NIST National Construction Safety Team Investigation of Hurricane Maria

NCST Advisory Committee Meeting – June 14, 2023

Cross-Project Panel Theme 1: Hospitals

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NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Hospitals Theme: Motivation

- Hospitals play a critical role in emergency response and recovery
- Hospitals in Puerto Rico are designed using the same building codes and standards as in the mainland U.S.
- Hurricane Maria's impacts on hospitals included:
  - Damage to hospital buildings, including extensive nonstructural damage
  - Loss of supporting infrastructure, including power, water, transportation
- Damages to hospital buildings and supporting infrastructure affected:
  - Functionality of hospitals
  - Access to hospitals
- Hospital ***accessibility*** and ***functionality*** played a significant role in deaths associated with Hurricane Maria

Hospitals Theme: Integration of Data Streams

Critical Buildings

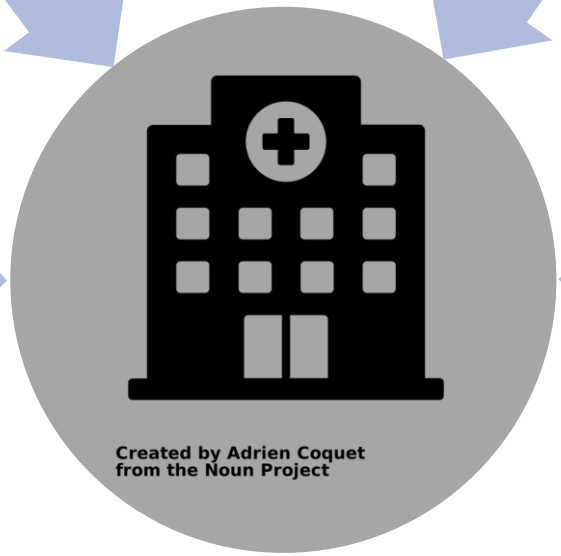
- Wind loads on buildings and rooftop equipment
- Damage to building components and contents
- Impacts on hospital functions

Morbidity & Mortality

- Causes of death
- Search for health care
- Damage to hospitals
- Disruption of hospital functions

Hazard Characterization

- Wind exposure, including topographic speedup
- Other hazards: rainfall, flooding, landslides



Recovery of Social Functions

- Damage to hospitals
- Disruption of services
- Recovery of services over time

Hospitals Theme: Integration of Analysis

Critical Buildings

What were the damages to buildings and impacts on supporting infrastructure?

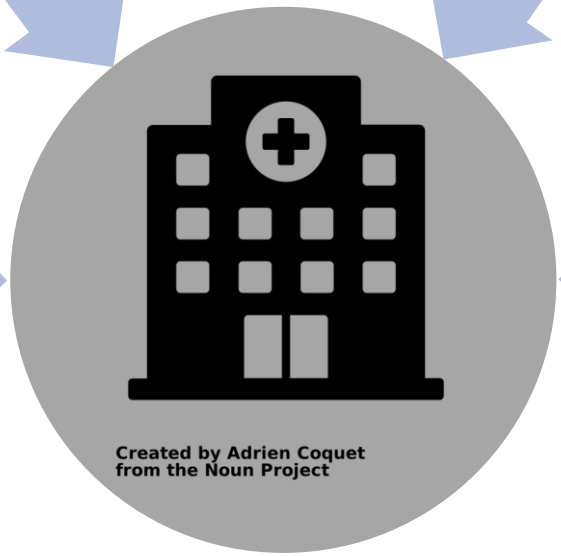
How did these affect hospital functions?

Morbidity & Mortality

What role did disruptions in hospital functions and access play in deaths?

Hazard Characterization

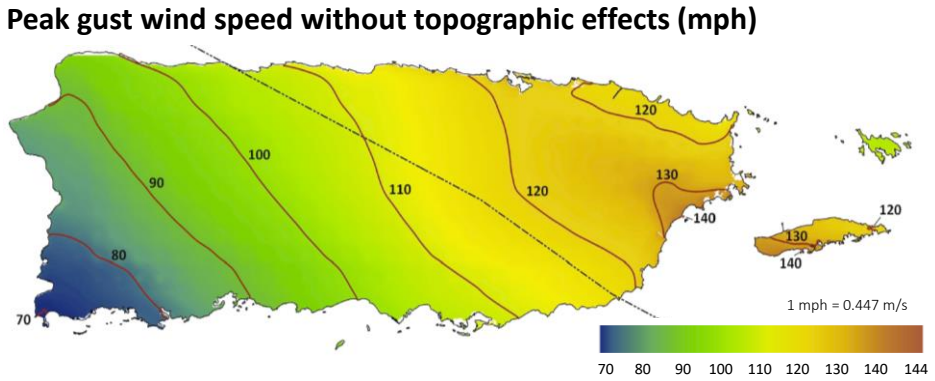
What were the hazard conditions at hospital sites?

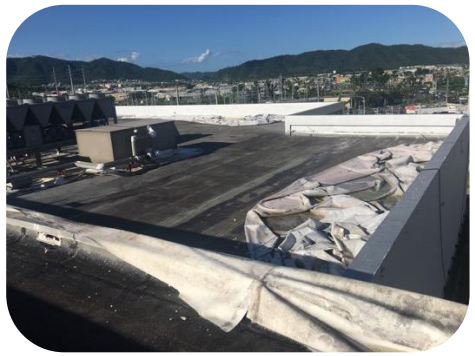


Recovery of Social Functions

How did hospital services recover over time following the hurricane?

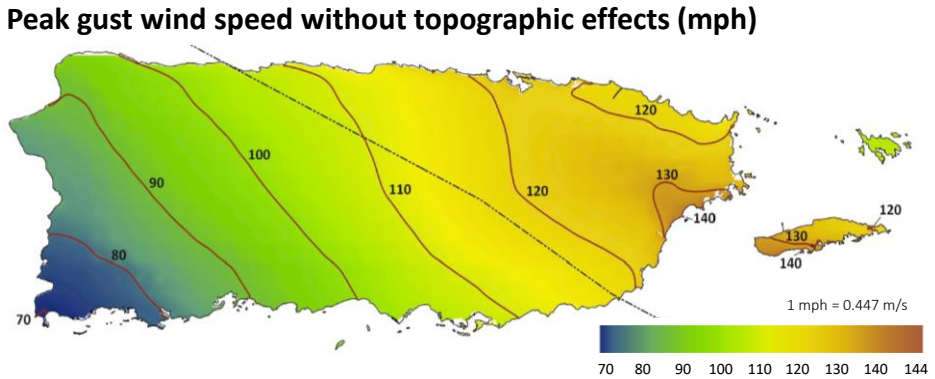
Hospitals Theme: Highlighted Projects





- Hazard Characterization
- Performance of Critical Buildings
- Morbidity & Mortality

Hospitals Theme: Highlighted Projects

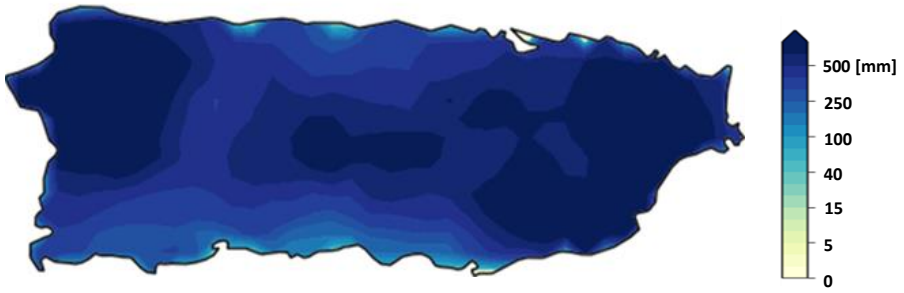


- **Hazard Characterization**
- Performance of Critical Buildings
- Morbidity & Mortality

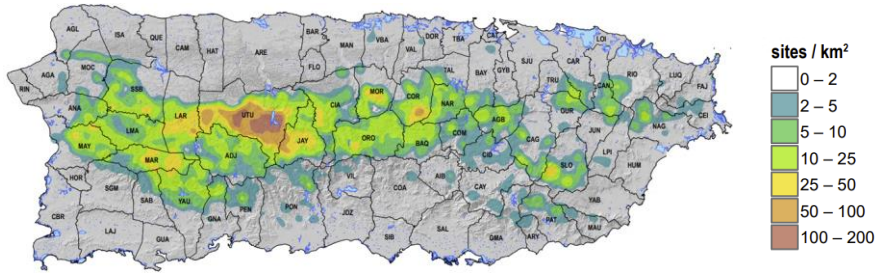
Hazard Exposure During Hurricane Maria

- Data collected on rainfall, inland flooding, landslides, and coastal inundation
- Hurricane Maria wind field model developed for Puerto Rico, including topographic effects

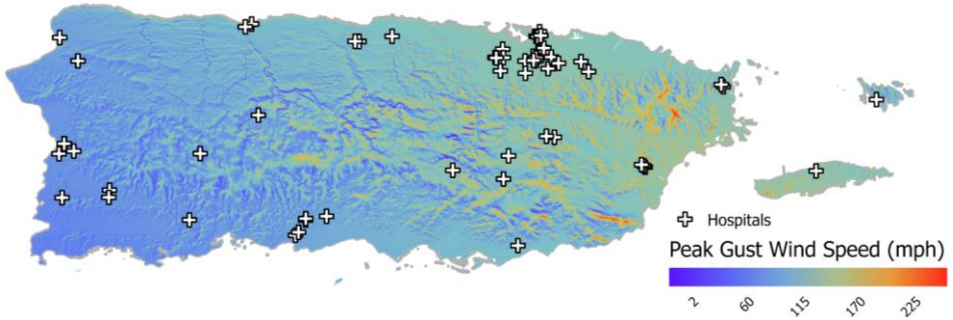
Total precipitation (NCEP Stage IV)



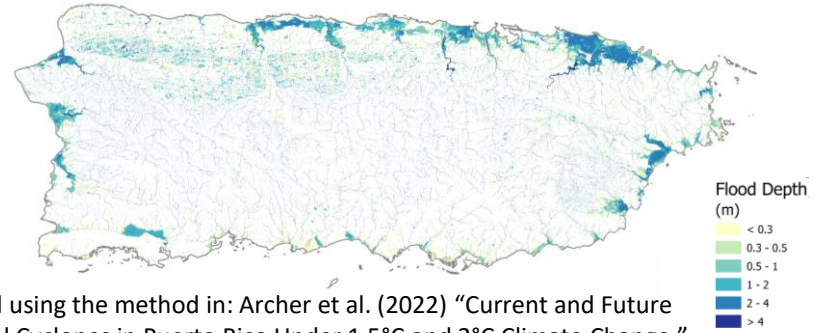
Landslide density (USGS)



Wind field model: peak gust speed with topographic effects

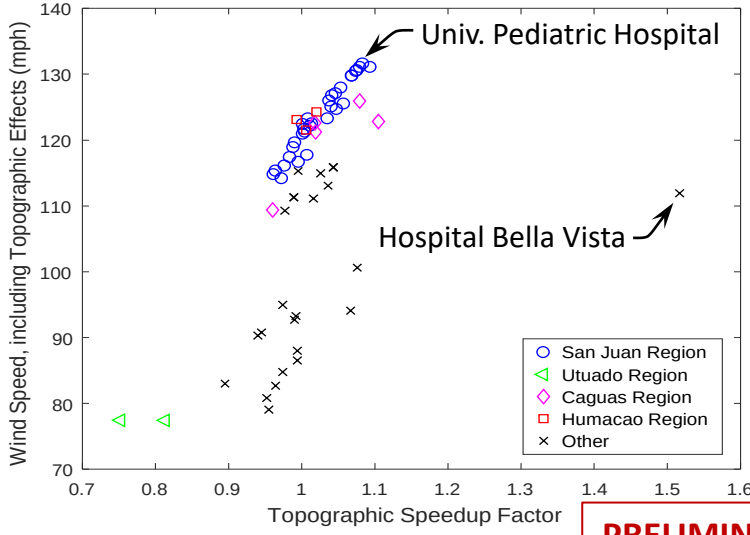


Flood depth modeling (Bristol U)



Flood depths computed using the method in: Archer et al. (2022) "Current and Future Flood Risk From Tropical Cyclones in Puerto Rico Under 1.5°C and 2°C Climate Change," *EGU General Assembly 2022*. <https://doi.org/10.5194/egusphere-egu22-2871>

Topographic Speedup Factor (TSF) at hospital sites



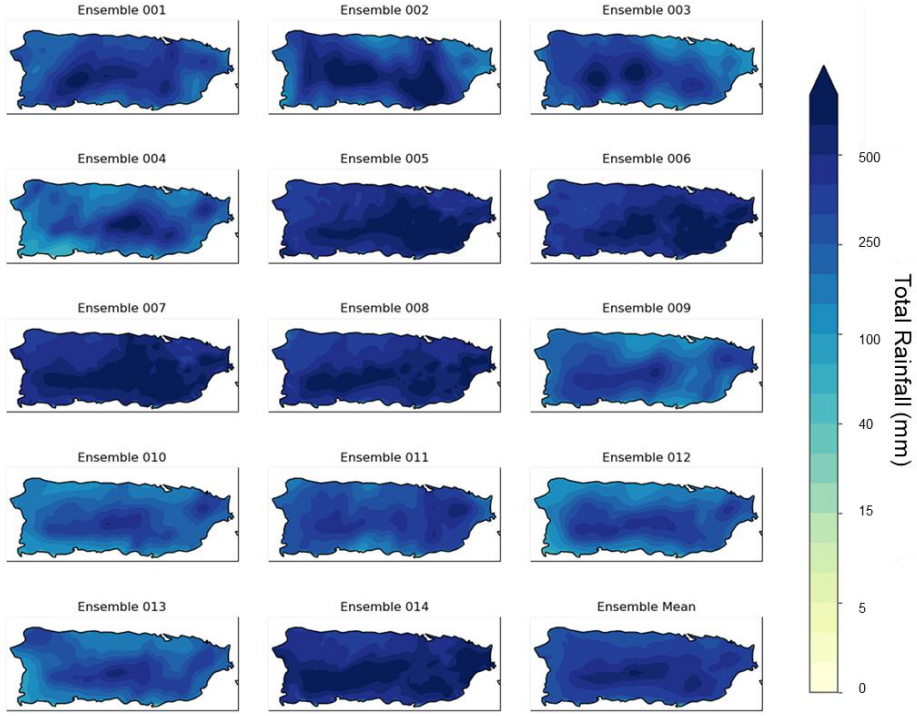
PRELIMINARY ANALYSIS

Analysis of Rainfall Data

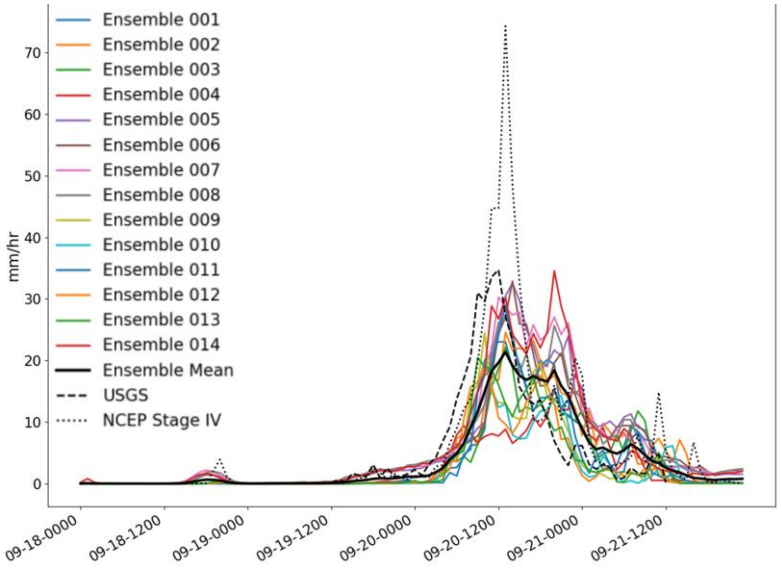
- Analyzed hindcast data from an ensemble of 14 high-resolution Weather Research and Forecasting (WRF) models and compared results to USGS rain gauges and NCEP Stage IV data
  - Ensemble mean tracks well with USGS gauge data
  - NCEP Stage IV rainfall exceeds USGS gauge data and WRF models
- Developed uncertainty model to understand the relationship between USGS gauge measurements and NCEP Stage IV data
  - Time-varying model indicates that the two datasets are well correlated initially but then deviate for some stations (likely associated with rain gauge failure)

Hurricane Maria WRF hindcast simulations

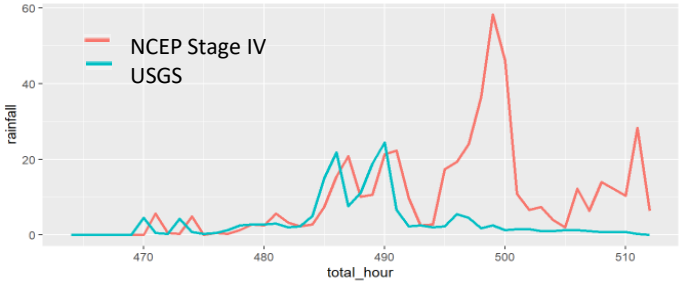
Performed by Prof. Aponte (UPRM) under NSF Award No. 1841979



Comparison of WRF ensemble results with island-wide averages of USGS rain gauge measurements and NCEP Stage IV data



Precipitation time-history at a station: USGS rain gauge vs. NCEP Stage IV



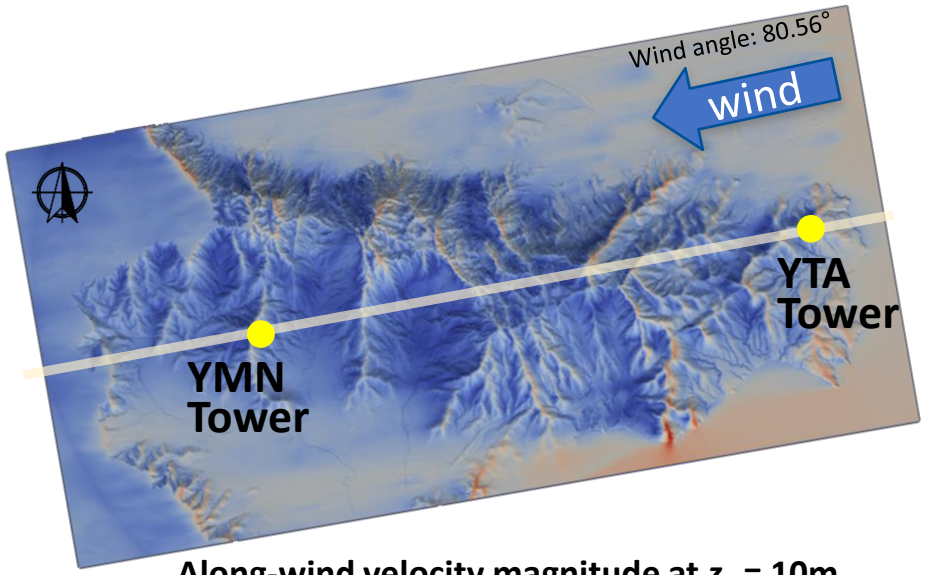
PRELIMINARY ANALYSIS

Field Measurements and CFD Modeling

- Completed 2nd year of continuous 3-s wind speed/direction measurements on 3 cell towers in Yabucoa region
- Repaired anemometers damaged by Hurricane Fiona and measured as-installed orientation angles of anemometers on YTA and YMN towers
- Performed CFD simulations using previously developed canopy model with satellite-based data on forest cover
- Compared flow field data from field measurements, wind tunnel tests, and CFD simulations

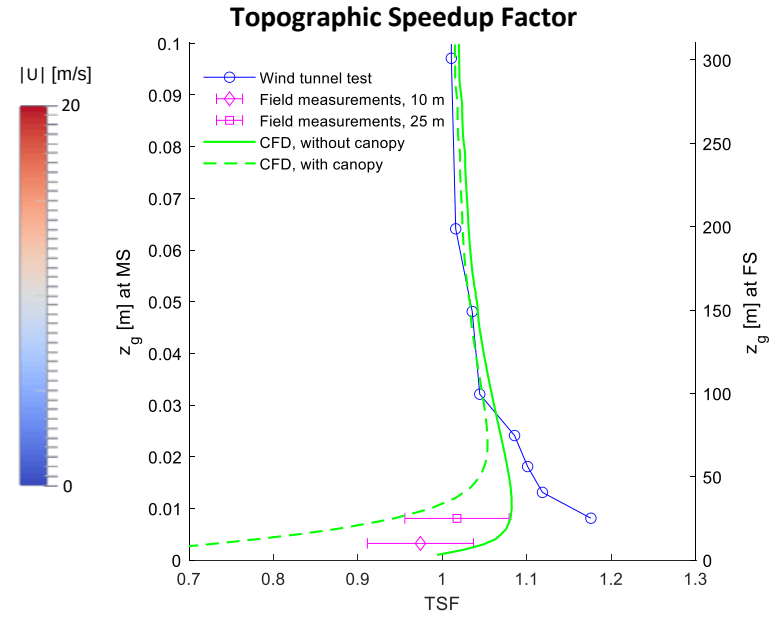
Anemometers as installed on YTA tower

CFD simulations of flow over topography and forest cover in Yabucoa region



Along-wind velocity magnitude at z_g = 10m

Comparison of field measurements, wind tunnel data, and CFD at YTA tower

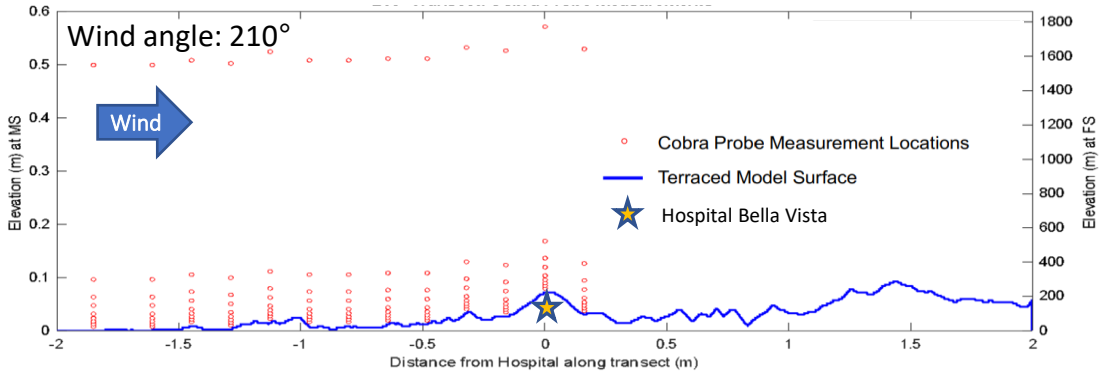


PRELIMINARY ANALYSIS

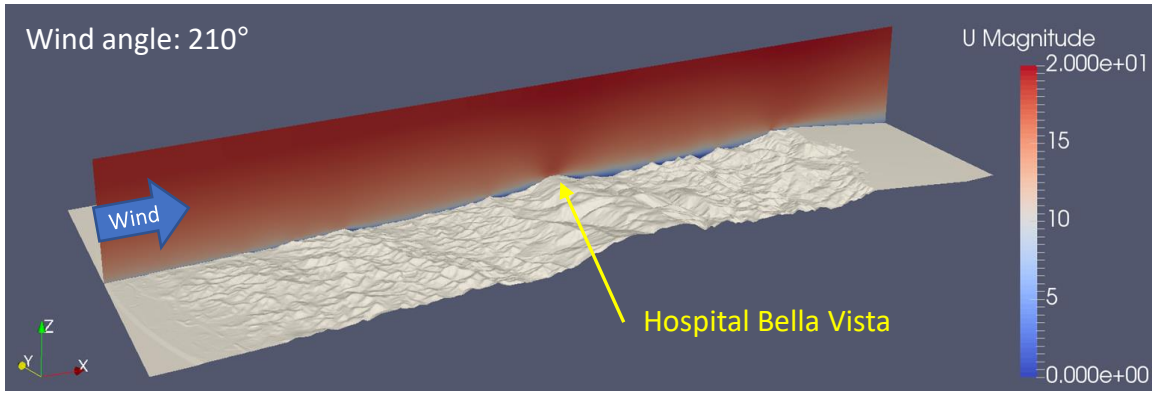
Wind Tunnel Testing and CFD Modeling

- Completed processing and curation of wind tunnel test data from topographic models
- Shared curated velocity probe data from PR topographic models with ARA to inform final wind field model
- Compared topographic speedup factor (TSF) from wind tunnel tests and Computational Fluid Dynamics (CFD)

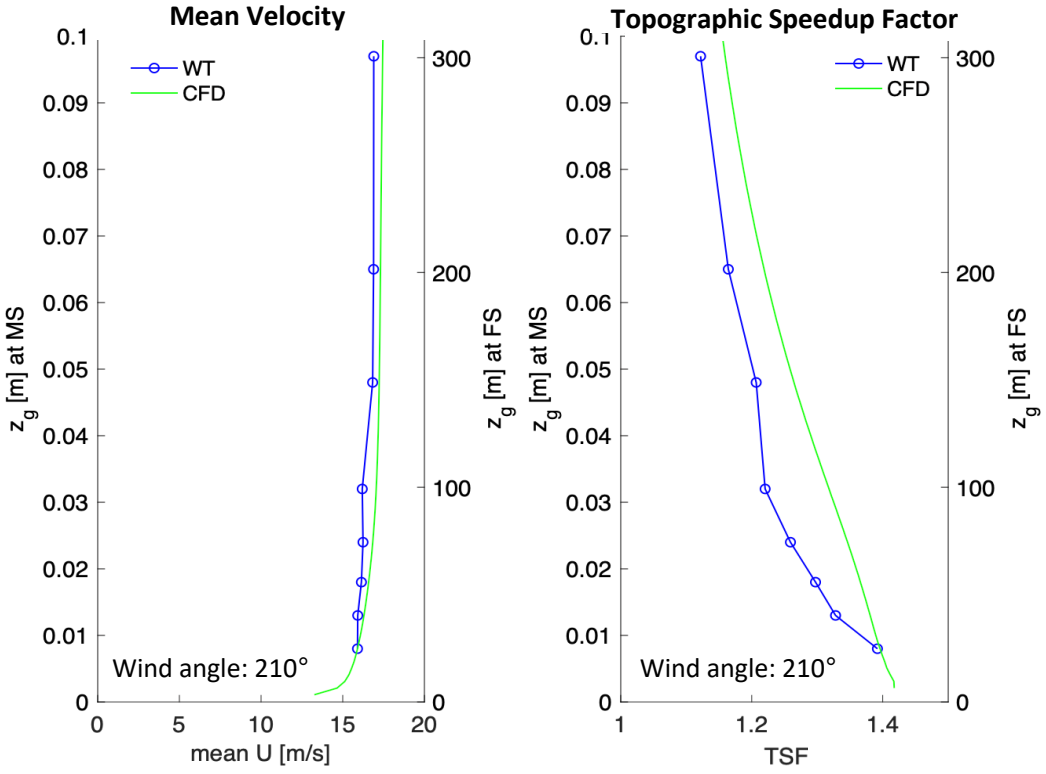
Wind Tunnel: Velocity probe measurement locations



CFD: mean along-wind velocity (U) magnitude

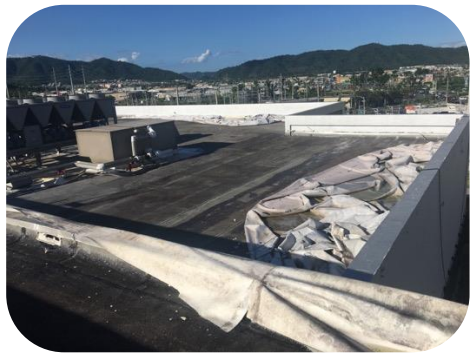


Topographic speedup at Hospital Bella Vista site



PRELIMINARY ANALYSIS

Hospitals Theme: Highlighted Projects



- Hazard Characterization
- **Performance of Critical Buildings**
- Morbidity & Mortality

Hospital Damage Observations

- Common themes at 5 selected hospitals: (preliminary observations from Phase 1 evaluations)
  - Roof cover damage
  - Rooftop equipment damage
  - Broken/damaged windows and doors
  - Significant water intrusion into buildings
  - Damage to interior finishes and contents

Phase 1: Initial document collection and review

Phase 2: Interviews, site visits, additional document review

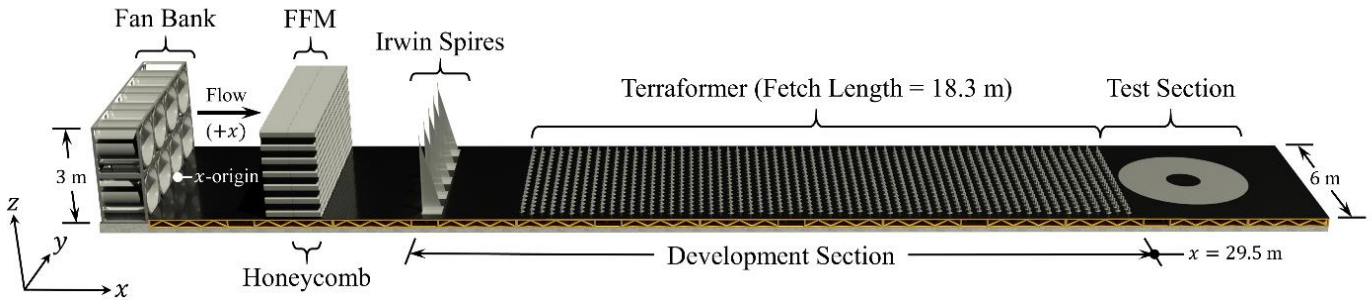
- Phase 2 site visits and interviews recently completed for all 5 of the selected hospitals:
  - Further details on damage to building components, systems, and contents
  - Information on impacts to hospital functions and operations



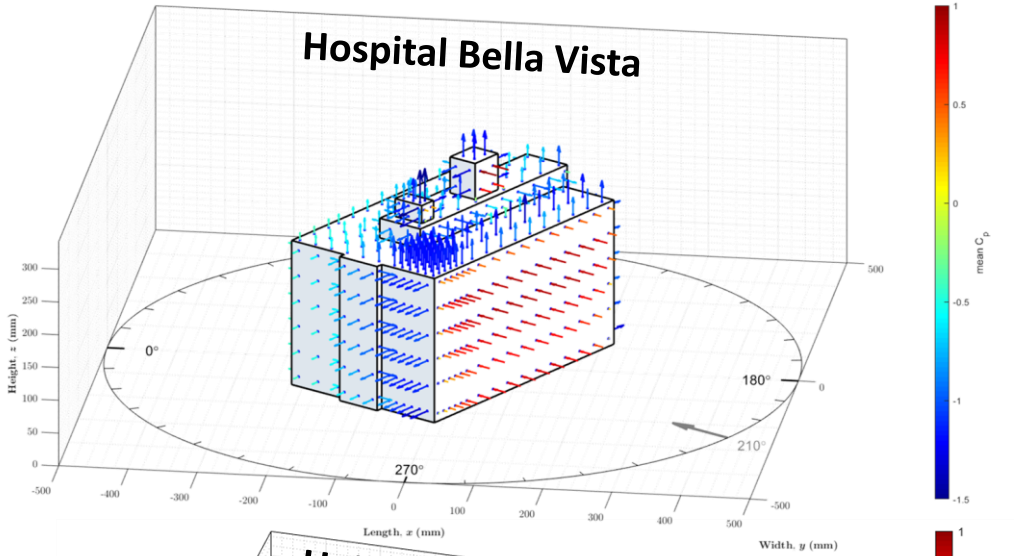

Wind Tunnel Test Data for Hospitals

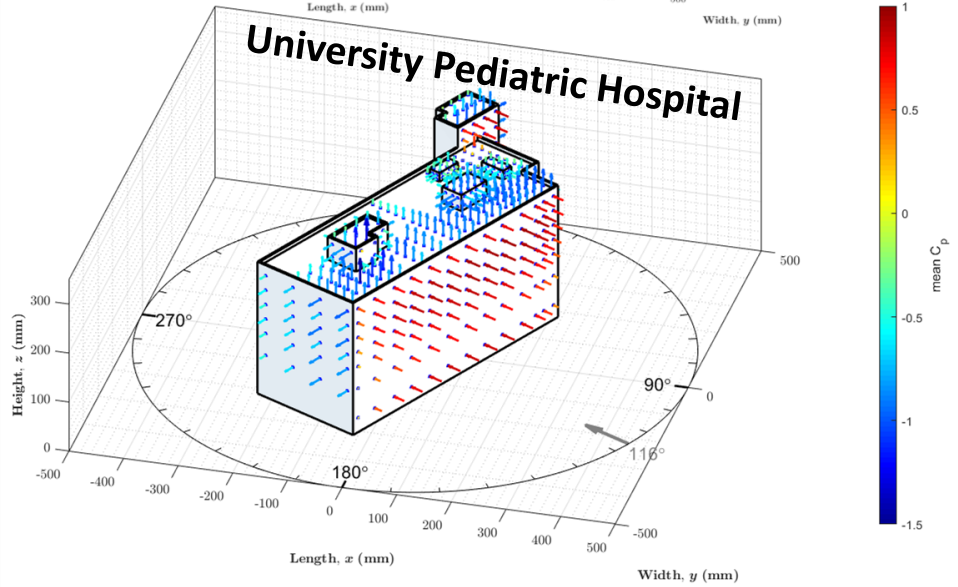
Completed Data Curation and Processing for Both Hospital Facilities:

- Measured pressure data normalized as nondimensional pressure coefficients
- Summary statistics calculated for measured data, including peaks estimated by fitting an extreme value distribution to the data
- Visualizations developed for measured pressures at tap locations



Boundary Layer Wind Tunnel at University of Florida





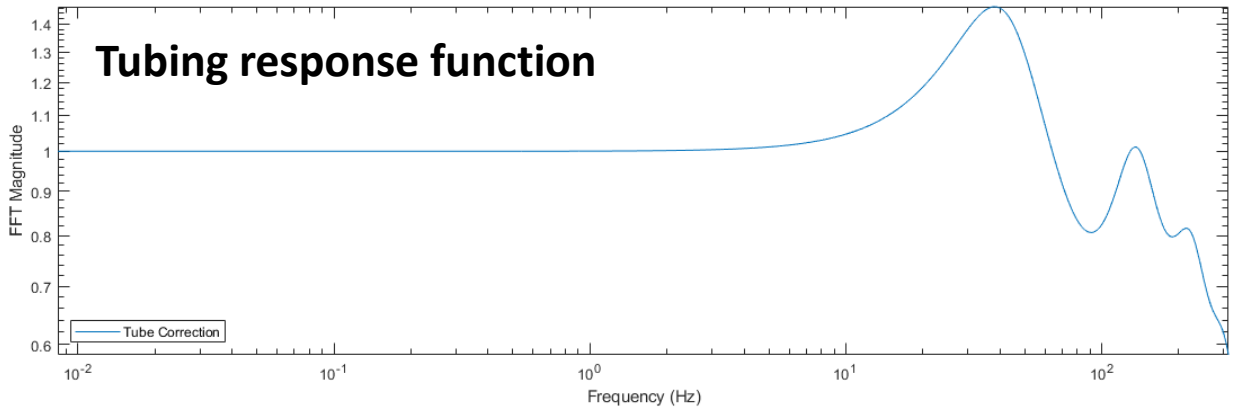
PRELIMINARY ANALYSIS

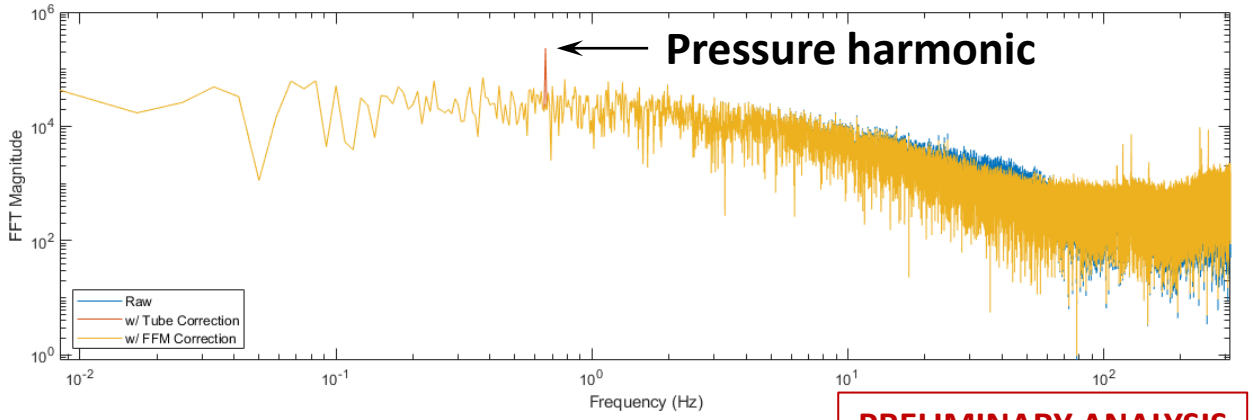
Wind Tunnel Test Data for Hospitals

Completed Data Curation and Processing for Both Hospital Facilities:

- Incorporated tubing response functions to correct for effects of tubing dimensions, temperature, and atmospheric pressure
- Applied filtering in frequency domain to eliminate harmonics in measured pressures caused by Flow Field Modulator (FFM)

FFM fan elements in Boundary Layer Wind Tunnel at University of Florida





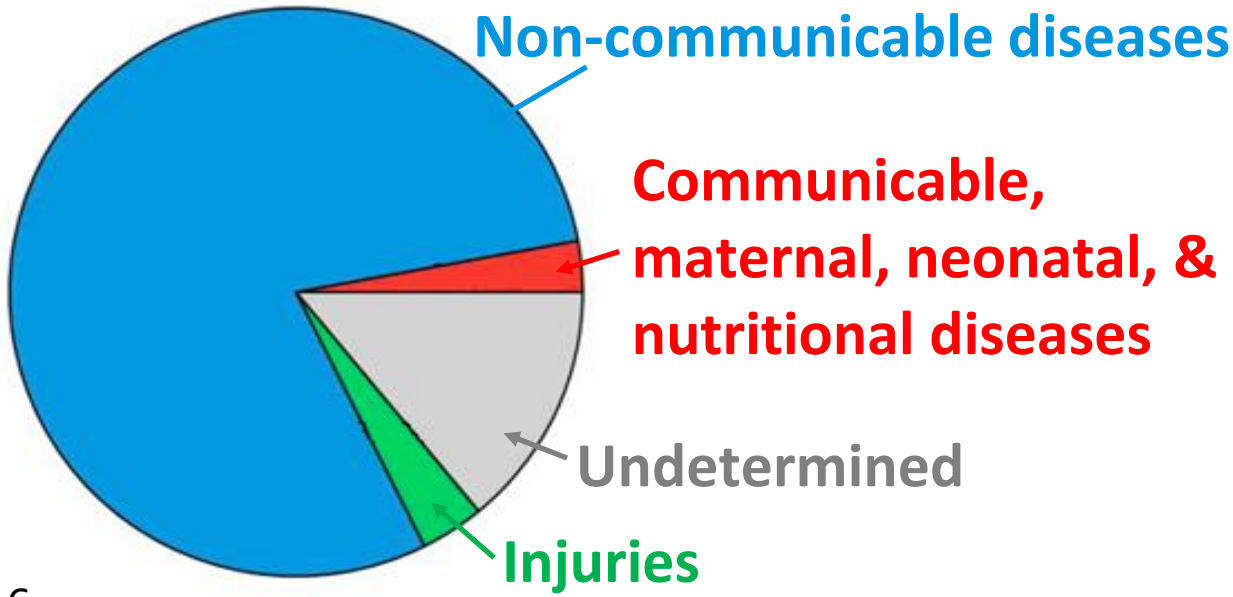
PRELIMINARY ANALYSIS

Hospitals Theme: Highlighted Projects

- Hazard Characterization
- Performance of Critical Buildings
- **Morbidity & Mortality**

Verbal Autopsy & Socio-Environmental Survey

- Objective is to ascertain the cause and conditions surrounding deaths that took place within 14 days after landfall.
- The population of the VA+S'E consists of all deaths (n = 1804) occurring between Sept 20 and Oct 4, 2017.



Place the ambulance (911) or alternative service took deceased to search for care	%
Emergency Room	22
Hospitalization services/hospitals	72
Primary health care centers/health center	2
Urgent care services	2
Other	2

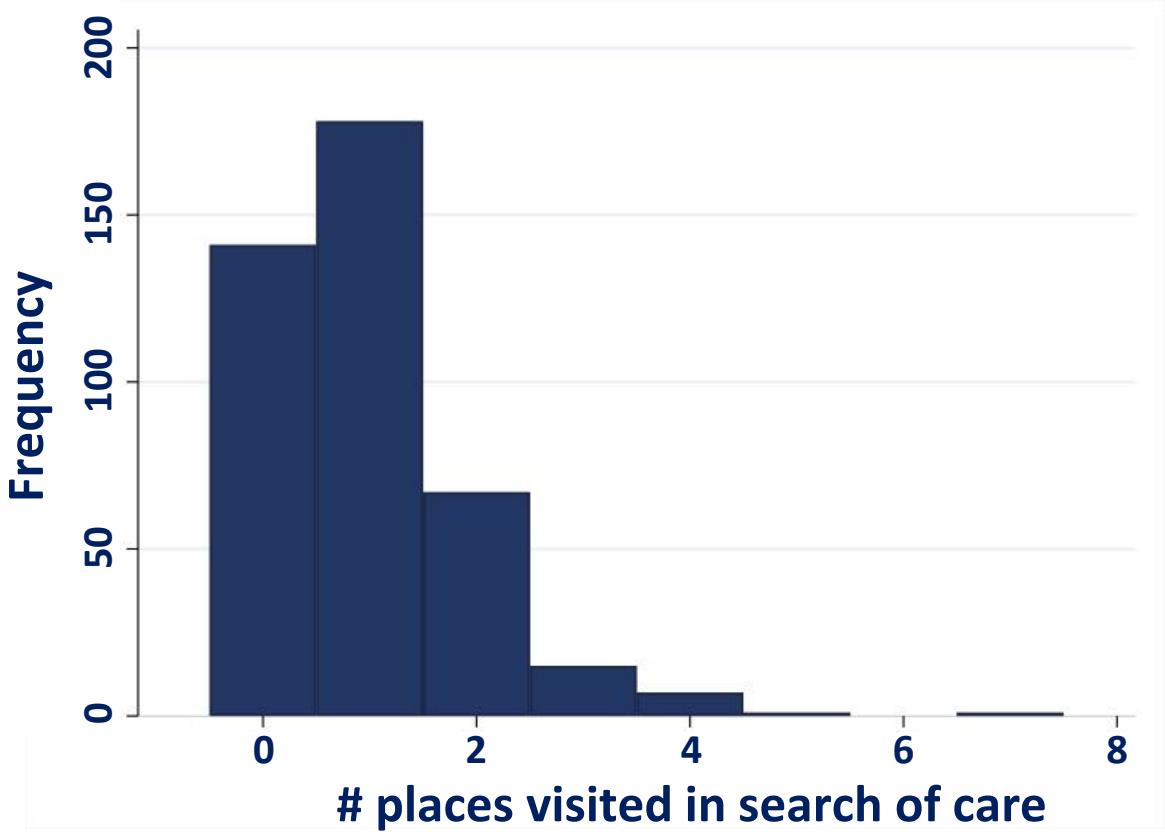
- A total of 410 interviews were conducted with next-of-kin informants.
- Of these, 11% of the deaths occurred the day of the hurricane's landfall, and 88% occurred in the 14 days after landfall.

PRELIMINARY ANALYSIS

Verbal Autopsy & Socio-Environmental Survey

Preliminary assessment of the VA=S'E data shows: ~66% of individuals sought health care in at least one place; ~47% of individuals with low socio-economic status didn't seek any care; and the more frequently mentioned hospital disruptions were power outages, loss of AC/ventilation, and shortage of staff.

Disruptions next-of-kin informants noticed where deceased was hospitalized	%
Power outage	96
A/C (ventilation) not functioning	71
A flood from rising water entered building	21
Rainwater entered building during the storm	30
Water leaked through the ceiling	23
Interruption of water service	19
Not enough staff	57
Not enough medical equipment	41
Medical gases (oxygen) were not available	15

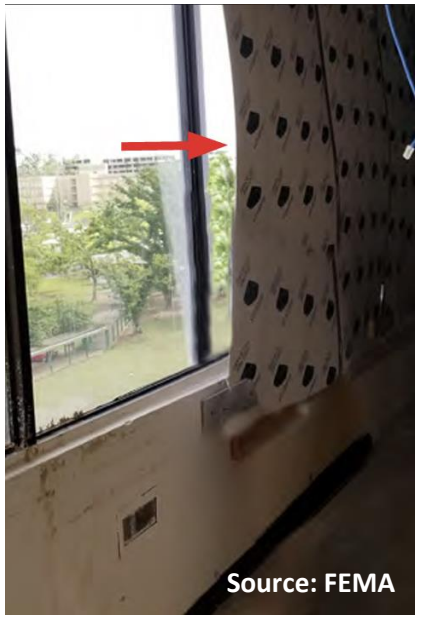


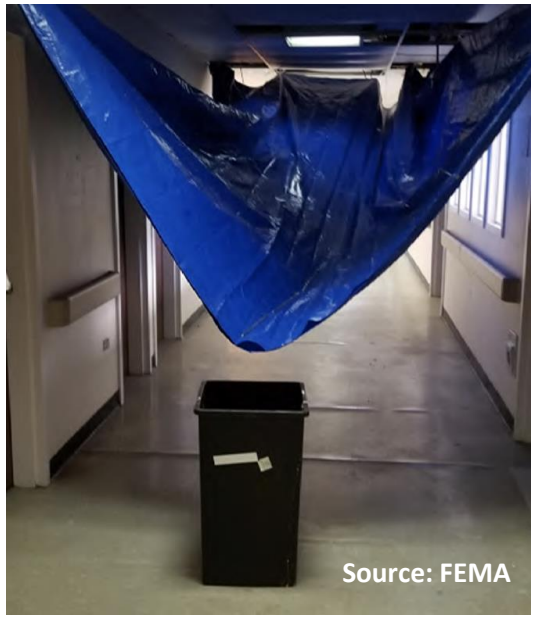
PRELIMINARY ANALYSIS

Hospital Function Surveys

Preliminary Observations from Hospital Function Surveys Supporting Mortality Assessment:

- Power generators of two hospitals had limited capacity and could not supply sufficient power.
- Of the 6 hospitals surveyed, all but one facility reported significant building damage (e.g., window/door and roof damage), resulting in rainwater ingress and flooding in most buildings.
- Damage forced patients, some critical, to be moved to hallways and other floors; moving patients was difficult due to loss of elevator functions (resulting from loss of power and flooding of machine rooms).
- Hospital personnel reported the following as significant challenges: inventory problems with fuel (diesel), medicine, water, and oxygen, as well as staff burnout (particularly 2nd week after landfall).





Questions?

Theme 1: *Hospitals*

DongHun Yeo, Joseph Main, Judith Mitrani-Reiser

Theme 2: *Sheltering*

Marc Levitan, Katherine Johnson, Maria Dillard

Theme 3: *Infrastructure Dependencies*

Ken Harrison, Jennifer Helgeson, Maria Dillard