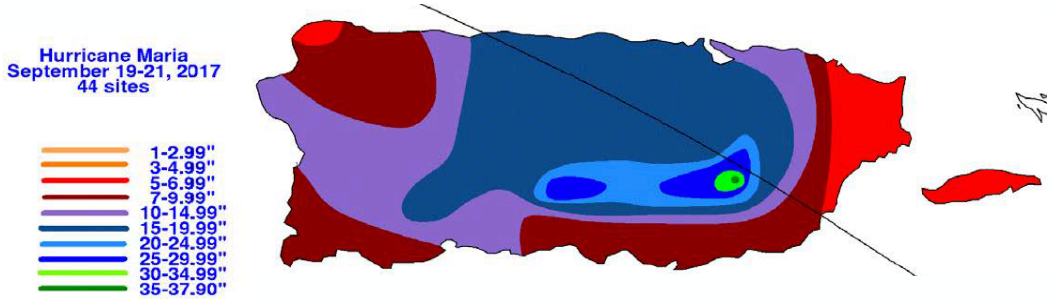


Peak gust wind speed at 10 m height above ground



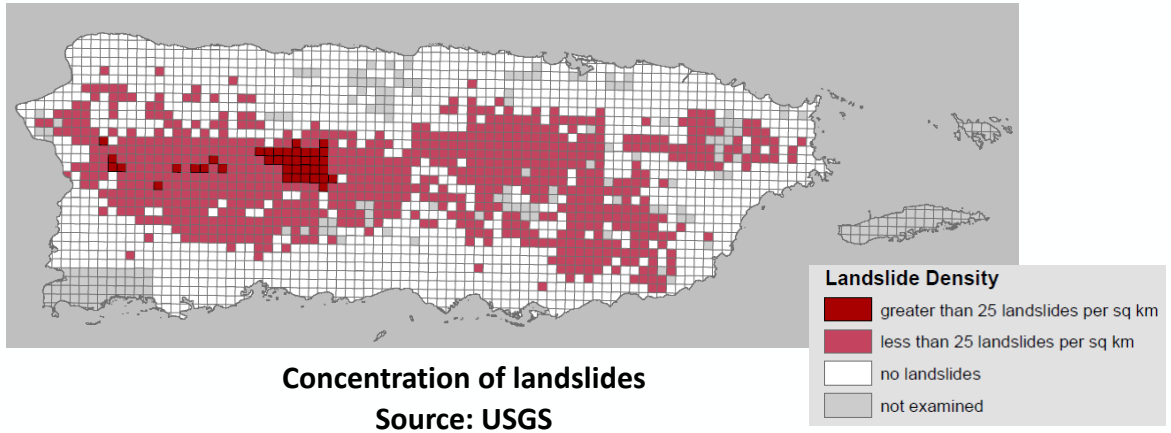
1ft = 0.3048m

Inundation above ground level
Source: NOAA/NHC



1in. = 25.4 mm

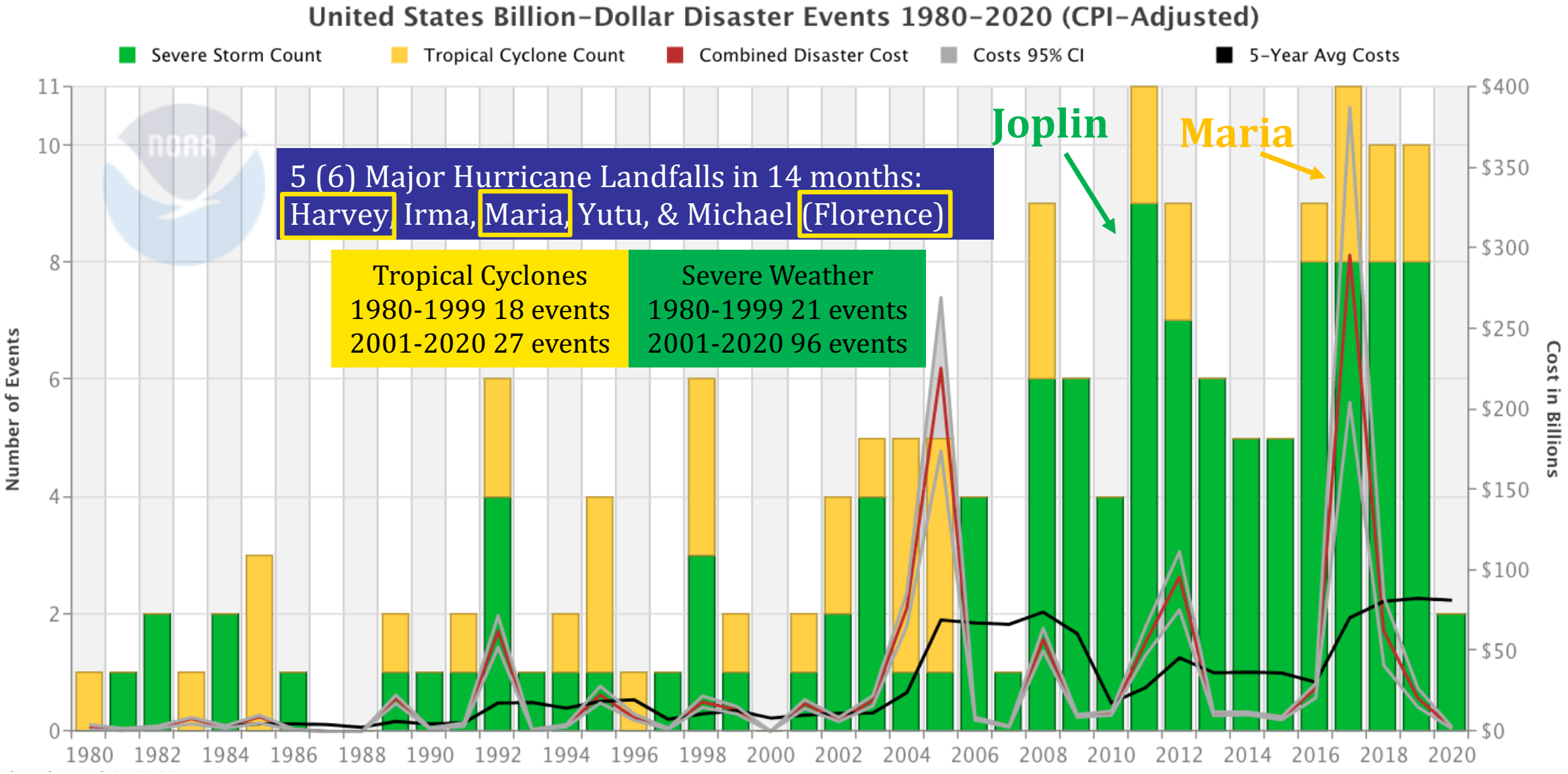
Precipitation in inches
Source: NOAA/WPC



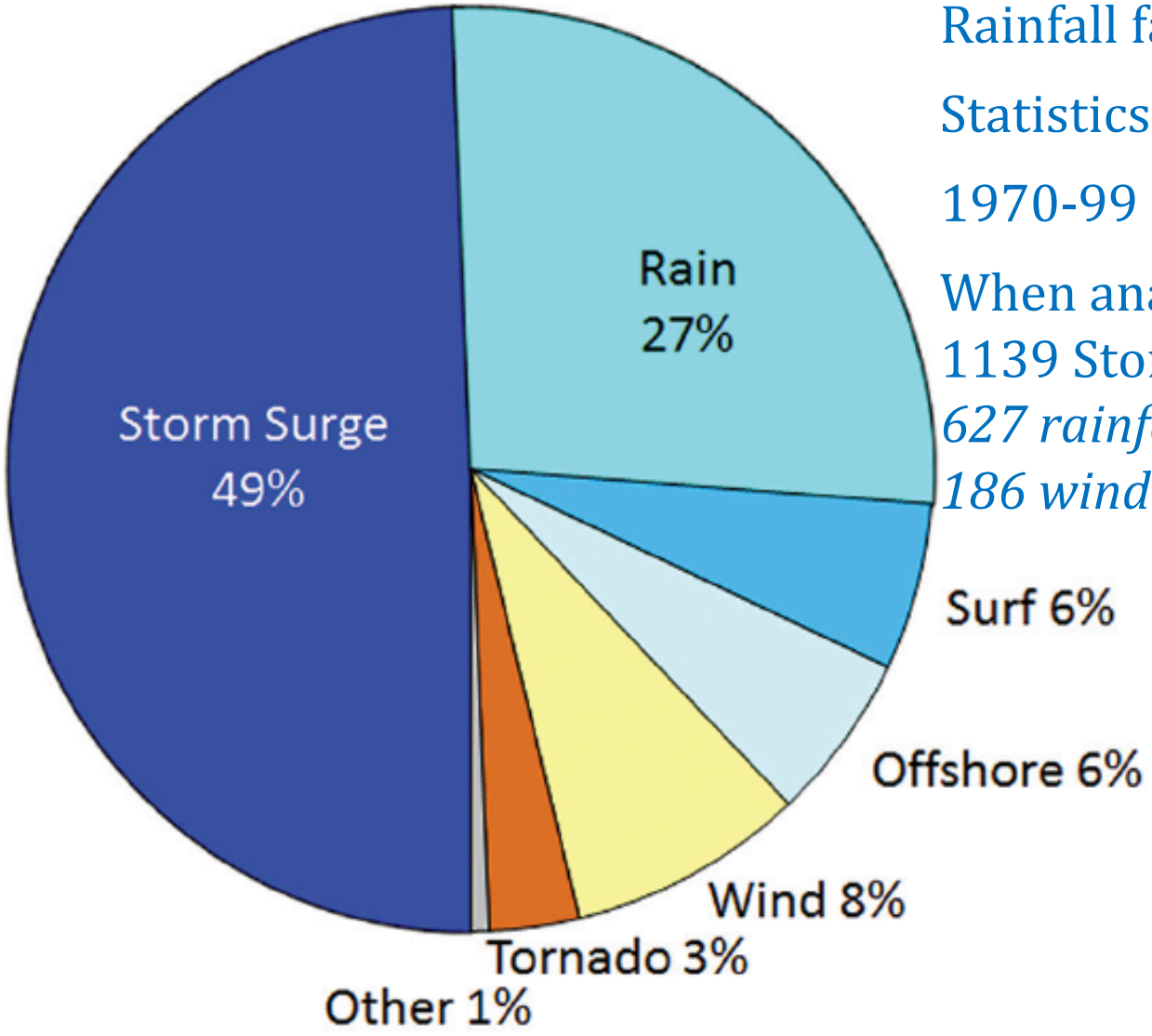
Concentration of landslides
Source: USGS

Hurricane Maria subjected Puerto Rico to multiple hazards: peak gusts exceeded 140 mph (63 m/s), peak coastal inundation exceeded 6 ft (1.82m), rainfall totaling up to 37 inches (939mm) causing inland flooding. The storm damaged instrumentation, resulting in challenges to the metrology of the hazards related to the windstorm.

Windstorm Related Disasters 1980 – 2020



Hurricane Fatalities as Function of Hazard 1963-2012



Rainfall fatalities ~2.5 times that of wind + tornado

Statistics are sensitive to outliers

1970-99 period had 6 storm surge related deaths

When analysis period expanded to 1963-2012:
1139 Storm Surge Fatalities
627 rainfall fatalities
186 wind fatalities

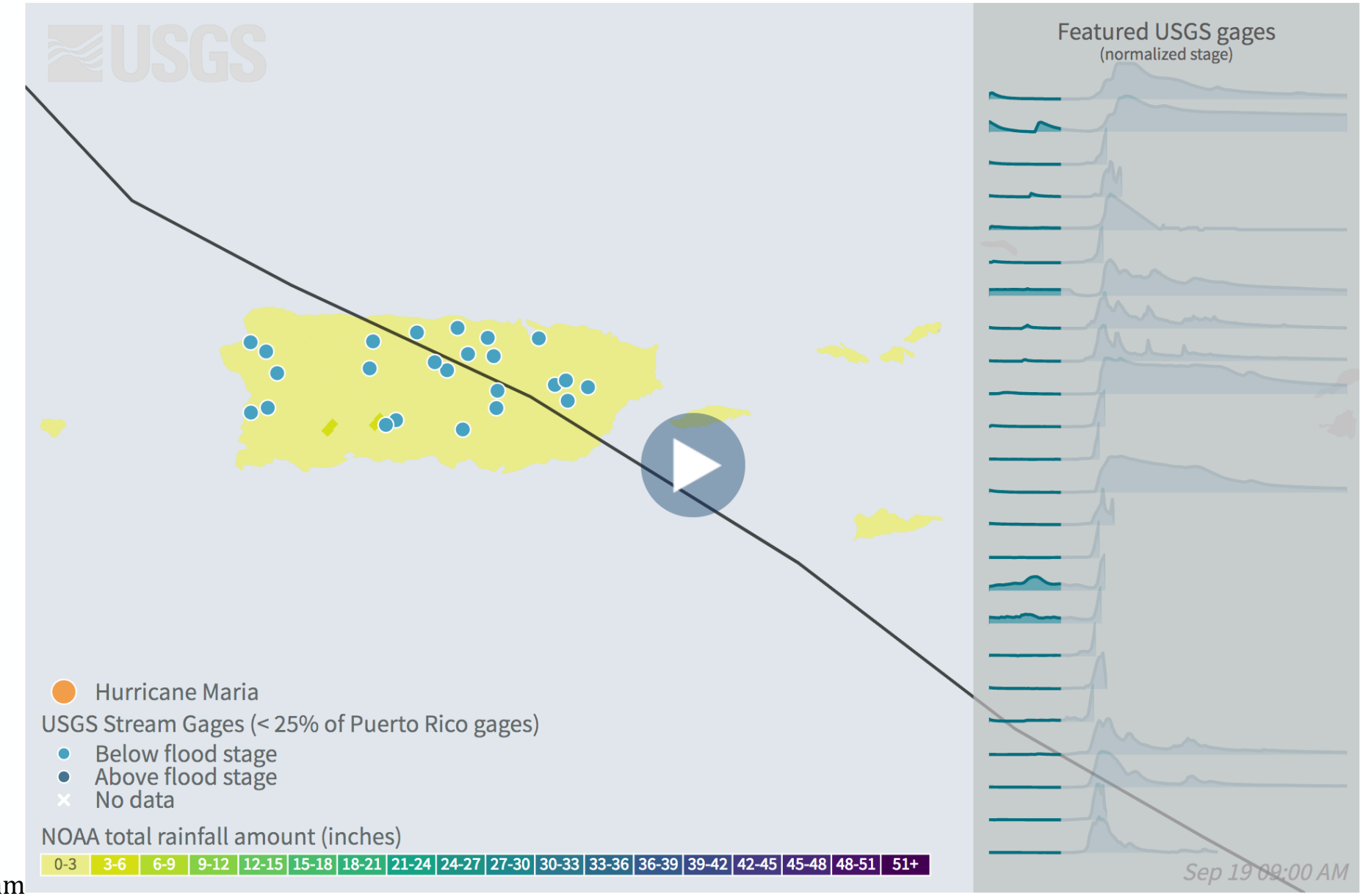
Data Source: NOAA/National Hurricane Center

Flood Hazard Measurement Challenges

	Zone	Description
	A	No base flood elevation determined
	AE	Base flood elevation determined
	AH	Flood depth of 0.3 to 0.9 meters (usually areas of ponding)
	AO	Flood depth of 0.3 to 0.9 meters (usually sheet flow on sloping terrain) alluvial fan flooding
	D	Areas in which flood hazard are undetermined, but possible
	VE	Costal flood with velocity hazard (wave action)
	X500	X500 - Areas of 500-year flood; areas of 100-year flood with average depths of less than 0.3 meters or with drainage areas less than 2.6 square kilometers

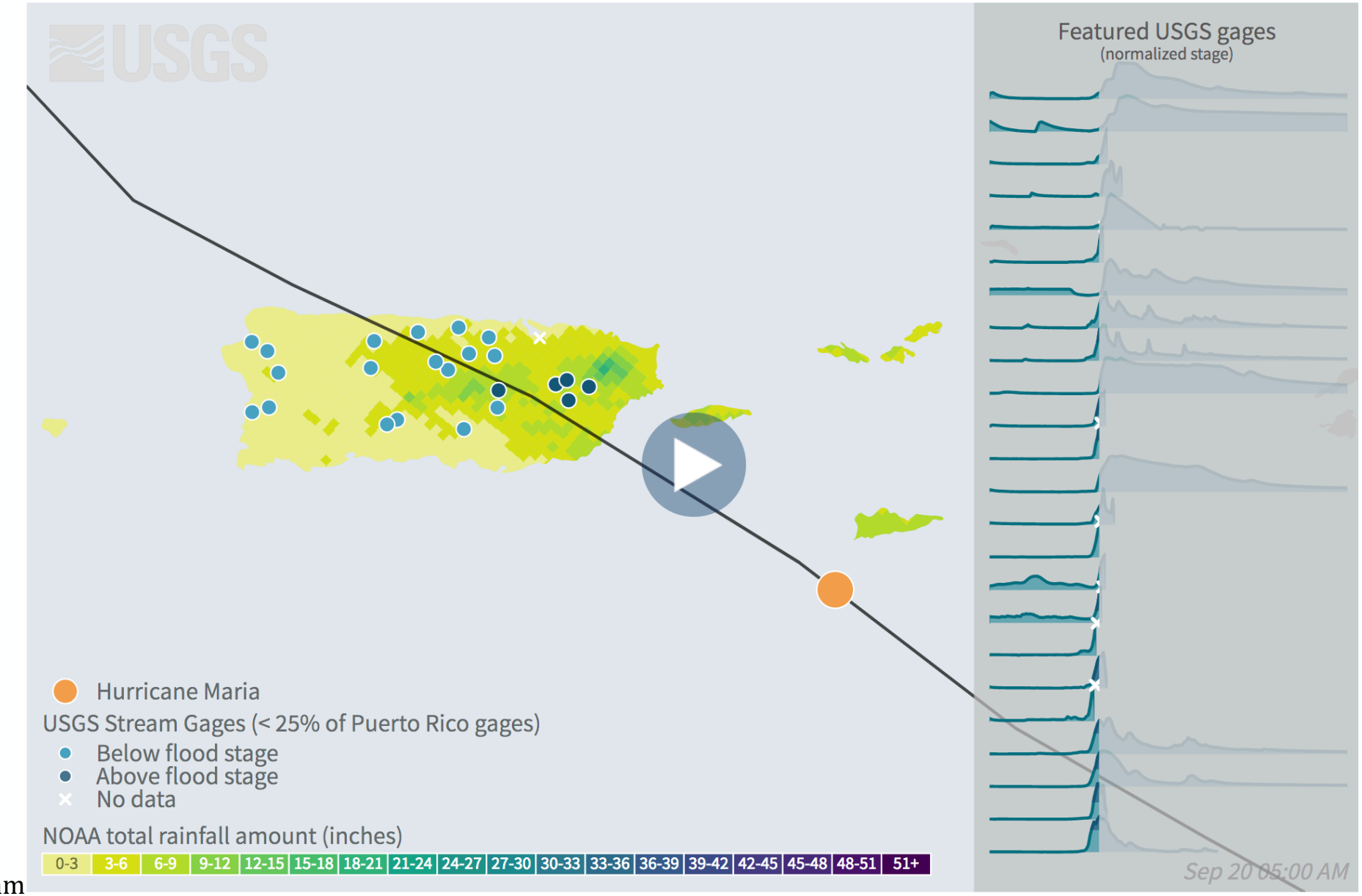
Source: FEMA

Flood Hazard Measurement Challenges



1in. = 25.4 mm

Flood Hazard Measurement Challenges



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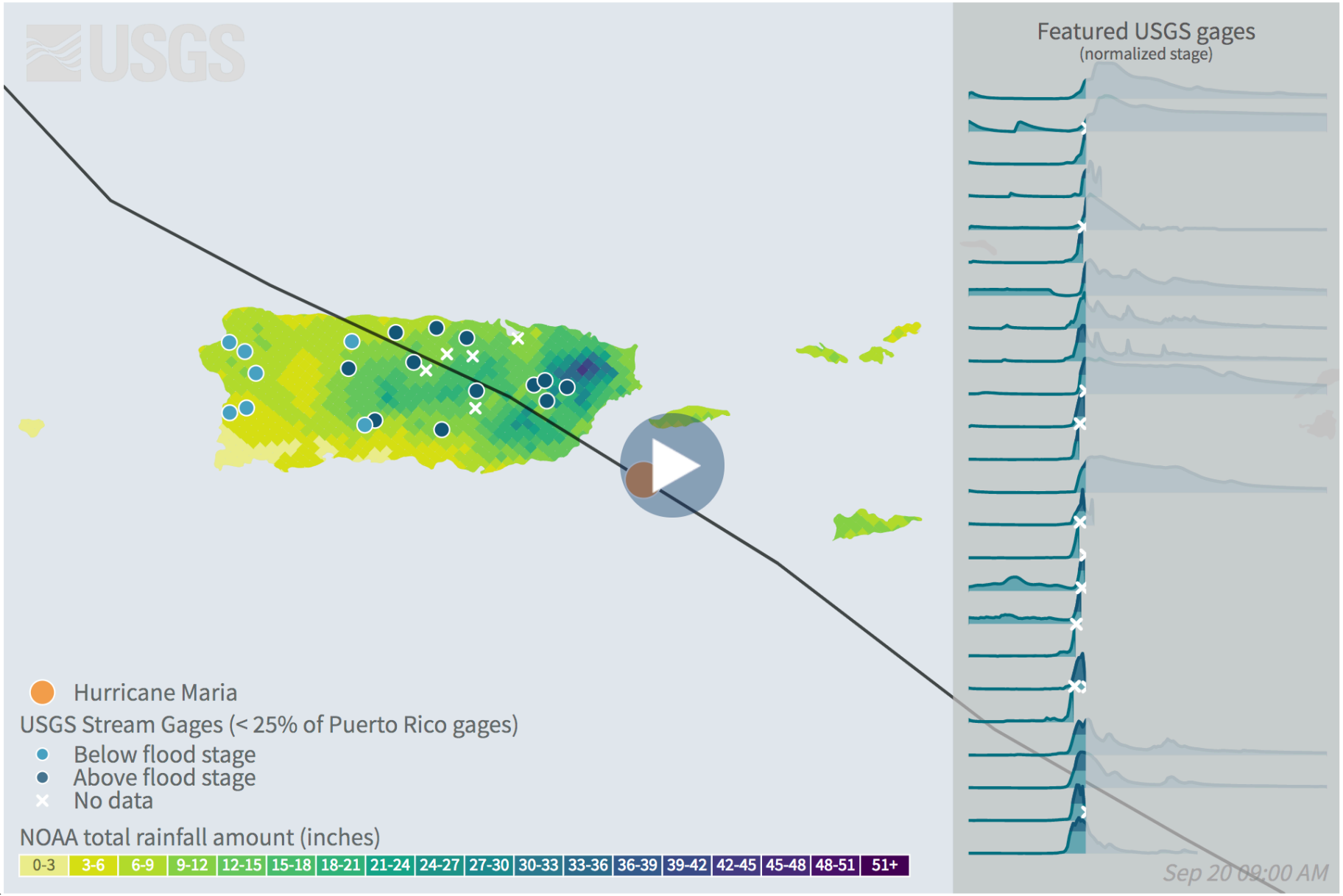
Flood Hazard Measurement Challenges



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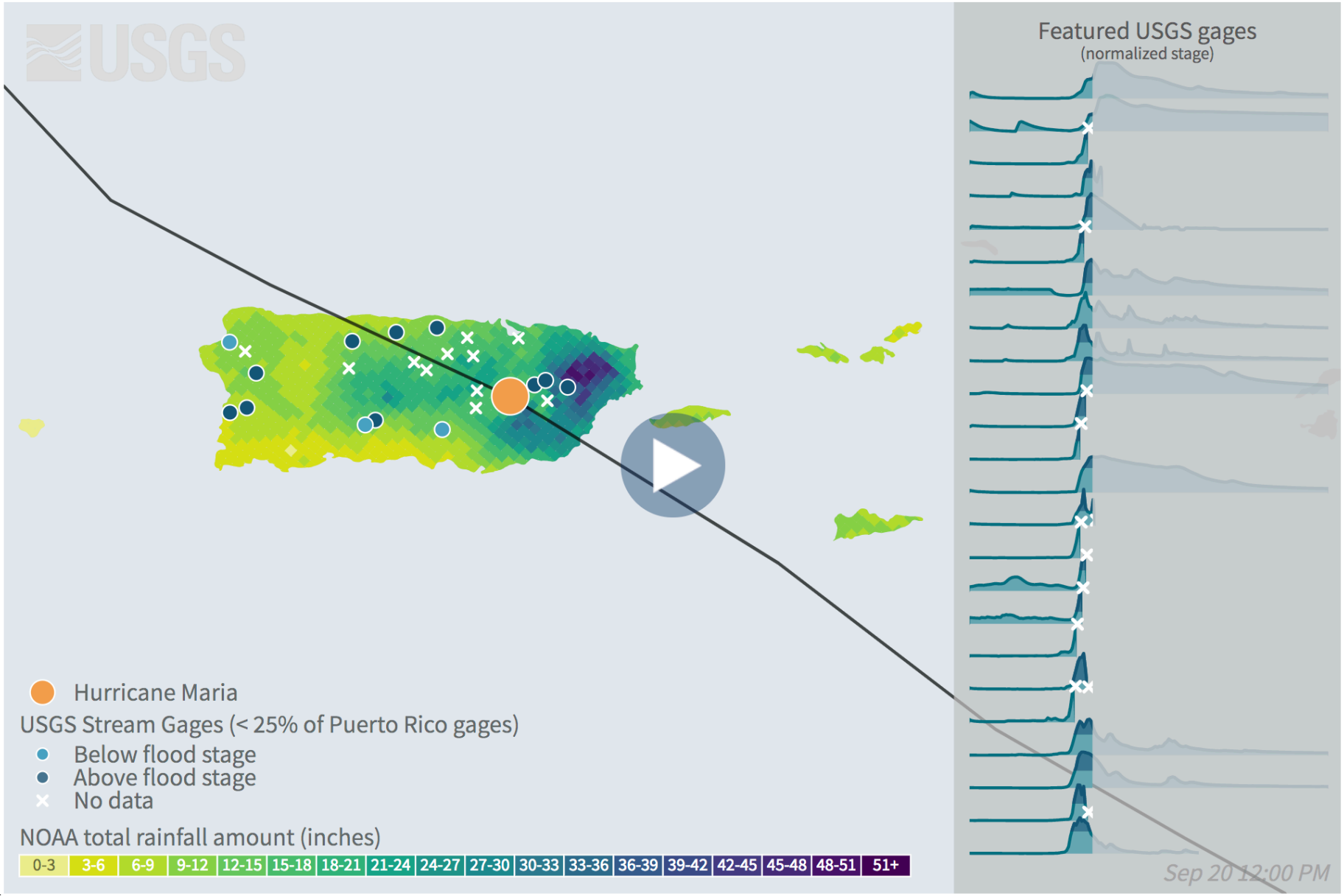
Flood Hazard Measurement Challenges



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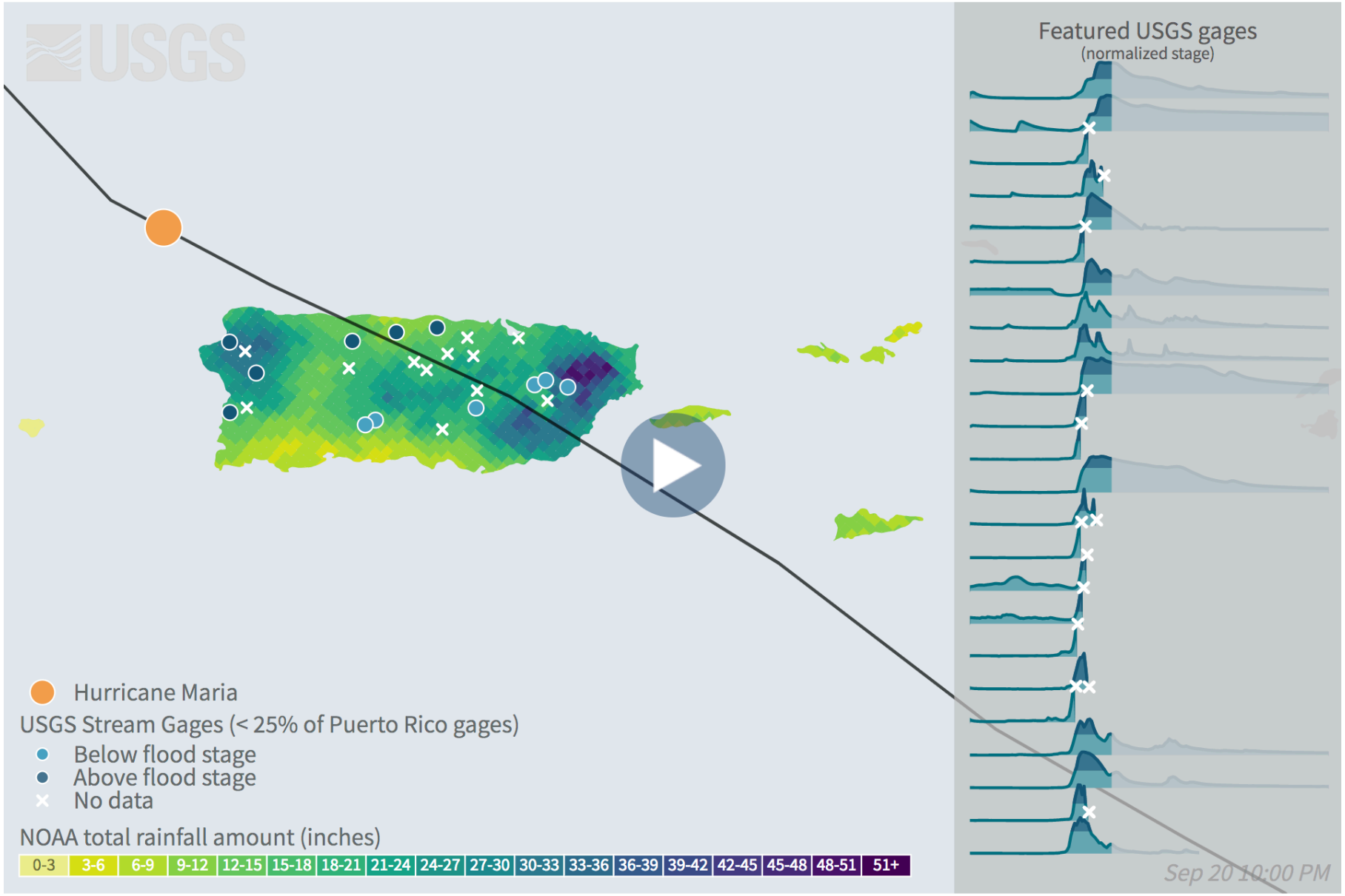
Flood Hazard Measurement Challenges



1in. = 25.4 mm

Rainfall Hazard Measurement Challenges

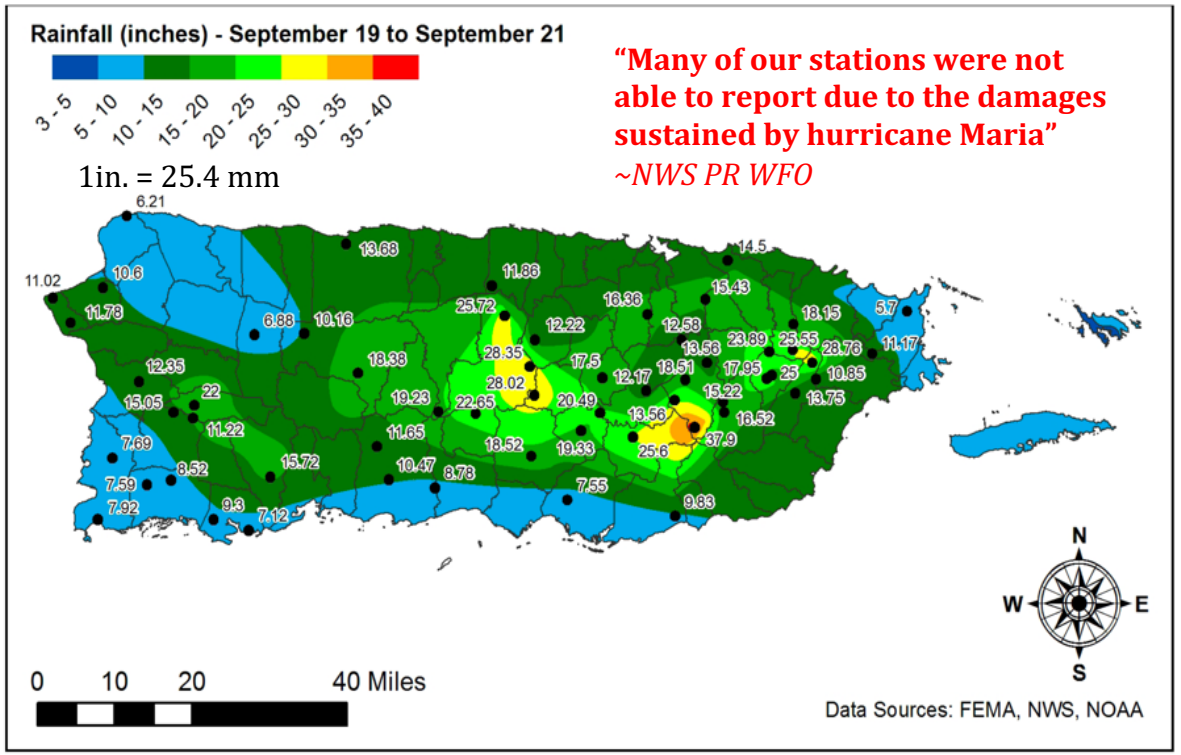
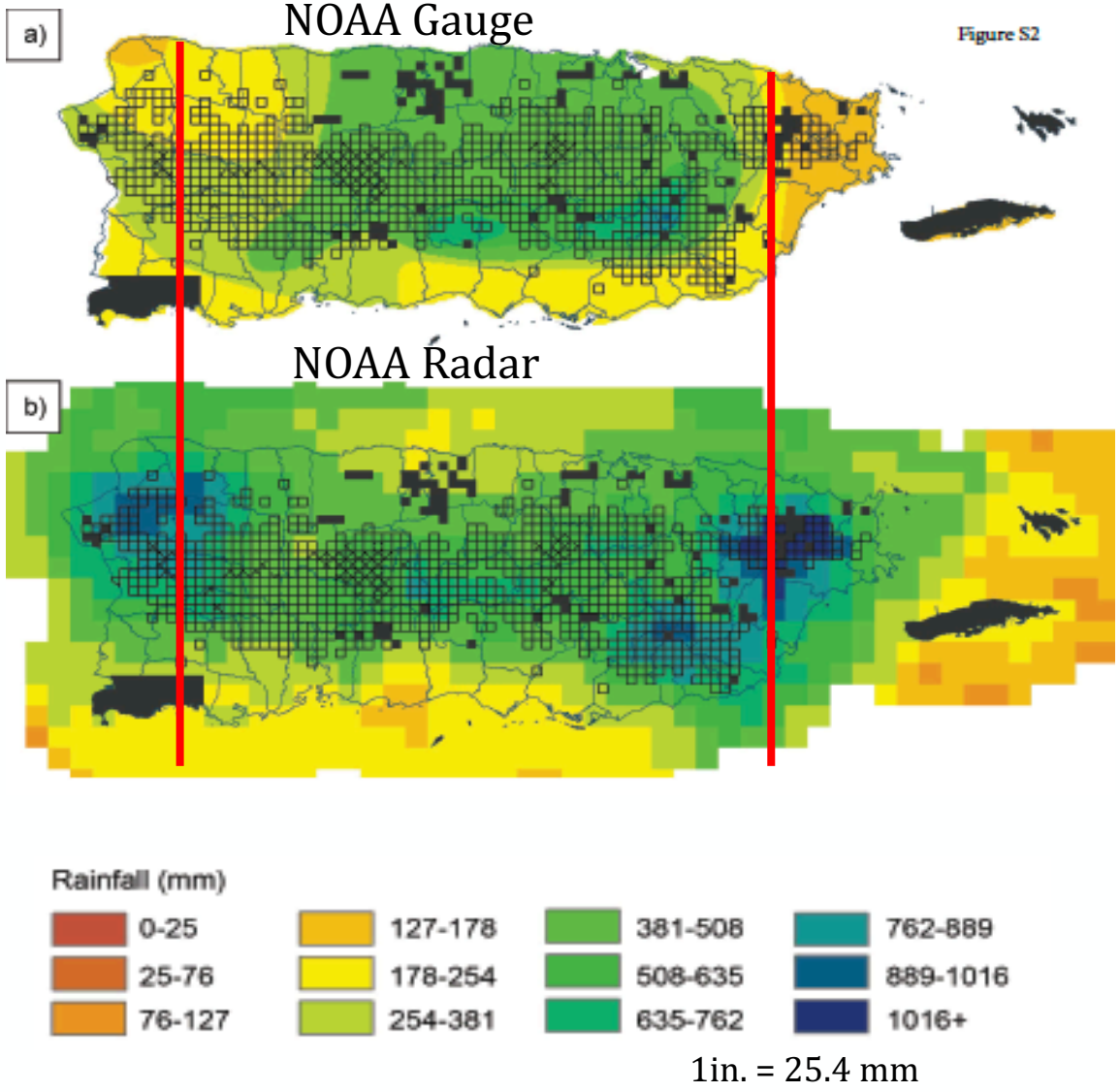


Figure 1-10: Estimated rainfall total from Hurricane Maria (National Weather Service 2017).

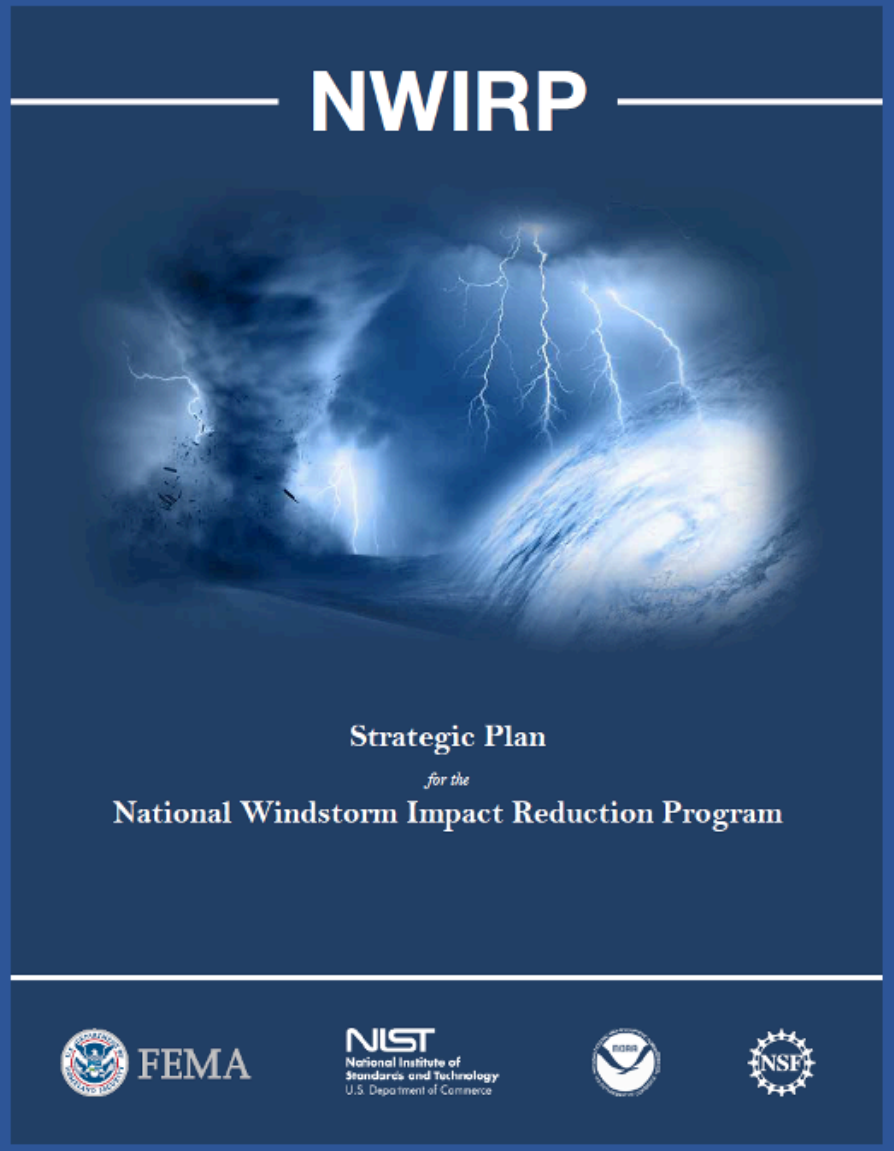


Source: Bessette-Kinton et al, 2019 (With Permission)

In portions of northeastern and central Puerto Rico, initial precipitation estimates between the two differ by up to 33 inches (838mm)!

NOAA Radar was destroyed, and many rain gauge measurements were lost.

National Windstorm Impact Reduction Program



The NWIRP Strategy

Vision: *A Nation that is windstorm-resilient in public safety and economic well-being.*

Mission: *To achieve major measurable reductions in the losses of life and property from windstorms through a coordinated Federal effort, in cooperation with other levels of government, academia, and the private sector. NWIRP will support research aimed at improving the understanding of windstorms and their impacts, and develop technical guidance and foster outreach initiatives encouraging the implementation of cost-effective mitigation measures to reduce those impacts.*

Congress directs NWIRP "to coordinate all federal post windstorm investigations to the extent practicable."

The Engineering Laboratory is conducting research on measurement science challenges for rainfall in extreme events, which complements the NCST work for Hurricane Maria

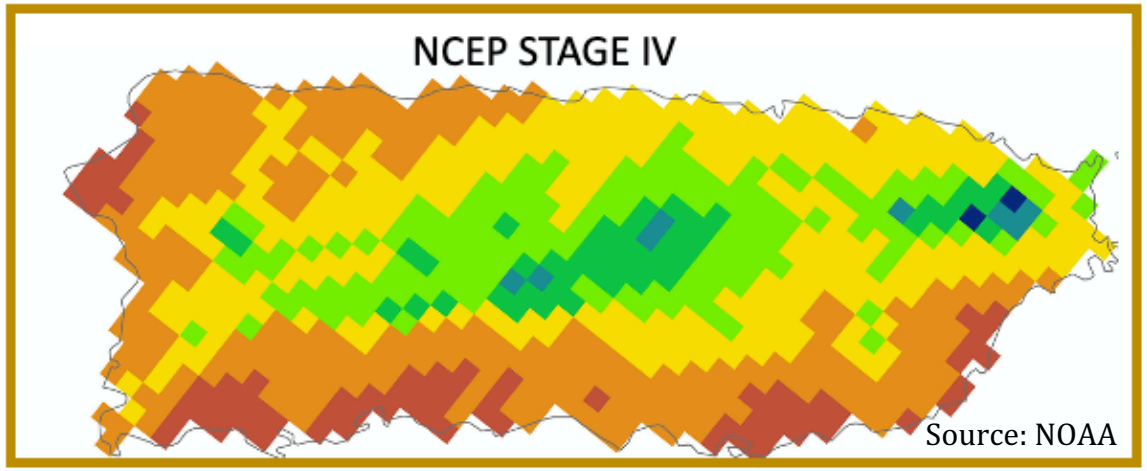
Data

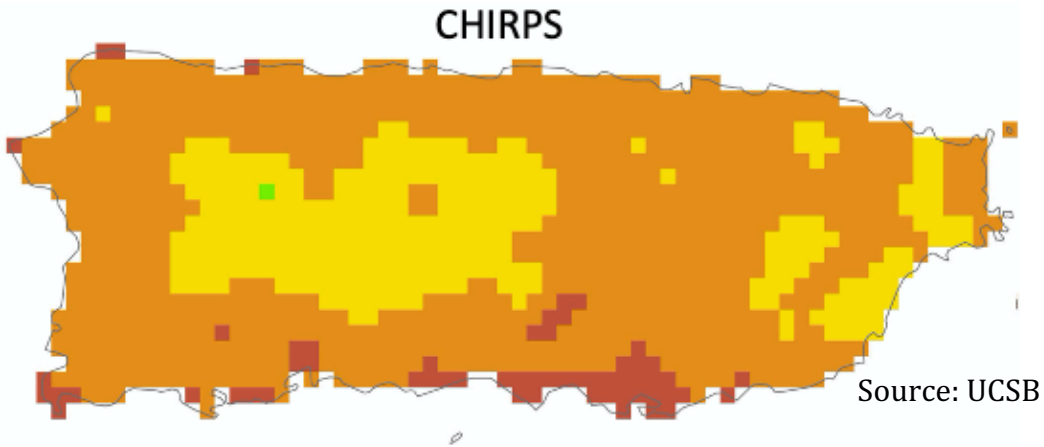
- Rain Gauge Network obtained from NOAA/National Weather Service.
- NOAA/NCEP Stage IV Data. Combines radar and gauges. 4km.
- UCSB Climate Hazards Infrared Precipitation with Stations (CHIRPS). Combines infrared satellite measurements with rain gauge data. 5km/daily/1981-present.
- NASA GPM/IMERG. Combines data from all GPM passive microwave instruments and merges with rain gauge estimates. 10km/30-minute/2014-present.

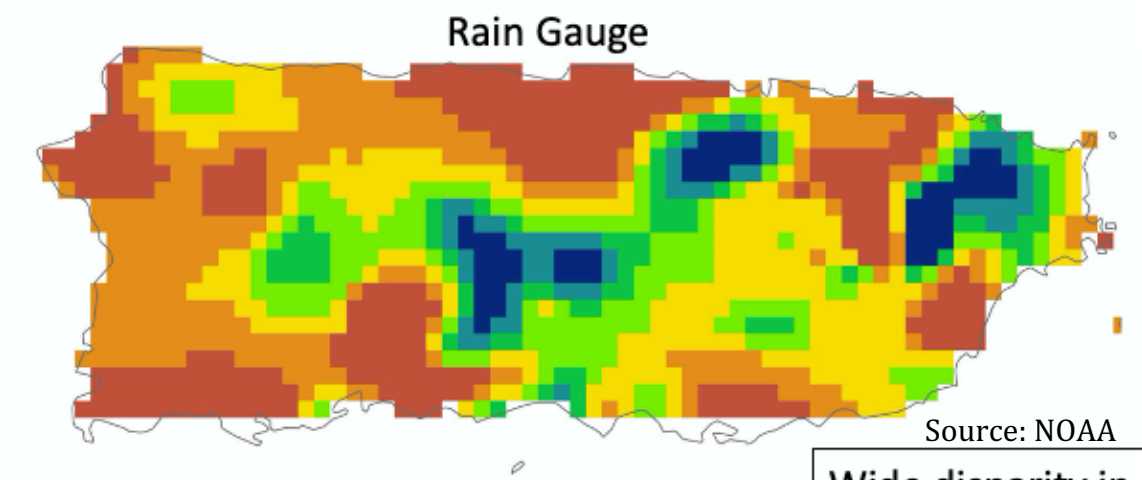
Points to Consider

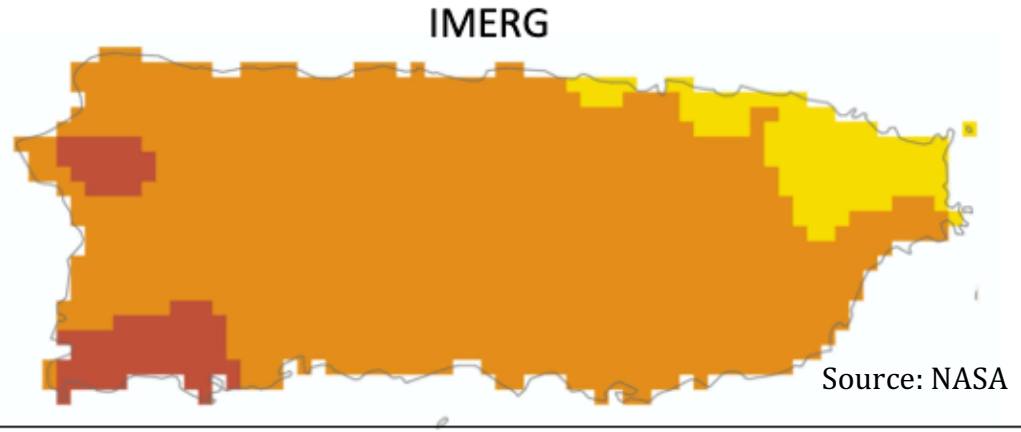
- Topography enhances rainfall production.
- Rainfall measurement systems may show significant variability.
- Rainfall can be used as a flood proxy in addition to or in the absence of large area-wide inundation estimates.
- Rainfall is the primary input to hydrologic models which are used to produce estimates of flood inundation and landslide density.

Total Rainfall for Hurricane Irma 5-7 September 2017 (4km)









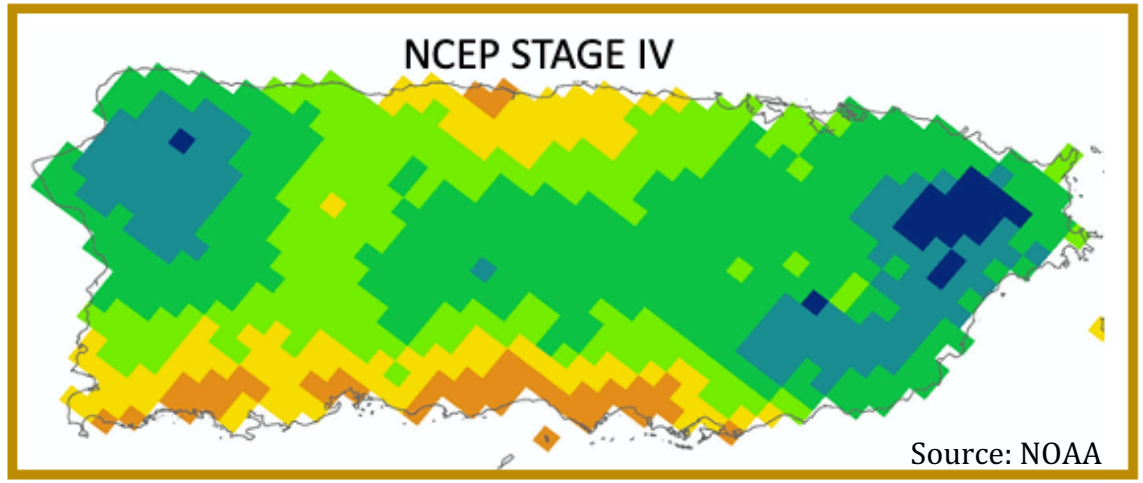
Total Rainfall (inches)

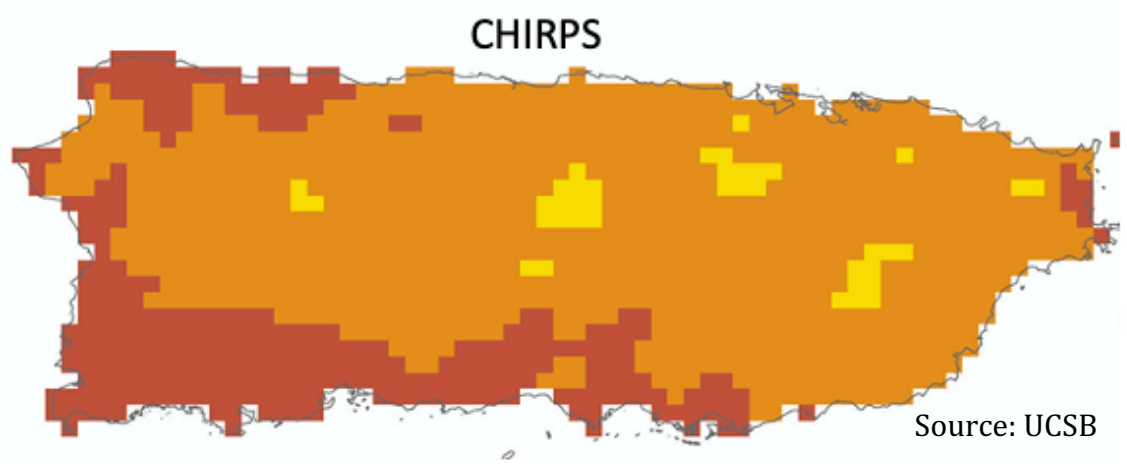
2-4 | 4-6 | 6-8 | 8-10 | 10-12 | 12-16 | 16+

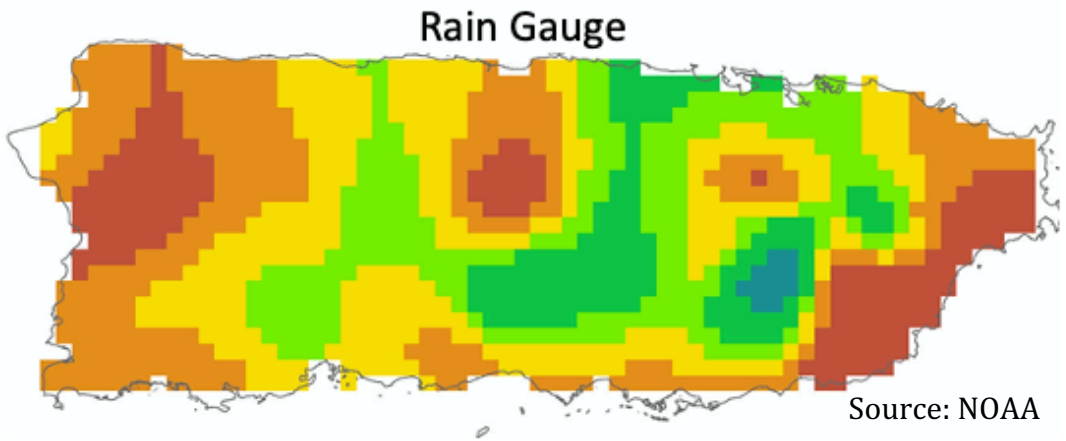
1in. = 25.4 mm

Wide disparity in rainfall measurements. Satellite systems do not capture same intensity and topographic influences despite merging of in situ data. ***However, biases appear to be much less than for H. Maria, especially in coastal areas.***

Total Rainfall for Hurricane Maria 19-21 September 2017 (4km)







Rainfall (inches)

5-10 | 10-15 | 15-20 | 20-30 | 30-40 | 40-60 | 60+

1in. = 25.4 mm

Wide disparity in rainfall measurements. Satellite systems **seemingly** fail to capture intensity and topographic influences despite merging of in situ data and show weaker spatial variability.