NCST Technical Investigation of Hurricane Maria (Puerto Rico)

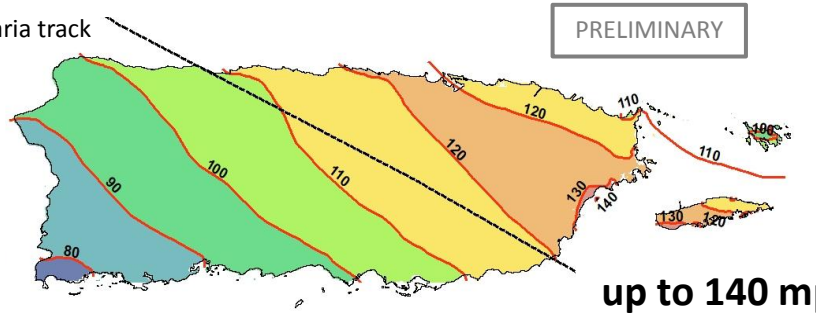
Hazard Characterization Project

Project Leaders: DongHun Yeo and Scott Weaver

Background: Hazards from Hurricane Maria (HM)

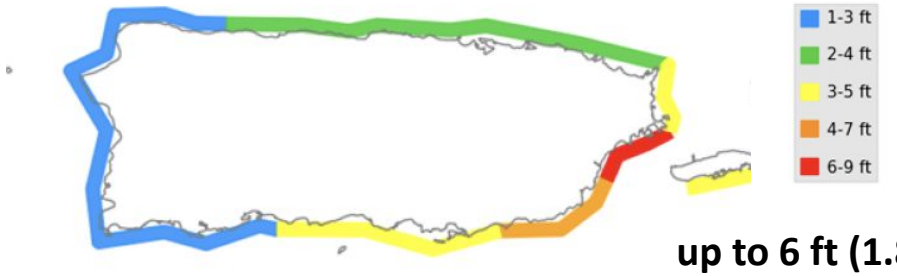
- Puerto Rico was subjected to multiple hazards due to HM: extreme winds, coastal inundation, and heavy rainfall, causing inland flooding and landslides
- Accurate characterization of multiple hazards is of fundamental importance for projects across the HM program
- HM caused extensive damage to instrumentation, introducing significant challenges in hazard quantification
- A combination of measurements and modeling is required to characterize spatial and temporal variation of hazards

Peak gust wind speed (flat terrain)



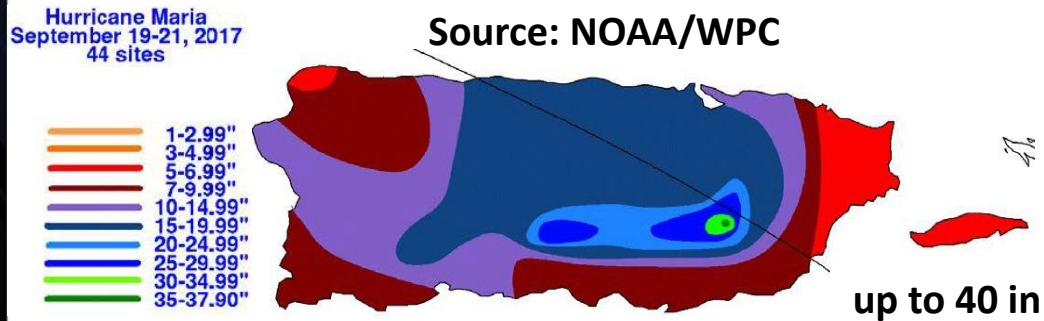
up to 140 mph (63 m/s)

Coastal inundation above ground level
Source: NOAA/NHC



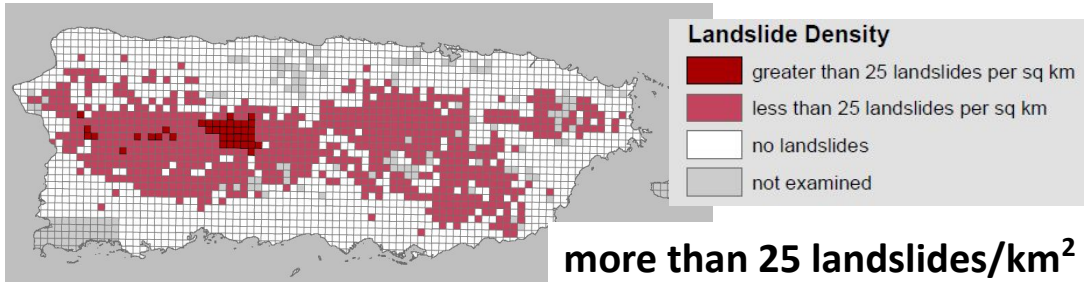
up to 6 ft (1.8 m)

Total rainfall accumulation
Source: NOAA/WPC



up to 40 in (100 cm)

Density of landslide sites
Source: USGS



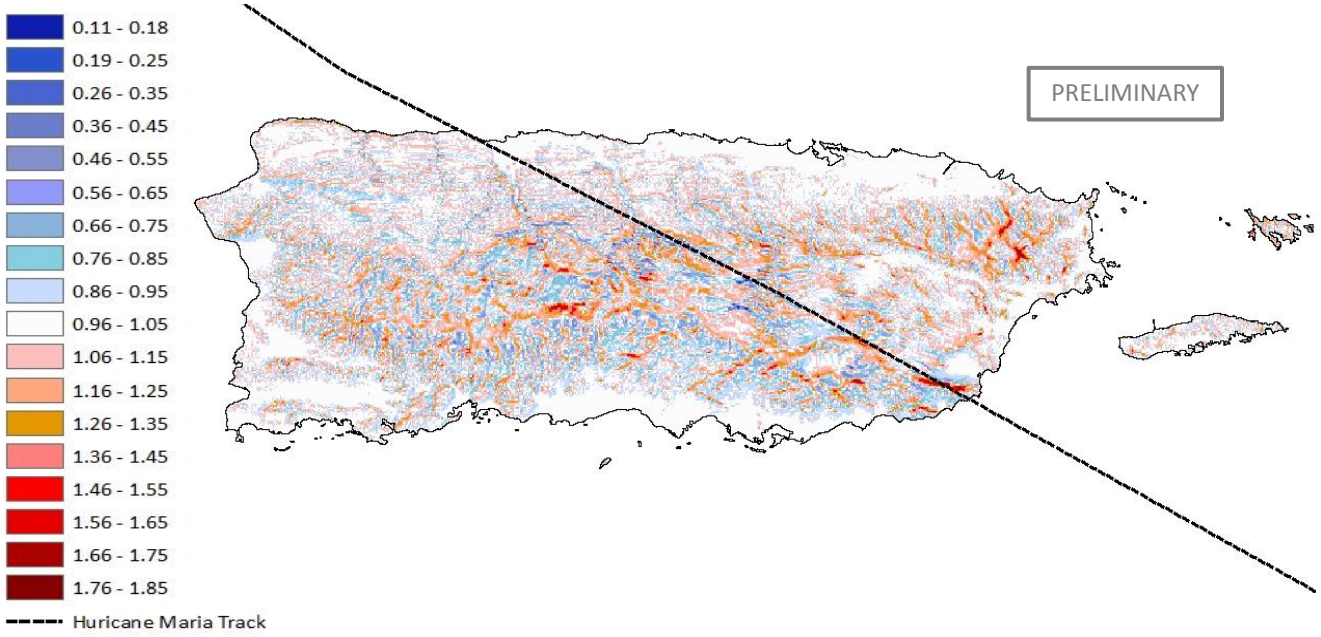
more than 25 landslides/km^2

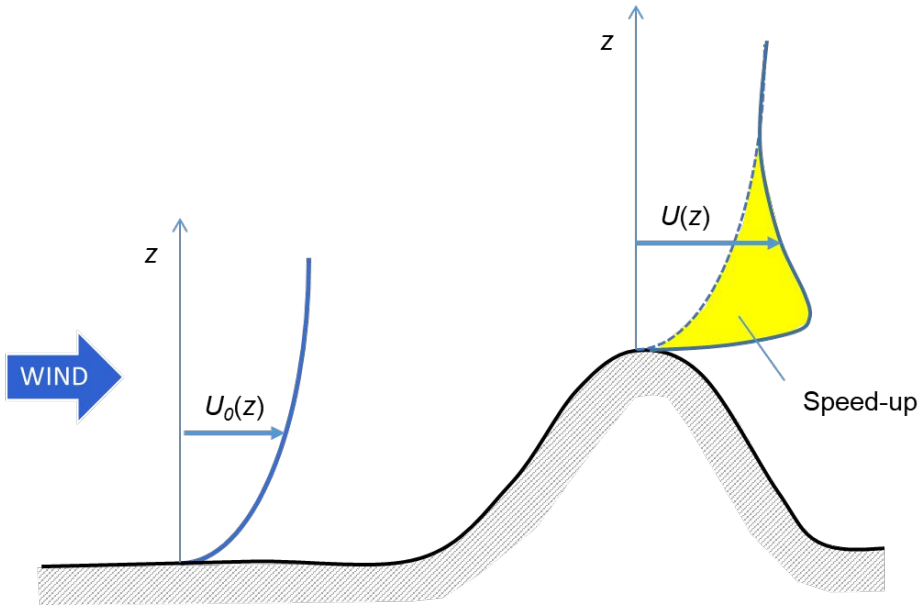
Wind Hazard

Motivation: Characterizing Topographic Speed-Up

- Preliminary analysis showed that Puerto Rico's mountainous topography could increase peak gust wind speeds by as much as 80 % when compared to the same weather pattern over flat terrain
- Quantifying this "**topographic speed-up**" is important in order to have an accurate understanding of wind loads experienced by buildings and infrastructure

Topographic Speedup Factor (TSF) at 10 m elevation





$$\text{TSF}(z) = \frac{\text{Peak gust speed with topo. corrections, } U(z)}{\text{Peak gust speed without topo. corrections, } U_0(z)}$$

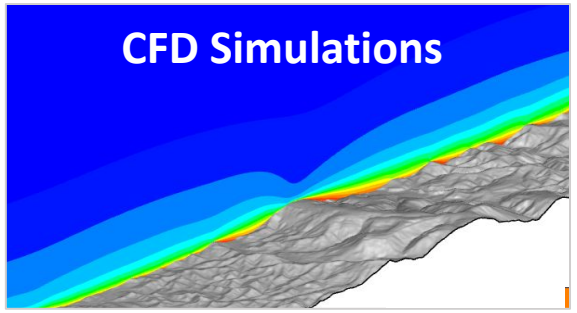
Wind Hazard

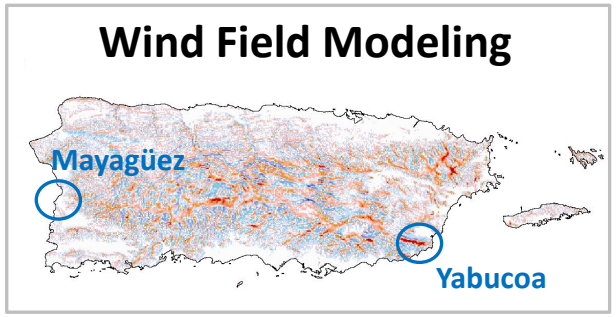
Objective

- Characterize the wind environment associated with Hurricane Maria's impact on Puerto Rico, including topographic effects

Project Plans

- Evaluate wind speed-up effects associated with Puerto Rico's topography using wind tunnel testing in conjunction with field measurements and Computational Fluid Dynamics (CFD) simulations
- Develop a hurricane wind-field model that accurately characterizes the wind environment associated with Hurricane Maria's impact on Puerto Rico, including topographic effects





Recent Progress: Wind Tunnel Testing

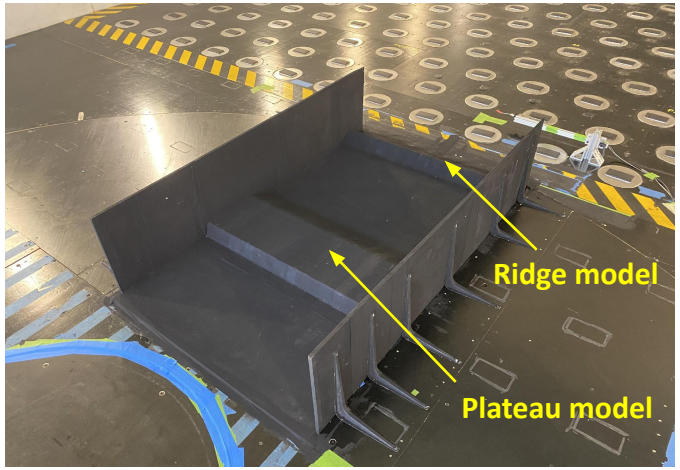
Contract with University of Florida to support wind tunnel testing tasks: model fabrication and testing

Wind tunnel measurements:

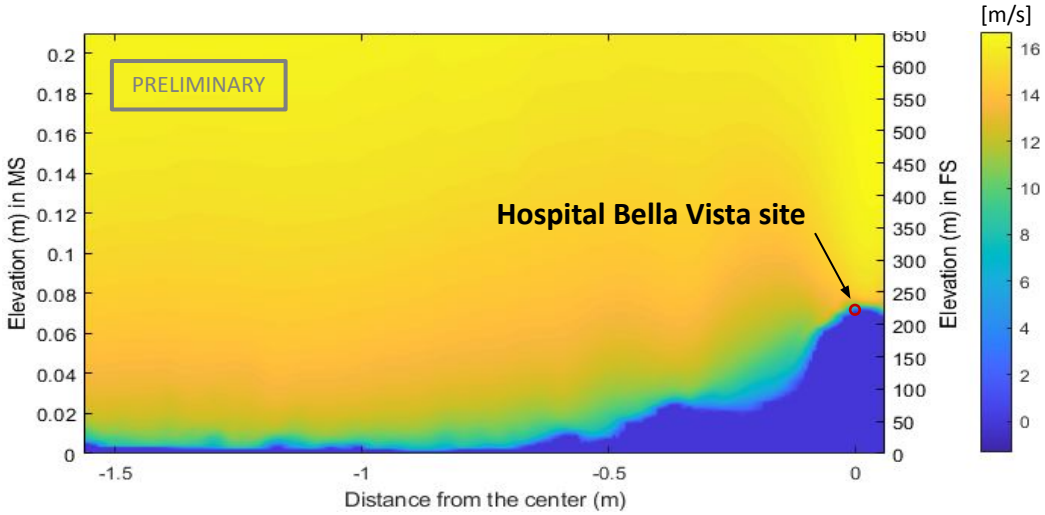
- Completed testing of generic ridge and plateau models with smooth surfaces
- Completed additional Cobra probe profile measurements over bare turntable to inform calculation of topographic speedup factors

Data processing and analysis:

- Completed post-processing of PIV (Particle Image Velocimetry)/Cobra probe data from Mayagüez topographic model to develop time series of 3D velocity across the measurement domain, along with summary statistics



Generic topographic models with smooth surfaces

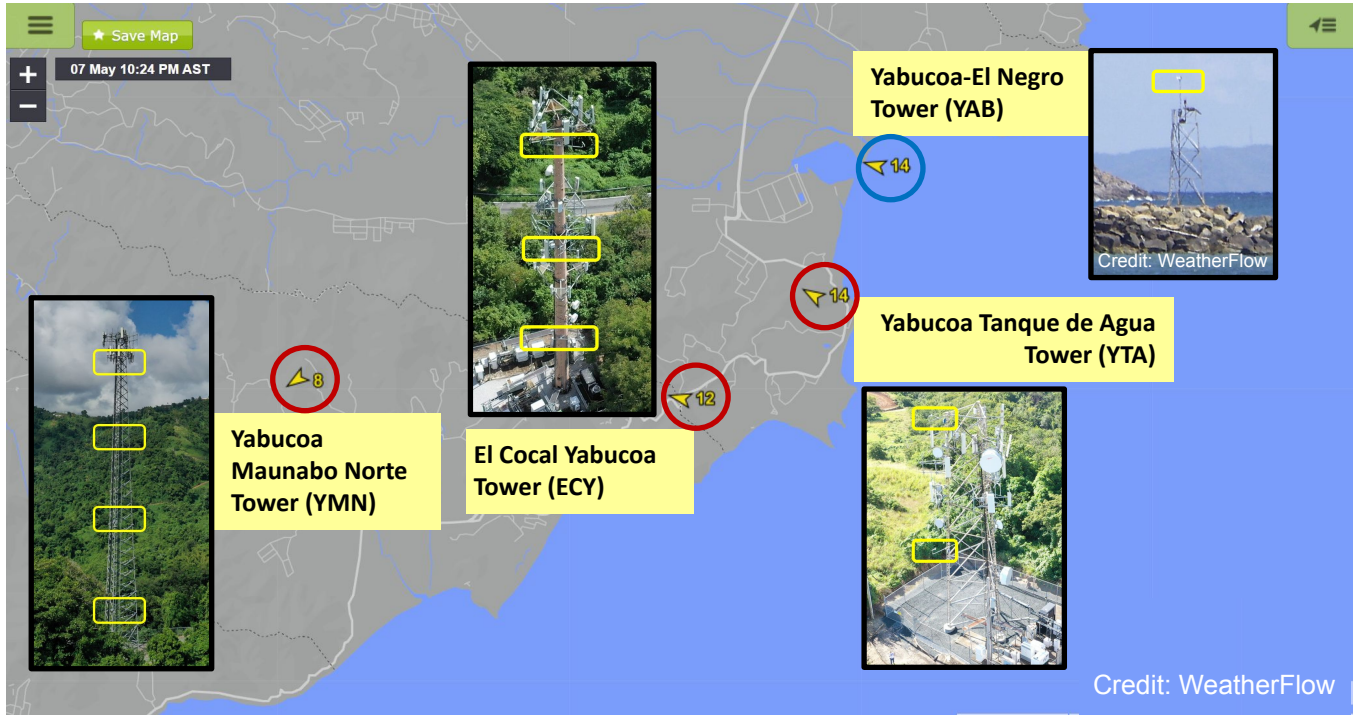


Time-avg. longitudinal wind velocity data of the Mayagüez model (wind direction 230°)

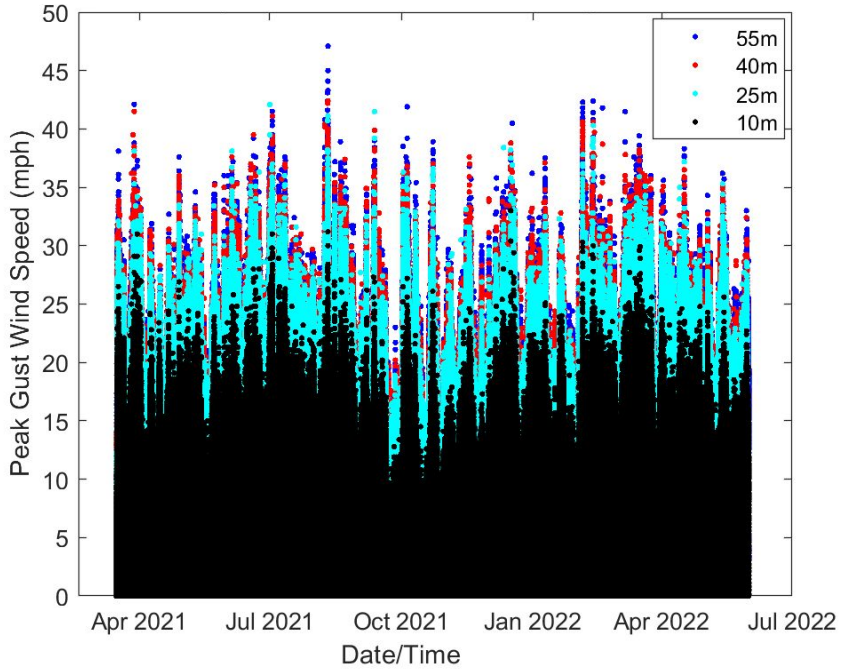
Recent Progress: Field Measurements

Contract with University of Florida/WeatherFlow to support anemometer installation/maintenance and data recording

- Completed collection of one-year long continuous gust wind speed/direction data from all anemometers on three towers in Yabucoa region since March 2021
- Reviewed the collected data for quality assurance and quality control
- Developed software tools to read raw measurement data, calculate statistics at synchronized time intervals, and store the resulting data in a format that facilitates analysis
- Started 2nd year data acquisition in March 2022



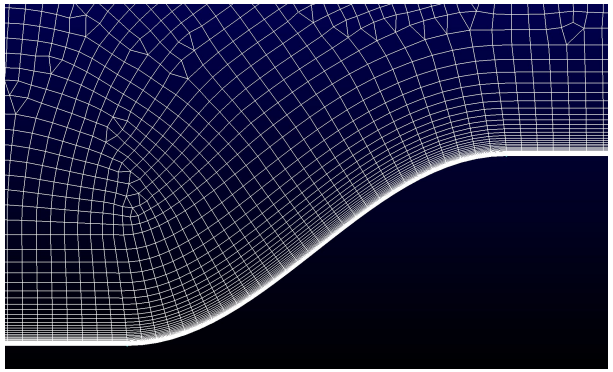
Three communication towers [YMN, ECY, YTA]
(+ one weather station tower [YAB]) for field measurements



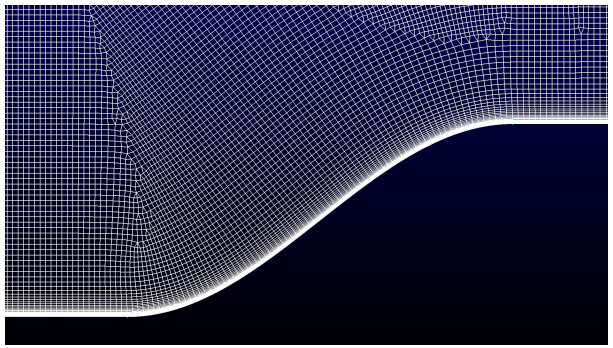
Field measurements from Tower YMN: horizontal gust wind (March 2021 - May 2022)

Recent Progress: CFD Simulations*

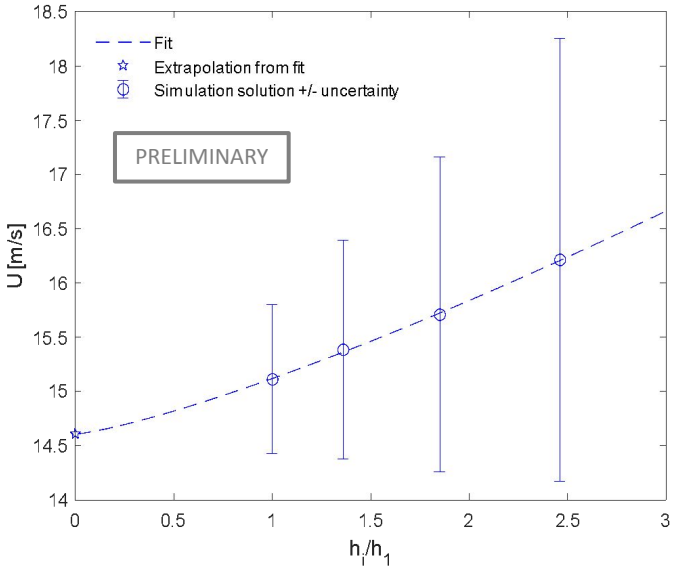
- Performed quantification of numerical error uncertainties in simulation results (generic cases)
- Developed and implemented a canopy model to account for effects of forest on flow field above complex topography
- Collected vegetation information (tree height, leaf area index, leaf area density profile) from satellite/LiDAR datasets for simulating flow above forest in Yabucoa



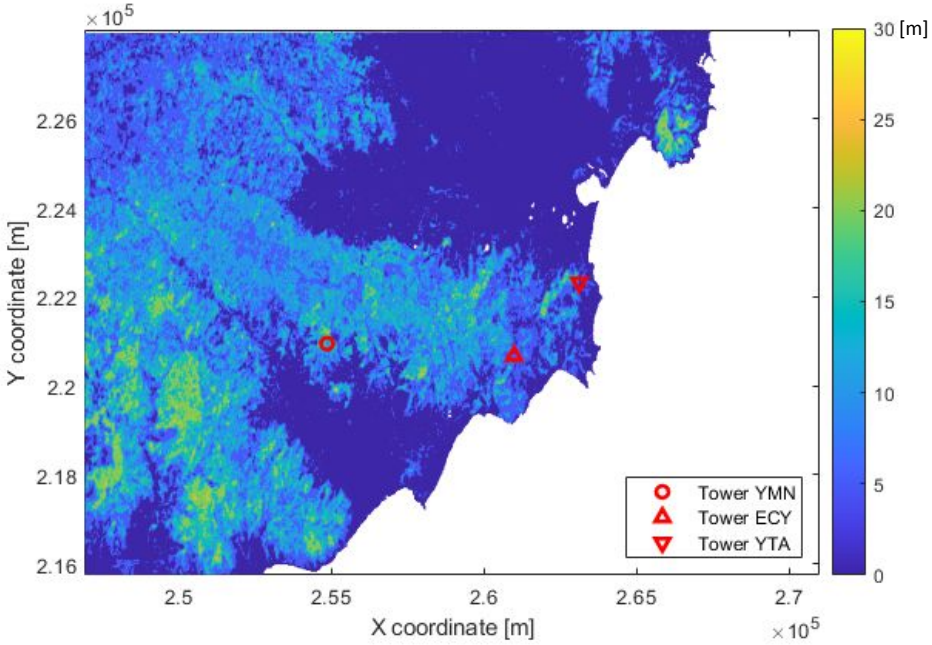
Coarsest grid



Finest grid



Simulation results and their uncertainties as a function of grid refinement



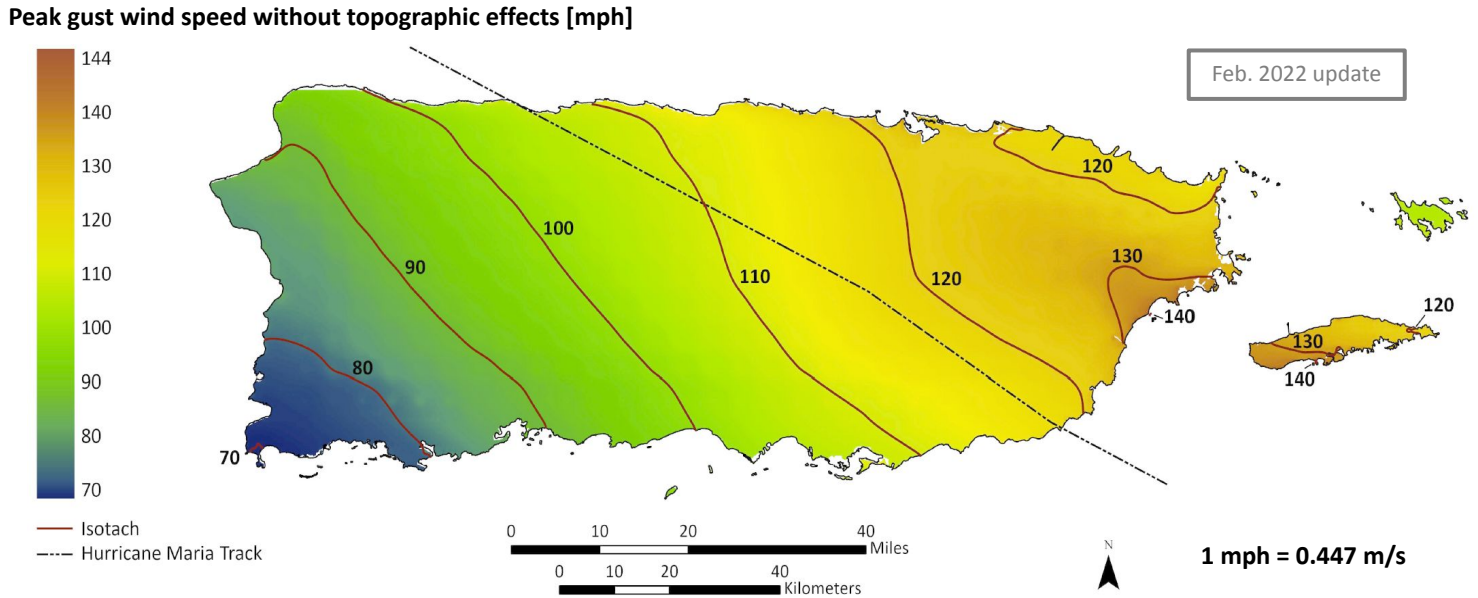
Tree canopy height in Yabucoa
Source: NASA

* OpenFOAM (open source) CFD code is used

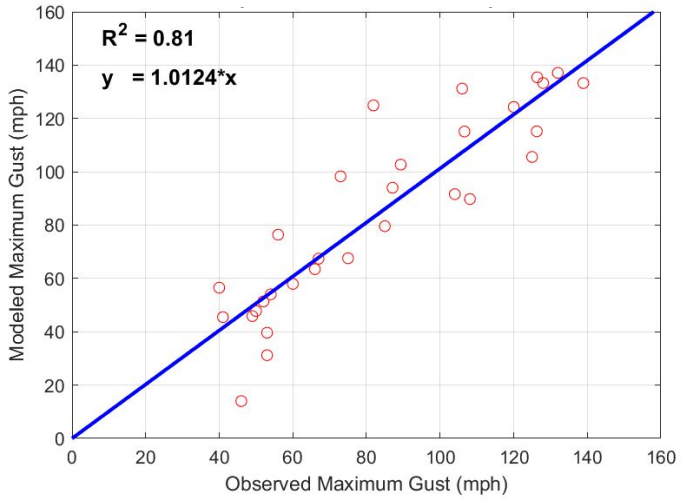
Recent Progress: Wind Field Modeling

Contract with Applied Research Associates to support wind field modeling tasks

- Completed improvements to Hurricane Maria wind-field model including:
  - Development and implementation of an automation procedure for optimization of model fitting to observed data
  - Incorporation of additional surface-level meteorological observations
  - Quantification of uncertainty associated with parameters of the wind-field model
- Model provides time histories of wind speed and direction across Puerto Rico during Hurricane Maria



Updated peak gust wind speed map (not including topographic speedup effects)



Comparison of max. gust wind speed: Model data vs. Observations

Wind Hazard: Next Steps

Wind tunnel testing

- Complete post-processing and curation of the exp. data from generic and Yabucoa topographic models
- Analyze the wind tunnel data and complete the uncertainty quantification of the measurements

Field measurements

- Measure anemometer orientation for improvement of accuracy in wind direction measurements
- Continue data collection for 2nd year (~ March 2023)
- Analyze the field data for topographic speed-up effects in Yabucoa

CFD

- Perform simulations accounting for the effects of forest cover on wind flow over topography in Yabucoa
- Complete the validation of CFD models against wind tunnel testing data and field measurements

Wind field model

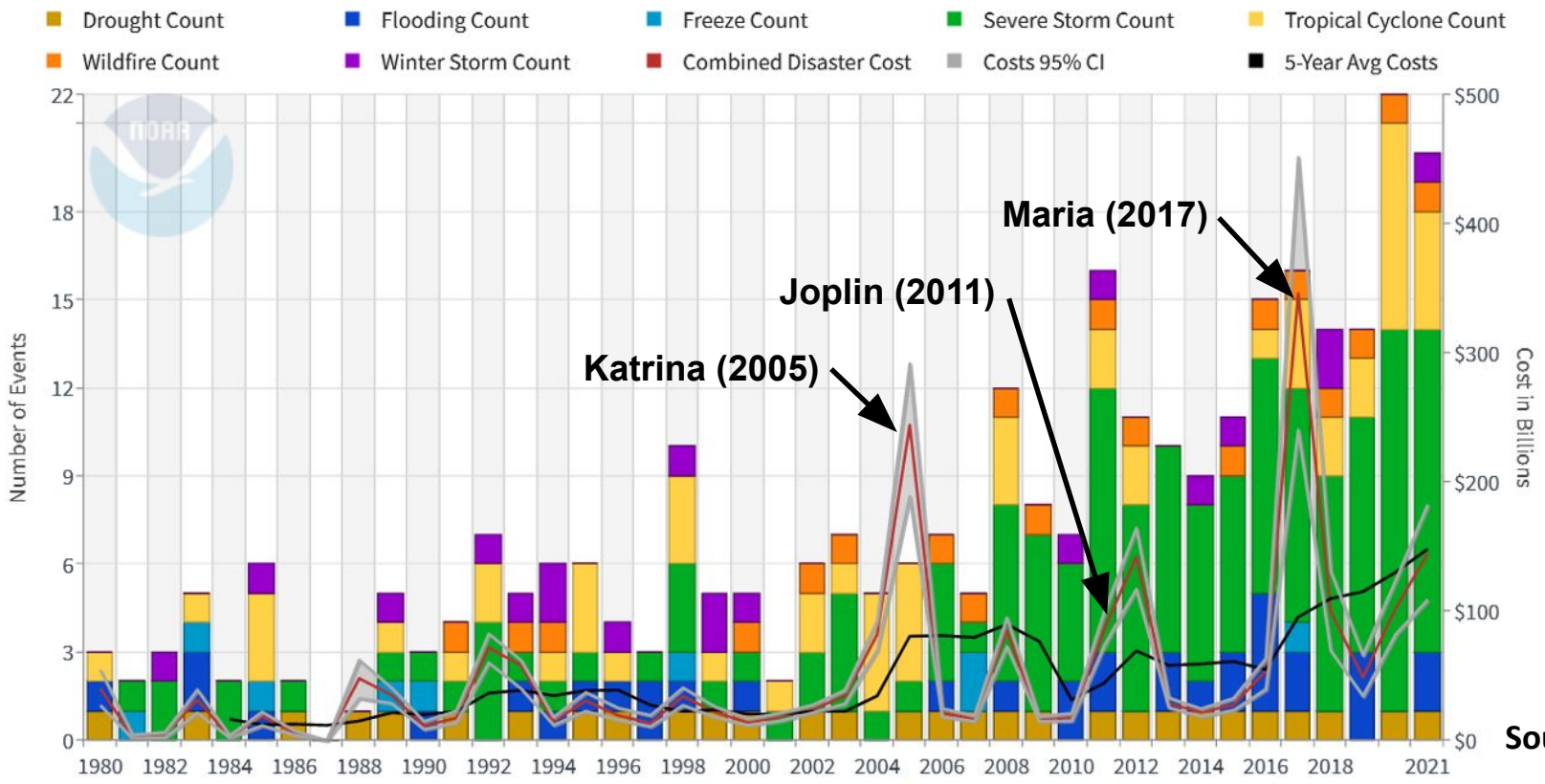
- Complete updates to topographic effects model based on comparisons with wind tunnel measurements
- Complete development of final wind field model to provide time histories of wind speed and wind direction across Puerto Rico for the duration of Hurricane Maria

Other Hazards

Motivation: Characterizing Wind and Water Impacts

- Impacts from other hazards such as storm surge or inland extreme rainfall cause the greatest economic damages and loss of life
- Extreme amounts of rainfall were observed across the entirety of Puerto Rico during Hurricane Maria
- Rainfall is a primary source of both flooding and landslides. Accurate rainfall measurements play an important role for post-windstorm investigations of other water hazards

U.S. Billion-Dollar Weather and Climate Disaster Events 1980-2021 (CPI-Adjusted)



Source: NOAA/NCEI

Other Hazards

Objective

- Document other hazards associated with the hurricane, including storm surge, rainfall, flooding, and landslides

Project Plans

- Conduct outreach to other federal agencies and organizations regarding data sources and modeling capabilities that may be available to better characterize the hazards and their spatial and temporal variation
- Assess an array of in-situ and remotely-sensed rainfall observations to better understand measurement platform differences as a function of event severity and/or other relevant parameters (e.g., topography)
- Evaluate the sub-daily rainfall evolution as a function of measurement platform and event severity to better understand the evolution of measurement biases and temporal relationships with the primary wind hazard

Recent Progress: Rainfall Data (1/3)

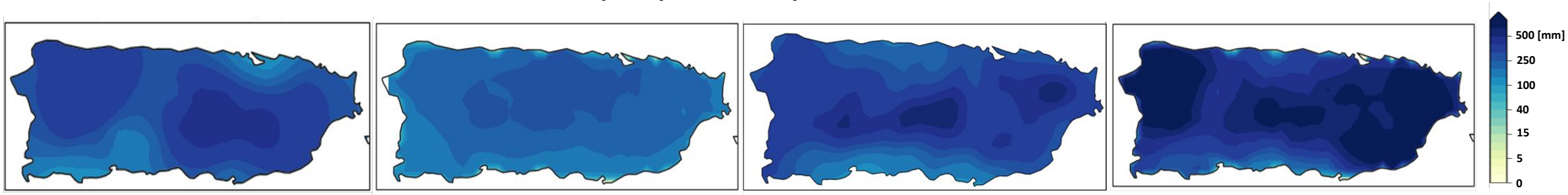
Data sources identified*

- **Pre-Hurricane Maria maps**: Precipitation frequency maps (NOAA, 2008)
- **Hurricane Maria data**:
  - Ground data: Rain gauges (NWS, USGS), NCEP Stage IV
  - Satellite data: IMERG, CMORPH-CDR, PDIR-NOW, PERSIANN-CCS, CHIRPS
  - Hindcast data: WRF (Weather Research and Forecast) model simulation
- **Post-Hurricane Maria maps**: N/A

Recent progress

- Collected 5 additional datasets (underlined above):
  - In-situ data: 5-min USGS gauge station data from San Juan Weather Forecast Office, NOAA (Mr. José Alamo)
  - Three remotely-sensed satellite datasets
  - 5-min WRF hindcast simulation data

Total precipitation: Sept. 19-21, 2017

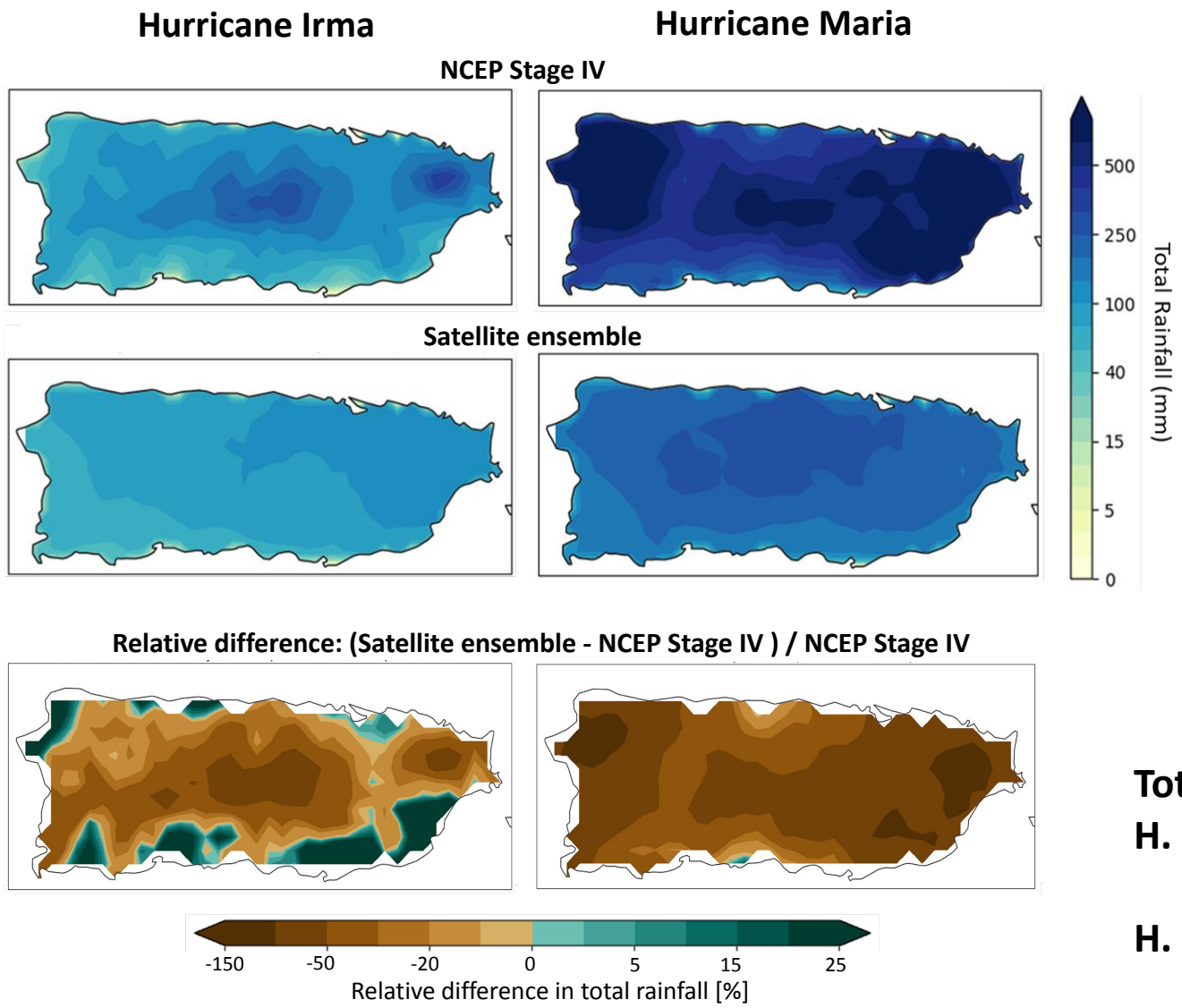


Gauge (USGS and NWS) | **Satellite ensemble** | **Simulation (WRF)** | **NCEP Stage IV ("Gold" standard)**

* Underlined for new data sources

Recent Progress: Rainfall Data (2/3)

- Performed rainfall analysis: Hurricane Irma vs. Hurricane Maria



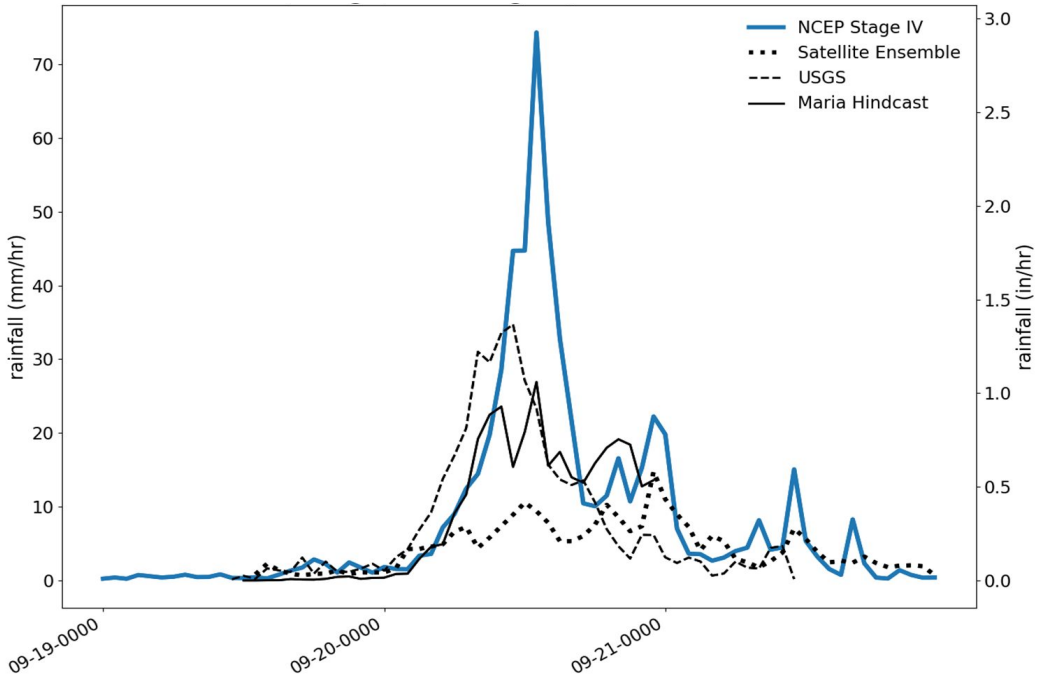
- H. Maria produced more rain across Puerto Rico compared to H. Irma
- The satellite ensemble significantly underestimated the rainfall for H. Maria relative to NCEP Stage IV, but the agreement was better for H. Irma

Total precipitation:
H. Irma (Sep. 5-7, 2017)
vs.
H. Maria (Sep. 19-21, 2017)

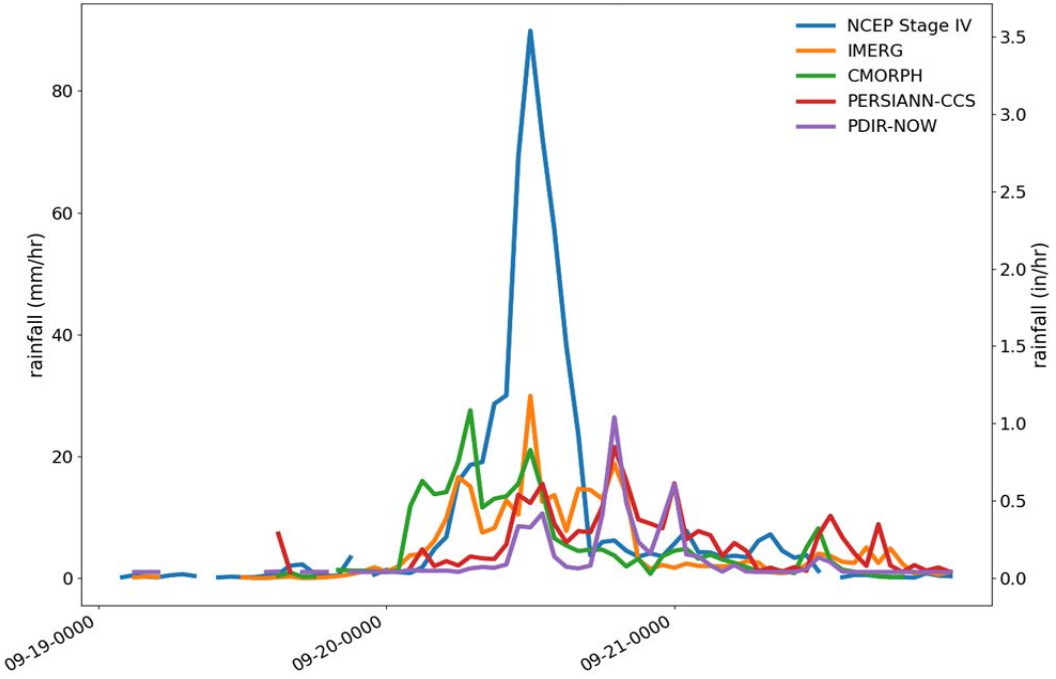
Recent Progress: Rainfall Data (3/3)

- Assessed hourly precipitation data
  - Average across Puerto Rico
  - Average for each study region: San Juan, Utuado, Caguas, and Humacao

Across Puerto Rico



San Juan Region



Hourly precipitation: Sept. 19-21, 2017

Recent Progress: Flood Data

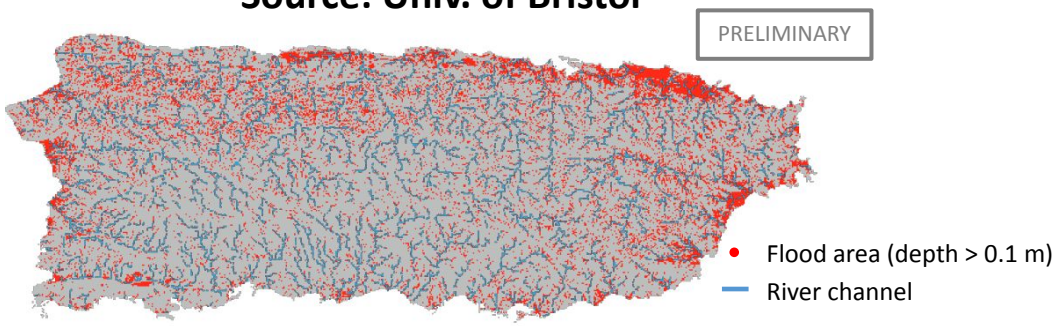
Data sources identified*

- **Pre-Hurricane Maria map**: Flood risk map (FEMA 2009-2017)
- **Hurricane Maria data:**
  1) Storm surge: Estimated storm surge inundation (NOAA/CERA 2017)
  2) Inland Flood: University of Bristol (in progress)
- **Post-Hurricane Maria map**: Flood risk maps (FEMA 2021), National storm surge hazard maps (NOAA 2018)

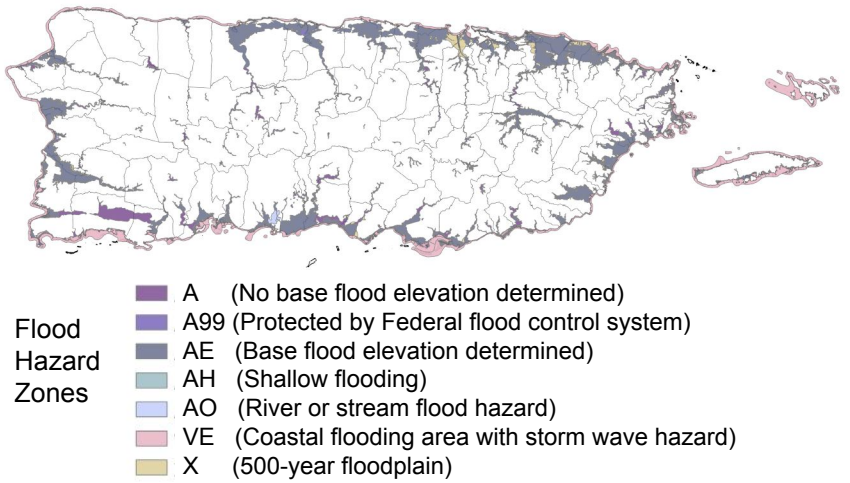
Recent progress

- Provided rainfall estimates to collaborators at University of Bristol as input for inland flood modeling for Hurricane Maria (underlined above)
- Collected post-hurricane Maria flood risk dataset (underlined above) and shared with the broader team to support analyses

Estimated inland flooding area (H. Maria)
Source: Univ. of Bristol



Post-Hurricane Maria flood risk map (100-year floodplain)
Source: FEMA



* Underlined for new data sources

Recent Progress: Landslide Data

Data sources identified*

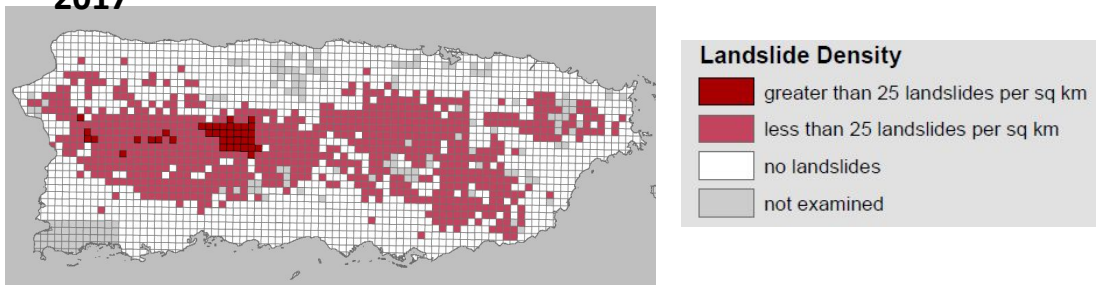
- Pre-Hurricane Maria maps: Landslide susceptibility map: USGS (2012)
- Hurricane Maria data: USGS (2017, 2019)
- Post-Hurricane Maria landslide susceptibility map: USGS (2020)

Recent progress

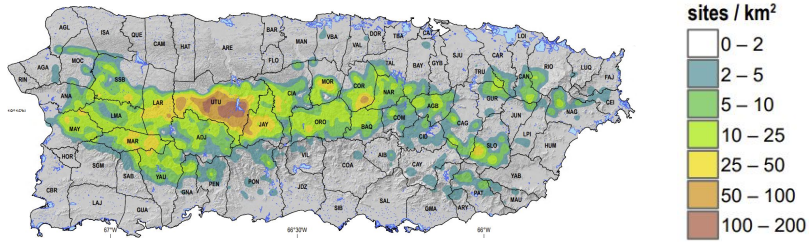
- Collected additional dataset on Hurricane Maria landslide density (underlined above)
- Compiled pre- and post-Hurricane Maria landslide risk maps and shared with the broader team to support analyses

Landslide density during H. Maria (Source: USGS)

2017

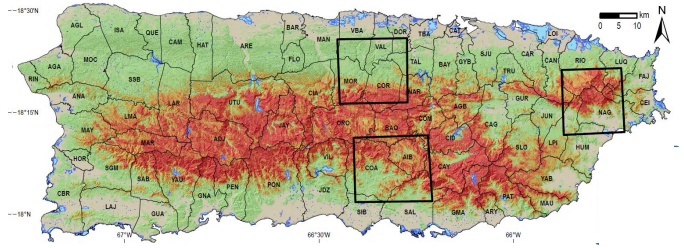


2019

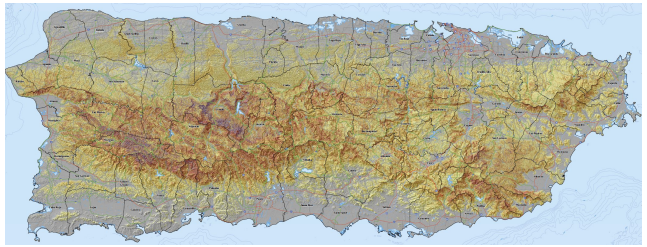


Landslide susceptibility maps (Source: USGS)

Pre-H. Maria (2012)



Post-H. Maria (2020)



* Underlined for new data sources

Other Hazards: Next Steps

Outreach for data

- Continue identifying data sources and modeling for other hazards

Rainfall Data

- Finalize comparative analysis of ground-based and space-based rainfall measurement platforms for Hurricane Maria
- Conduct ensemble WRF modeling of Hurricane Maria to augment measurements and characterize variability in rainfall estimates.
- Conduct climatological analysis of rainfall data sets to contextualize the historical magnitude of Hurricane Maria's rainfall

Flood Data

- Evaluate the impact of variable rainfall measurements on flood estimates for Hurricane Maria using flood modeling methodologies in collaboration with academic scientists

NCST Technical Investigation of Hurricane Maria's Impacts on Puerto Rico

Hazard Characterization Project

Project Leaders: DongHun Yeo (NIST) and Scott Weaver (NIST)

Project Team: Luis Aponte (Univ. of Puerto Rico at Mayagüez), Dereka Carroll-Smith (PREP Research Associate, Univ. of Maryland-College Park), Joel Cline (NOAA), Yunjae Hwang (PREP Research Associate, Johns Hopkins University), Marc Levitan (NIST), Joe Main (NIST), Cynthia Rivas (NIST)

Contractor Teams: Applied Research Associates, Univ. of Florida, WeatherFlow

Acknowledgement: Rameche Somassoundirame (former PREP Research Associate, Johns Hopkins University), University of Bristol (collaborator)