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Hurricane Ian Workshop #2 Report

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Abstract

This report summarizes the second Hurricane Ian workshop, held on March 17 and 18, 2025, in Fort Myers, Florida. This second Ian workshop focused on the state of research for coastal surge and wave hazards and impacts on the built environment. Participants highlighted lessons learned and technologies developed or leveraged for reconnaissance efforts. Novel experimental campaigns and numerical model simulations were also presented, sharing integrated approaches to capture primary and cascading hazards and preliminary work applying these to interactions with the built environment. A common thread was found using Fort Myers Beach as a test bed to communicate the urgency and importance for collaborative approaches, to share data and information among agencies, researchers, practitioners, and to develop better understanding of model capabilities for prediction storm impacts from coastal surge and waves. The report concludes with strategies to be considered and potential avenues for future research including: the exploration and continued development of new technologies (e.g., sensors), methods for capturing data (e.g., surveys), continued testing either in a laboratory (e.g., scaled hurricane surge experiment), or in-situ opportunities (e.g., Rodanthe testbed).

Keywords

Building damage; Built environment; Coastal flooding; Flood hazards; Hurricane Ian; Numerical modeling; Overland flow**;** Storm surge; Waves**.**

Preface

Hurricane Ian Workshop #2 and this resulting report were conducted in support of NIST's congressionally funded study of Hurricane Ian, through the National Windstorm Impact Reduction Program. The workshop report should also be a valuable tool for any organization, agency or individual conducting research on Hurricane Ian and its impacts. The workshop was chaired by Daniel Cox from Oregon State University (OSU). Funding to conduct the workshop was provided to OSU from NIST, through an Interagency Agreement between NIST and the National Science Foundation (NSF) that provided supplemental funds to an existing NSF Natural Hazards Engineering Research Infrastructure (NHERI) award to OSU.

Acknowledgments

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1. Introduction

Hurricane Ian (2022) formed in the central Caribbean Friday September 23 becoming a hurricane on September 26 and passing over Cuba on September 27, (NHC, 2022) [1]; (NWS, 2022) [2]. Hurricane Ian made landfall in the continental United States on September 28 in Florida and continued to North Carolina (NHC, 2022) [1]. Hurricane Ian had an estimated peak intensity of 140 knots (260 kph) and induced storm surge inundation levels of 10 to 15 feet (3.05 to 4.57 meters) above ground level in places such as Fort Myers Beach, FL [1]). In addition to wind, pressure, and storm surge, Hurricane Ian induced extreme rainfall with some areas such as Placida, FL, receiving more than 15 inches of rain (38.1 centimeters) over 12 hours (NESDIS, 2022) [3]. Altogether, in the United States, Hurricane Ian was responsible for at least 156 fatalities and an estimated $112.9 billion total damage [1].

Reconnaissance efforts were conducted by the National Oceanic and Atmospheric Administration (NOAA), the Structural Extreme Events Reconnaissance (StEER) network, the United States Geological Survey (USGS), Federal Emergency Management Agency (FEMA), local organizations and academic institutions. These efforts have provided a wealth of data to better understand the hurricane surge and wave hazards and the mechanisms of damage to the built environment. Numerous articles have since been published on Hurricane Ian and its impacts. These studies span from erosion and deposition of coastal areas captured by field observations (Wang et al., 2024) [4], evaluation of normal and reverse surges based on meteorological data and numerical simulations (Heidarzadeh et al., 2023) [5], damage assessments using aerial imagery and LiDAR (Hauptman et al., 2024) [6], and virtual damage assessments (Figueira et al., 2025) [7].

Despite the wealth of data and ongoing efforts to analyze and publish studies, there remains significant knowledge gaps in the conditions which impacted the coastal communities (e.g., nonstationary winds, wave characteristics), secondary hazards resulting from wind and surge (e.g., rain intrusion, entrainment and transport of debris), and impacts on the built environment (e.g., roof failures, loading responses). Strategies for the improvement of the measurement science required for developing datasets, models, and validation and are therefore important to help understand this and similar hazards.

The first Hurricane Ian workshop was held on June 6 and 7, 2023, in Reston, Virginia, to synthesize data that had been collected for the storm. The second Hurricane Ian Workshop, and the focus of this report, was held on March 17 and 18, 2025, in Fort Myers, Florida, to provide an opportunity for the members of these reconnaissance teams, authors of published and ongoing works, and other researchers to discuss ongoing work, highlight research gaps and opportunities, and make recommendations for further work. A third workshop was held on September 6, 2025, in Alexandria, VA, to focus specifically on numerical modeling of hurricane surge and wave hazards in the built environment. The three workshop reports are archived on DesignSafe.org (Cox et al., 2025) [8].

2. Workshop Objectives and Report Organization

The NIST Hurricane Ian Study is an ongoing project centered on characterizing coastal flood hazards, quantifying storm surge loads on infrastructure, providing guidance for existing codes and standards, improving meteorological and engineering estimates of the hazard, improving preparedness and response practices, and more. Altogether, the damage and casualties resulting from such a large-scale event has prompted researchers, both NIST affiliates and other expert researchers, practitioners, and community members, to work towards understanding the various environmental, infrastructural, and social components in this disaster. The 2025 Hurricane Ian Researcher's Workshop was a NIST-supported, two-day, in-person workshop hosted in Fort Myers on March 17th and 18th. The objective of this event was to provide the opportunity for researchers to discuss the measurement science of landfalling hurricanes and their impacts on the built environment while identifying knowledge gaps and approaches for ongoing and future research. Using the landfall of Hurricane Ian on Fort Myers as a case example, the workshop and this report outline a research plan with respect to coastal wind and surge events.

The workshop was designed to include a series of sessions dedicated to presenting past, ongoing, and proposed works as they apply to different aspects of Hurricane Ian and the associated research efforts. The workshop format largely consisted of a mix of short, single-track presentations and small group discussions. Following the workshop, there was an optional half-day visit to Fort Myers Beach to observe recovery efforts.

3. Pre-Workshop Survey

Prior to arriving at the workshop, participants were asked to respond to a pre-workshop survey that focused on identifying key knowledge gaps related to the primary and secondary overland hurricane hazards, the impacts of these hazards on the built environment, and their awareness of prior research roadmap reports issued by NIST and the NSF. The survey was sent to 41 expected participants, and 28 responded to the survey, giving a participation rate of 68 %. The specific wording of the questions and a summary of the responses to each are provided as follows.

3.1. Question 1. What would you consider are the top knowledge gaps in our ability to model and measure the primary overland hazards during hurricanes (i.e., wind, flood, and storm surge)?

Some of the common themes that emerged in responses to this question included the following:

- **Overland surge/wave modeling**. Respondents noted the need to improve accuracy of modeling wave dynamics, interactions with the built environment (including dynamic interactions that update the topography and features as they interact with the surge and waves), smaller-scale features, and time-series of surge and wave rather than just peaks.
- **Overland surge/wave measurements**. Several respondents noted the need for more robust, low-cost measurement solutions that could be deployed over higher spatial resolutions to measure time series of surge and wave dynamics.
- **Accurate modeling and measurements of wind speeds in the landfall transition region**. Several respondents highlighted the need for improved spatial resolution of robust measurements in the landfall region. Several respondents also mentioned the need for more accurate modeling of wind speed changes across heterogeneous exposures, which would also require more dense arrays of surface wind measurement instruments.
- **Hazard data synthesis across different sources and instruments**. Related to wind specifically, multiple respondents noted that different methods for measuring wind speeds in landfalling hurricanes often lack agreement. These uncertainties propagate down to the impacts modeling and validation.
- **Higher-resolution exposure data**. Respondents noted that the spatial and temporal resolution of exposure and topography data is often inadequate for accurate modeling. Better data is needed.

3.2. Question 2. What would you consider are the top knowledge gaps in our ability to model and measure the secondary overland hazards associated with hurricanes (i.e., scour, water-borne debris, wind-borne debris)?

Responses to this question were more concentrated, primarily focusing on better data for debris modeling and validation. Many respondents noted that debris measurements are sparse, and even when they are captured, both wind-borne and water-borne debris measurements typically only capture the source and destination of the debris, with no information on transport trajectory and speeds and limited information on the debris characteristics. These higher levels of information are critical to model validation and to probabilistically characterizing these secondary hazards.

Measuring and modeling scour was also mentioned by several respondents, noting the importance of scour on impacts, but also the difficulty in modeling the small-scale features (e.g., presence of structures, vegetation) that drive scour. There is also a lack of data for validating scour modeling.

3.3. Question 3. What would you consider are the top knowledge gaps in our ability to model and measure the impacts of wind, flood, and cascading hazards associated with hurricanes (i.e., load and response of structures, damage to components)?

Responses to this question were more varied than those to the first two questions. A few themes still emerged from the most mentioned knowledge gaps, which included the following:

- Better links between site-specific hazard conditions and resulting impacts. This was mentioned specifically for wind (speed and direction) and rain but would apply to storm surge and wave action as well.
- Better understanding of water ingress issues, including the hazard conditions leading to ingress, the actual source of the ingress, and the source-specific impacts (e.g., interior flood impacts vs wind-driven rain impacts).
- Combined hazard impacts. Improved methods are needed for separating out wind and water impacts in post-event reconnaissance, and improved modeling of these simultaneous hazard conditions is needed. Validating such models would require more time-series measurements of coincident hazard conditions as was mentioned previously.
- Understanding uncertainty propagation in modeling efforts from primary hazards down to impacts.

3.4. Question 4. How would you characterize your familiarity with the following previously issued roadmaps and strategic plans as they relate to the topics and knowledge gaps mentioned above?

Respondents were asked to report their familiarity with several previously issued roadmaps and science plans that related to the topic of the present workshop. For each of the three previous documents, the responses were reasonably distributed between being unfamiliar, generally aware, and familiar. For every document though, the number of respondents who characterized themselves as unfamiliar was greater than the number of respondents in either of the other two categories. The results are summarized in Figure 1.

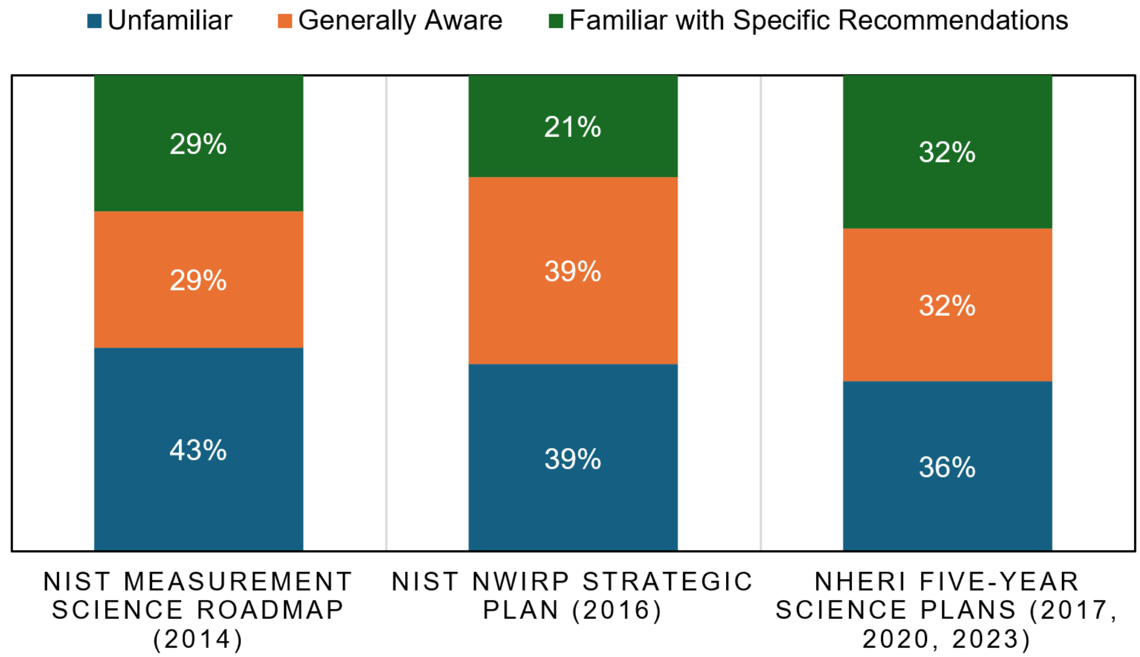

Figure 1. Respondents' reported level of familiarity with prior research roadmap documents.

4. Session #4: Knowledge Gaps in Measurement Science of Primary Hurricane Hazards

Session #1 focused on knowledge gaps in measurement science related to the overland conditions of wind and flood that impact coastal communities. Three framing talks covered scaling of hazard modeling, monitoring efforts, and reconnaissance analysis. In the following breakout sessions, participants were prompted to speak on these topics and others which addressed the characterizations of the hazards and hazard impacts on structures in order to develop research action plans that address the identified knowledge gaps. Slides for the three presentations are available on DesignSafe under Project PRJ-6122 (Cox et al., 2025) [8].

4.1. "Wind and Flood Hazards: Regional to Local Scale" by Rick Luettich, Matt Bilskie, Casey Dietrich, Zach Cobell

Rick Luettich, a distinguished professor at the University of North Carolina and the founding director of the University of North Carolina (UNC) Center for Natural Hazards Resilience, presented outputs of modeling efforts to characterize hazards induced by Hurricane Ian at multiple spatial scales (Figure 2). Models for Hurricane Ian wave, surge, and inundation studies are conducted to forecast and reanalyze storm pathways and effects and develop probabilistic ensembles. Modeling outputs (e.g., water depth above ground, significant wave height, and wind speed) can be compared with meteorological data and observed high water marks. To reduce the resolution from a regional to local scale the integration of the ADCIRC and SWAN (Advanced Circulation Model and the Simulating Waves Nearshore model), (with higher resolution on land, effects of structures, has a newly developed channel algorithm) and coupling higher resolutions/engineering scale models such as XBeach 2D are considered. In order to get from current output products (e.g., meteorological forcings for wind and hydrodynamic studies, which are coarsely scaled) to damage scales the following knowledge gaps were identified for continued investigation: the most important causes of variabilities (and the methods to model this), the downstream prediction impacts (e.g., morphological response, damage debris), how to construct and use probabilistic hazard data with respect to ensembles, and the impacts and extents of compound flooding.

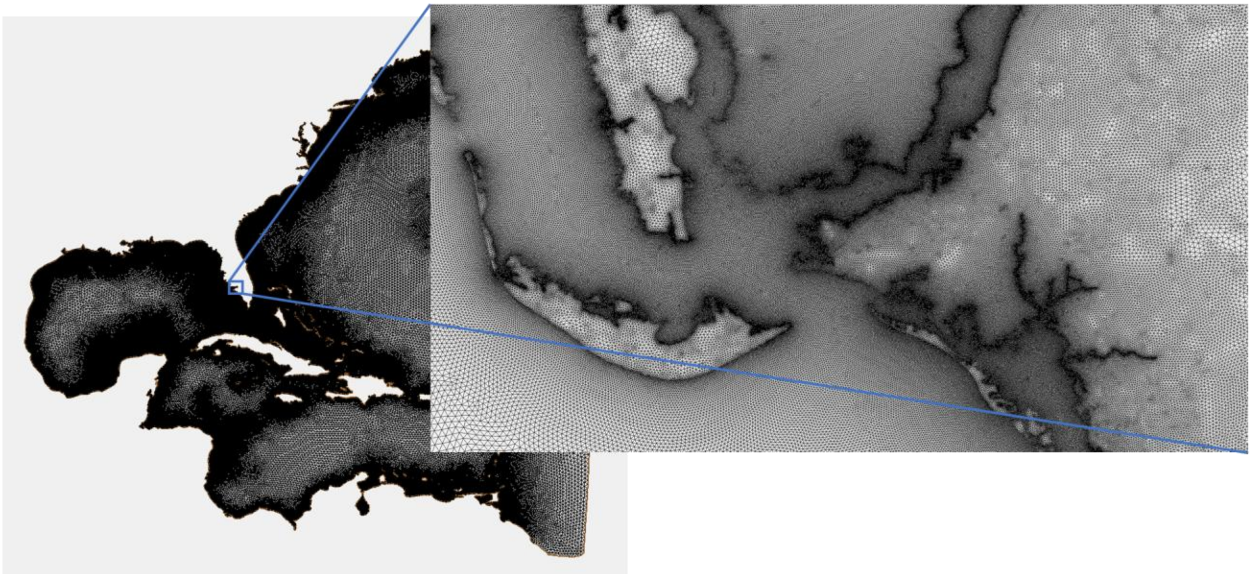

Figure 2. EGOM ADCIRC+SWAN model computational grid with a max resolution of approximately 50 to 100 meters.

4.2. "Florida Coastal Monitoring Program and Project Sentinel" by Brian Phillips

Brian Phillips, a professor of Civil and Coastal Engineering at the University of Florida, presented an overview of the Florida Coastal Monitoring Program (FCMP), which has successfully deployed high fidelity surface wind measurement platforms in advance of 46 landfalling hurricanes since 1999. Dr. Phillips summarized the historical and current capabilities of the program, and described the 10 m and 15 m weather stations at the core of the deployments (Figure 3). These stations each contain multiple 3-axis Gill anemometers in addition to sensors for measuring air temperature and barometric pressure, all of which are powered by a high capacity battery, allowing for fully remote operation. The data is transmitted in real-time to monitoring platforms via cellular or satellite links. By deploying up to five towers, in coordination with other efforts from researchers at Texas Tech University, the University of Illinois at Urbana Champaign, the Florida Institute of Technology, and many others, researchers are able to capture surface conditions that fill an observational gap between the inland and offshore regions of landfalling hurricanes. Dr. Phillips also described the Sentinel program -- a new class of temporary monitoring station engineered for simultaneous surface-level wind and water measurements at the shoreline. The Sentinel consists of a 10 m tower with a 3-axis Gill anemometer, tiltmeter, and air temperature and barometric pressure sensors at the top of the tower, and water temperature, salinity, and pressure sensors at the base of the tower. The first Sentinel was constructed and deployed in 2022 for Hurricane Ian. Two Sentinels were successfully deployed in 2024. Additional funding from a National Science Foundation Major Research Instrumentation grant and from the US Army Corps of Engineers is currently facilitating the construction of several more and the expansion of the instrumentation to include video, Real Time Kinetic Positioning (RTK) GPS, LiDAR, chem/bio sondes, and wave/current sensors.

Dr. Phillips concluded the presentation by summarizing the observations and lessons learned from the deployments during Hurricanes Ian (2022), Helene (2024), and Milton (2024), which included simultaneous measurements of 106 mph 10 m, 3 s peak wind gusts and 1.7 ft/s water depth above the base during the landfall of Hurricane Milton. Overall, the Sentinel systems, in combination with the other FCMP systems, fill critical data gaps in measuring the intensity of hurricanes in the landfall and transition regions.

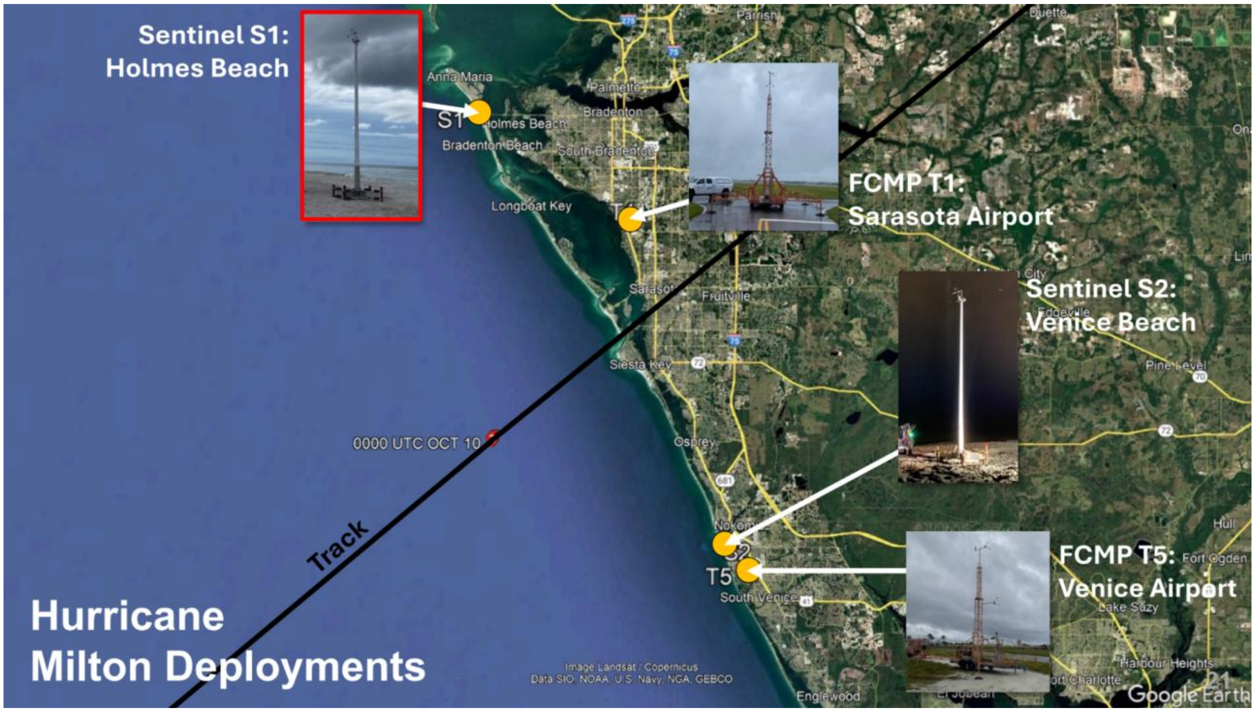

Figure 3. “Surge and Wave Measurement and Deduction from Hurricane Ian” by Jenna Brown and James Kaihatu

4.3. “Surge and Wave Measurement and Deduction from Hurricane Ian” by Jenna Brown and James Kaihatu

James Kaihatu, a professor of Civil & Environmental Engineering at Texas A&M University, presented data collected by both the United States Geological Service USGS and StEER the Structural Extreme Events Reconnaissance network. The USGS Coastal Storm Response included coordination between the USGS, NOAA, NWS, US Department of Homeland Security, FEMA, and the US Army Corps of Engineers. The pre-storm preparation included forecasts of total water levels and coastal change, equipment deployment, and data collection at pre-deployed gages. Post-storm activities included collection of high-water marks (HWM) and aerial imagery. Hurricane Ian datasets included: 392 pressure transducers, 121 barometric pressure sensors, 242 water level sensors, 28 wave height sensors, 365 HWMs. These data points provide valuable information that characterize the impacts of Hurricane Ian. A chief concern within the research community is that there is a lack of sustained funding for sensor deployments which is at odds with interests to increase the availability of real-time data. Post-storm as well, StEER has conducted building damage and high-water mark surveys. The damage survey included identification of building damage state including features of interest such as balcony collapse, and mechanisms of damage including debris-induced damage, flow channeling, and debris damming. The damage surveys were often performed in conjunction with high water mark surveys using leveling rod, laser rangefinders, and RTK measurements to identify surge and surge-wave conditions at the structures.

4.4. Breakout Discussions

Participants in the breakout discussions were prompted to consider what the knowledge gaps were in measurement science of wind and surge or wave hazards, why these gaps exist, and what implications there are for the built environment. Discussions identified knowledge gaps that largely fall under data and modeling challenges or gaps in damage assessment and its associated uncertainties. An overarching need for more data collection and reporting at greater resolutions was echoed. In order to support these efforts there is a coupled interest in the advancement of measurement and modeling tools. Supplementary data in developed areas and/or with higher frequency would help to parse out localized impacts and capture shorter term fluctuations. While improving the level of detail in computational, experimental, or observational datasets, there needs to be attention directed towards the discrepancies between these data types.

4.4.1. Knowledge Gaps Related to Modeling

Data capture and resolution problems come into play when simulating impacts and interactions with the built environment. For instance, many models are relatively accurate in simulating waves offshore but fail to maintain reliability once topographic variability as a function of structures, vegetation, morphology, and otherwise are considered. Atmospheric and engineering models exhibit discrepancies when comparing surface-based observations and those utilizing air-borne and dropsonde technologies. There are additional challenges that come from comparing laboratory experiments to the real-world, particularly at the community scales. Some advancements have been made that combine models such as ADCIRC+SWAN to more accurately capture storm surge and wave behavior, though here again scaling challenges occur.

4.4.2. Knowledge Gaps Related to Measurements

Capturing and interpreting in-situ measurements poses different challenges. Instruments are subject to damage or loss during extreme events which make fine-scale and continuous measurements difficult. From the beginning, difficulties in capturing the data are being tackled through the development and deployment of instrumentation such as the SENTINEL. Such measurement devices provide valuable data on storm characteristics such as wind speeds, but limitations arise due to uncertainties of the track and safety concerns for personnel needed for deployment. Post-event data capture also provides difficulties. Gaps in knowledge and data arise from inaccuracies that arise from inconsistencies in evaluating high-water marks or separating wave effects from total water level. These gaps may be addressed in part by real-time monitoring and backtracking video footage to better estimate water elevation and the associated damages.

5. Session #2: Knowledge Gaps in Measurement Science of Cascading Hazards

Session #2 focused on knowledge gaps in measurement science related to the cascading hazards associated with landfalling hurricanes. The session began with three lightning talks - focusing on scour and sediment transport, water-borne debris, and water intrusion respectively - then moved to breakout discussions at each table. As with the previous session, participants were asked to discuss the key knowledge gaps on this topic, the implications of those knowledge gaps on the impacts to the built environment, and the reasons these knowledge gaps exist. Slides for the three presentations are available on DesignSafe.org (Cox et al., 2025) [8].

5.1. "Cascading Hazards: Erosion/Scour" by Jane Smith, Brad Johnson, Ali Abdolali, Nick Cohn, Annika O'Dea, and Jennifer Wozencraft

Jane Smith, a research professor at the University of Florida and an emeritus senior scientist at the US Army Corps of Engineers (USACE) Engineering Research and Development Center (ERDC), presented an overview of sediment's role in cascading failures. During an event composed of wind, waves, and surge, major morphological changes occur. These may take the form of dune failure or breach which can result in flooding, wave damage, and overwash of sediment. Alternatively, scouring may result in structural failure and other infrastructure damage. Modeling these morphological changes requires consideration of the complexities of sediment transport (e.g., nonlinearities, currents, inhomogeneity in sediments, initiation of motion, interactions with vegetations). One dimensional, two dimensional, and one-line models all aim to capture the erosion and accretion processes though two-dimensional models are generally too computationally expensive for probabilistic simulations. Future work may hope to capture the missing physics at a higher fidelity leveraging AI. The reliance on empiricism to validate these models indicates a need for more data for which Hurricane Ian may provide a valuable testbed. The conclusion of this presentation was an outline for the types of data that would be of use:

1. Topo/bathy data
    a. Need time histories of change - erosion/accretion
    b. Documentation through storms - every storm
    c. Innovative measurements: lidar, drone, satellite
2. Sediment transport
    a. Transport rate, volume, forcing & response
    b. Interaction with vegetation and infrastructure
    c. Improved measurement technology (acoustics)
3. Data repositories
    a. Model development/validation
    b. Artificial intelligence (AI)

c. Joint experiments - Lab and Field

5.2. "Wind and Flood Cascading Hazards: Debris as a Pressing Example" by Jamie Padgett

Jamie Padgett, a professor at Rice University, presented an overview of debris as a critical cascading hazard challenge. The talk began with emphasizing the magnitude of impacts generated by debris (e.g., cost, structural damages, functionality impairment, health risks). Notably, Lee County's debris removal operation exceeded 6.5 million CY [4.97 million m^3] (vegetation, construction and demolition), and the statewide generation exceeded 12 million CY [9.2 million m^3]. Numerical models and experiments have been developed to characterize waterborne debris transport. Important advances in understanding the in-situ complexities such as interaction with neighborhood topographies are being made by researchers. Figure 4 shows ongoing work to describe shielding and channeling influencing loads and cascading failures that turn into debris. Hurricane Ian offers an opportunity to validate this work through comparative analysis of debris detection in the data. This detection has implications that may assist removal and recovery planning as well as prediction approaches. Key takeaways were that: (1) Debris is a complex, multi-hazard, coupled system, cascading challenge with major practical implications, (2) there is so much to do in this space, (3) Hurricane Ian could provide a valuable learning opportunity to tackle some of these unanswered measurement and modeling questions.

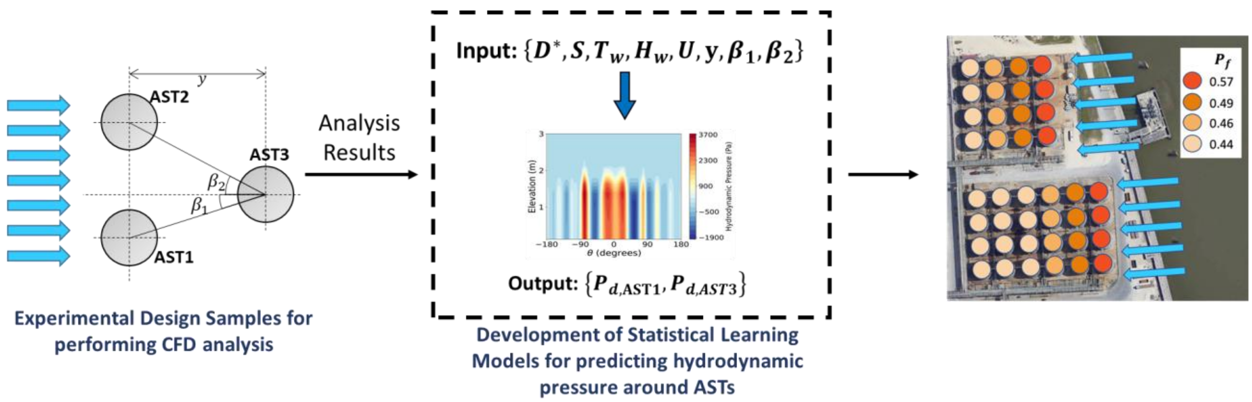

Figure 4. Framework for modeling the shielding and channeling processes that result in debris generation during a hazard event.

5.3. "2025 NIST Hurricane Ian Researcher's Workshop: Water Intrusion" by David Webb

David Webb, an engineer in the applied economics office of the National Institute for Standards and Technology, presented an overview of the NIST Hurricane Ian study on water intrusion. The talk began by highlighting that water intrusion into buildings is still a driver of economic losses, even though structural failures during design-level and below wind events are becoming more scarce. The presentation then identified and expounded on four key knowledge gaps related to water intrusion, namely:

1. How prevalent is the water intrusion problem? Existing literature and public datasets rarely distinguish wind-driven rain from other forms of water damage, and there are no concerted efforts focused on observed water intrusion post-event. Therefore, there is a need to quantify what type of damage occurs and how much damage occurs due to water intrusion from wind-driven rain.
2. What type of damage and how much damage is caused by water intrusion? These data are important to ground-truthing estimates from catastrophe models like HAZUS Hurricane and the Florida Public Hurricane Loss Model.
3. What are the primary pathways of ingress? Laboratory testing has looked at individual pathways, but field measurements of the performance of the building envelope as a system for preventing water intrusion are missing beyond anecdotal data and case studies.
4. How successful are mitigation measures? Laboratory tests show successful performance of mitigation measures such as secondary water barriers installed on roofs, but these are performed on new installations in laboratory settings. The real-world performance of these systems is lacking.

5.4. Breakout Discussion

The breakout discussions at the six different tables covered a wide range of topics around the theme of knowledge gaps in cascading hazards. Several general topics related to cascading hazards that emerged across all tables consisted of the following: (1) Knowledge gaps related to sediment and scour; (2) Knowledge gaps related to water-borne debris generation and transport; and (3) Knowledge gaps related to wind-borne debris lofting, transport, and strikes; and (4) Knowledge gaps related to wind-driven rain. Some specific knowledge gaps within these topics are summarized below. One common theme that emerged across the water- and wind-borne debris topics was the need to obtain clear evidence from field data of their current relative importance to impacts. For example, wind-borne debris impacts have been well documented in past storms, prior to modern building code enforcement and ASCE 7 standards, with wind-borne debris breaking windows or otherwise breaching the envelope leading to internal pressurization. But it is unclear whether this remains a significant problem given modern requirements for impact resistant glazing, and potentially reduced volume of wind-borne debris due to the impacts of modern building codes reducing damage.

5.4.1. Knowledge Gaps Related to Sediment and Scour

- Scour models are based on steady state conditions, and it is unclear whether these models are appropriate to short-term, transient hurricane conditions.
- Pathways are needed between the regional storm surge models (e.g., ADCIRC) and the localized 2D scour models such that input parameters for the scour models can be extracted from the regional models and applied for localized scour modeling.

- Time-series of scour and sediment transport during storms are needed rather than just final post-storm conditions.

5.4.2. Knowledge Gaps Related to Water-borne Debris and Transport

- The sequence of debris generation, transport, and impact lacks field measurements. Before and after representations of water-borne debris are relatively common, but the sequence of events, coupled with hazard conditions, are rarely if ever captured.
- It is unclear to what extent floating debris directly contributes to cascading damage. Transport speeds and impact energy are needed, along with evidence of direct impacts of water-borne debris during coastal storms.

5.4.3. Knowledge Gaps Related to Wind-Borne Debris and Transport

- Structured datasets of wind-borne debris from past storms that include key features such as debris shape, mass, liftoff location, impact location, transport mode (e.g., tumbling) are lacking.
- Quantification of the current relative importance of wind-borne debris as a cascading hazard is needed. Much of the past research on wind-borne debris in hurricanes was driven by the propensity for glazing failures and envelope breaches that could lead to internal pressurization. It is unclear whether this remains a significant concern in light of the recent improvements to codes and standards and the requirements for impact-resistant assemblies in coastal regions.
- Debris transport and impacts occurring from cyclone-induced tornadoes remains a significant problem, and structured datasets and improved modeling is still needed.

5.4.4. Knowledge Gaps Related to Wind-Driven Rain

- Building-scale field measurements of wind-driven rain and rainwater ingress are needed. Binary indicators would be an improvement given the current lack of publicly available data, but structured datasets with detailed information on the timing of water intrusion, source of intrusion, impacts to interior contents, and building metadata (year of construction, type of roof, presence of secondary water barriers, type of windows, etc.) would be the most useful.
- More appropriate test standards for water intrusion through commercial products and systems are needed. Current test methods limit water intrusion testing to 15% of the design wind pressure. What the appropriate combination of wind pressure and rain rates should be for design conditions and product testing remains a key knowledge gap.
- The precise sources (e.g., windows, doors, roofs) of water intrusion into typical buildings during hurricanes remains largely unknown.

- The probabilistic relationship between wind pressure, rainfall rates, and resulting water intrusion rates (i.e., fragility surfaces) for different building typologies, envelope systems, and damage levels, including undamaged, is lacking.

5.4.5. Other Knowledge Gaps

- How uncertainty in the primary hazards propagates to uncertainty in the cascading hazards remains a significant knowledge gap
- Improved coupling between the primary hazard models and cascading hazard models are needed for dynamic storm simulations.

6. Lunchtime Keynote from Dr. Chris Daly

Dr. Chris Daly of Florida Gulf Coast University was invited to present a keynote presentation at lunchtime and was titled "*Morphosedimentary impact of Hurricane Ian (2022) storm surge along the Gulf Coast of southwest Florida; lessons for building resilience capacity.*"

7. Session #3: Knowledge Gaps in Measurements Science of Hurricane Impacts

Session #3 focused on knowledge gaps in measurement science related to wind, flood, and cascading hazards on the built environment. The featured session talks discussed response effort findings and damage assessments. These talks were again followed by breakout groups discussing gaps and potential research that deepens understandings of loading and response of structures such as damage to components and cladding, failures, and failure mechanisms. Slides for the three presentations are available on DesignSafe under Project #PRJ-6122 (Cox et al., 2025) [8].

7.1. "StEER Response to Hurricane Ian & Lessons Learned" by Shafiq Alam*, Tracy Kijewski-Correa, David Prevatt, Khalid Mosalam, and David Roueche

Mohamand Shafiqual Alam, an assistant professor in the Civil, Environmental and Construction Engineering Department at the University of Hawaii at Manoa, presented an overview of the Structural Extreme Events Reconnaissance (StEER) response to Hurricane Ian (2022) and lessons learned. Since Ian's landfall, StEER teams conducted reconnaissance works in 3 different levels: (1) Level 1 focused on virtual data gathering, (2) Level 2 capturing Street-Level Panoramas, and (3) Level 3 focused on hazard measurement (high-water marks) and performance assessment (structure, foundation, and MEP systems). The StEER teams collected more than 160 HWMs and conducted damage assessment for more that 260 buildings in Fort Myers Beach, San Carlos Island, and Sanibel Island, including both quota-based sampling (every third structure, every post 2000 buildings) and critical case sampling based on unique features and observed damage. Note that the StEER team also captured high-resolution obliques and nadir imagery using unmanned aerial vehicles (UAV) for Fort Myers Beach (3.5 sq. mi.; 9.0 km^2), San Carlos Island (1 sq. mi., 2.6 km^2), and the majority of Sanibel Island (4 sq. mi.; 10.1 km^2). The goal of StEER is to publish collected data as quickly as possible, so researchers and practitioners can benefit. For example, the Streel-level panorama data has been loaded into Google Maps and Mapillary where it can be viewed with other community-sourced panoramic imaging. As another example, the HWMs and performance assessment data is gathered in an open-platform app, named Fulcrum that is accessible by different users in the community. **Error! Reference source not found.** shows an elevated wood-frame house experienced severe damage to the elevated floor and balcony due to the hydrodynamic wave uplift force.

Figure 5. Severe structural damage to the elevated floor and balcony of a wood-frame house due to the hydrodynamic wave uplift force.

7.2. "Virtual Damage Assessment and First-Floor Elevation Estimation: Application and Lessons Learned from Fort Myers Beach, Florida, and Hurricane Ian (2022)" by Mehrshad Amini

Mehrshad Amini, assistant professor in the Civil and Environmental Engineering Department and Ocean Engineering Department at the University of Rhode Island, presented his on-going work about Virtual Damage Assessment (VDA) and first-floor elevation (FFE) measurement for buildings located in Fort Myers Beach, FL, impacted by Hurricane Ian (2022) (Figueira et al. 2025) [7]. The VDA method benefits from available resources, such as the aerial imagery collected by NOAA, aerial drone footage collected by the StEER team, Lee County Damage Assessment (LCDA) database, and 360 street view footage collected by Oregon State University. The damage scale included component damage level ratings from DS0 (no damage) to DS6 (complete damage) adopted in this study (Tomiczek et al. 2017) [9]. Figure 6 shows overall VDA results of 3,408 buildings for which 3,118 buildings had full damage assessment and 290 buildings had partial damage assessment. The uncertainty in damage state is observed as plus/minus one damage state. One of the limitations of this dataset is that it does not include the interior damage since it was not practical to assess virtually. The FFE results are also available for all buildings but are not presented here for brevity. Note that the VDA dataset is publicly available in Designsafe (Amini et al., 2024) [10]. The VDA dataset can be used for future model-to-data and model-to-model validation of coastal damage prediction, including damage models from HAZUS and United States Army Corps of Engineers (USACE).

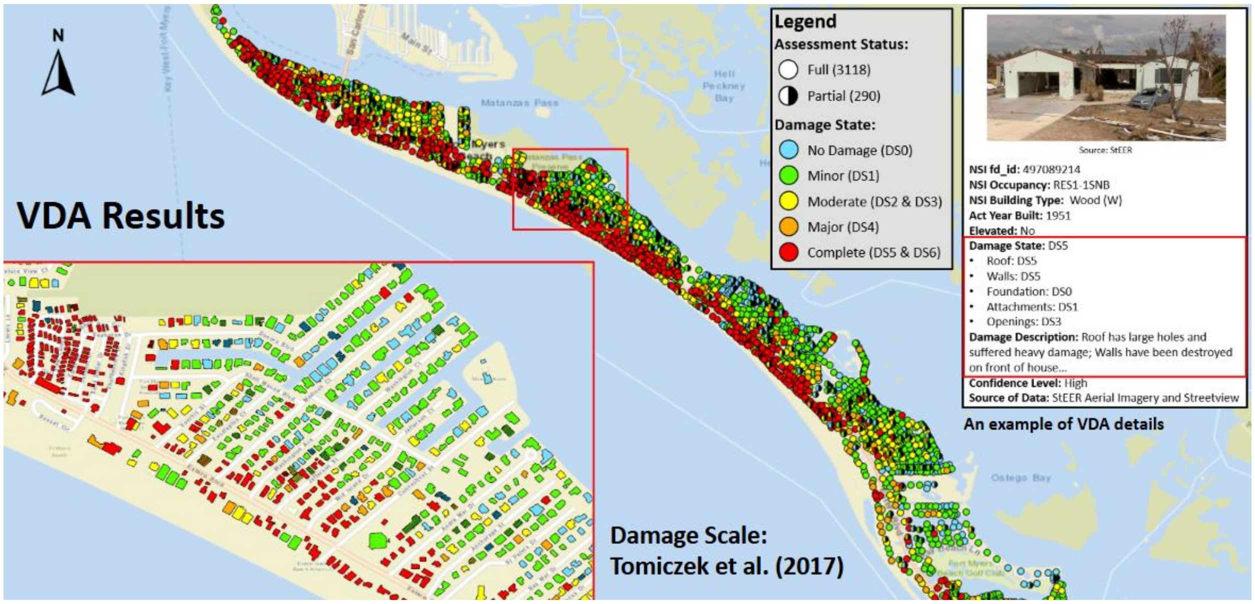

Figure 6. Overall VDA results of 3,408 buildings from which 3,118 buildings with full damage assessment and 290 buildings with partial damage assessment.

8. Session #4: Strategies for Addressing Knowledge Gaps and Improving Measurement Science of Landfalling Hurricanes

Session #4 focused on brainstorming strategies to improve our understanding and measurement science related to wind, surge, and wave hazards, cascading hazards, and wind/flood impacts on the built environment. Lightning talks highlighted tradeoffs and opportunities of in-situ measurement strategies, vision-based approaches for measuring wind flow fields and storm surge velocity, post-event evaluation limitations, data sharing platforms, and measurement/modeling across spatial scales. Similar to previous sessions, lightning talks were followed by breakout groups which strategized new instrumentation, data collection methodologies, data set synthesis, and improvements to be made. Slides for the six presentations are available on DesignSafe under Project #PRJ-6122 (Cox et al., 2025) [8].

8.1. Lightning Presentation #1: "In-Situ Measurement Strategies: Tradeoffs and Opportunities" by Jennifer Bridge

Jennifer Bridge, an associate professor in the Department of Civil & Coastal Engineering at the University of Florida, presented an overview of the benefits and disadvantages of in-situ measurements (Table 8-1). The considerations largely were associated with (1) target location, (2) deployment time, (3) spatial resolution, and (4) cost. Table 8-1 details the opportunities and tradeoffs presented. Examples of in-situ measurement deployments were given to describe advantages and disadvantages. Examples included the FCMP Instrumented House Program, a state funded campaign that provided retrofits to homes in exchange for homeowner cooperation in pre-instrumenting and mounting sensors before a storm. This concept is extended to an opportunity for the instrumentation of houses in Rodanthe (Section 9.2). This would be a medium duration deployment to evaluate performance and failure mechanisms when subjected to wind, waves, and flooding.

Table 8-1. Breakdown of considerations for in-situ measurements

		Opportunities	Tradeoffs
Target Location	Known a priori	• Focused on specific impact • Enables careful pre-event planning and deployment • Can establish access and permissions	• May not capture event or impacts of interest • Timeline to achieving data collection goals increases
	Event-driven	• Successful deployment more likely to capture event of interest	• Requires careful planning for rapid mobilization • Less control over variables
Cost	Lower	• Can achieve higher spatial resolution/more sensors • Instrumentation may be considered expendable	• Higher development costs • May have lower data quality • May require more sophisticated data processing
	Higher	• Proven data quality • Often more robust • Known data products	• Fewer instruments deployed • Less likely to use in riskier deployment conditions
Deployment Timeline	Long-term	• Capture the boundary conditions and evolution of hazard/impacts • Develop community relationships • More system development opportunities	• System maintenance • Deterioration, vandalism • Locked into a single location • Higher deployment costs
	Single Event	• Lower cost • Targeted measurements • Minimal maintenance	• May miss critical precursors, cascading events, related factors

8.2. Lightning Presentation #2: "Resolving Near-Surface Wind Flow Fields with Vision-Based Approaches" by David Roueche

David Roueche, an associate professor of structural engineering at Auburn University, highlighted the potential for using vision-based approaches for measuring near-surface winds during hurricanes. The presentation summarized the methods and findings of a recently completed project that focused on estimating wind speeds using the motion of large-mass wind-borne debris in tornadoes as captured by everyday video cameras used by the public (e.g., smartphones and security cameras). The presentation also included a summary of a set of experimental testing conducted at the Florida International University Wall of Wind that developed a structured dataset of wind-borne debris transport, with multiple cameras with overlapping fields of view capturing the flight of debris objects with known mass and geometry through a background flow field that was previously measured under steady state conditions. Dr. Roueche also highlighted some limitations and lessons-learned from the vision-based approach, namely (1) the necessity of knowing the camera intrinsic parameters (e.g., focal length, pixel resolution) and extrinsic parameters (location and orientation within the 3D scene) in order to get accurate results; and (2) the need for more diverse, labeled datasets so that computer vision and AI for recognizing, classifying and tracking debris motion can be fully leveraged.

8.3. Lightning Presentation #3: "Development of a Low-Cost, Overland Storm Surge Flood Depth, Velocity, and Wave Sensor" by Marc Levitan

Marc Levitan, the lead research engineer for the National Windstorm Impact Reduction Program at NIST, presented progress in developing a low-cost sensor package for measuring flood depth, velocity, and waves from overland storm surge. The development of this sensor package directly addresses some of the existing knowledge gaps identified in the NIST windstorm and coastal inundation R&D roadmap report (Coulbourne et al., 2014) [11], including Topic 21: Effects of over-land flow on waves and other coastal inundation hazards, and Topic 23: Field data collection of flood loads. The storm surge sensor is being developed by McQ Inc., and will utilize low-cost commercial, off-the-shelf (COTS) sensor components, including video camera(s) and barometric pressure sensors. The sensor package will be rapidly deployable and facilitate real-time data transmission in addition to onboard storage for redundancy. The design details will be published to allow for customization and commercialization. The target date for completion of the prototype sensors and publication of documentation is autumn 2026.

8.4. Lightning Presentation #4: What's on the inside matters" by Graham Brasic

Graham Brasic, a structural engineer and partner at Jezerinac Group in West Palm Beach, FL, presented on the structural components and failures following hurricane events such as Hurricane Ian (Figure 7). To begin, the concept of "survivorship bias" was introduced with respect to structural performance during a hazard event and how measurements and observations may influence research and scientific understanding. The damage and performance of the environment was described through imagery and different damage types and material performance. The presentation concluded with the statement that "there are no such things as natural disasters" but rather "natural events occurring where humans choose to live/build". The proposed solutions are (1) don't build in areas where disaster occurs, or (2) learn how to build responsibly within those areas.

Figure 7. Failed column without collapse.

8.5. Lightning Presentation #5: "Shared and Flexible Simulation Platform to foster Collaborative Research" by Adam Zsarnóczay

Adam Zsarnoczay, a senior research engineer at Stanford University and associate director of the National Hazards Engineering Research Infrastructure (NHERI) SimCenter, presented an overview of the NSF NHERI SimCenter as a platform to facilitate the design, construction, and research use of hurricane testbeds (Figure 8). The SimCenter has a suite of simulation, analysis, and visualization tools that have already been leveraged for previous hurricane testbeds such as Lake Charles, LA (Hurricane Laura (2020)) and Fort Myers (Hurricane Ian (2022)). The testbeds include building and other infrastructure inventories, hazard simulations, street-level panoramic and high-resolution aerial imagery, post-storm building performance datasets, and more. Through the integration of the SimCenter and DesignSafe, additional datasets and workflows can be added on to the existing testbeds by other researchers to facilitate a broad array of use cases.

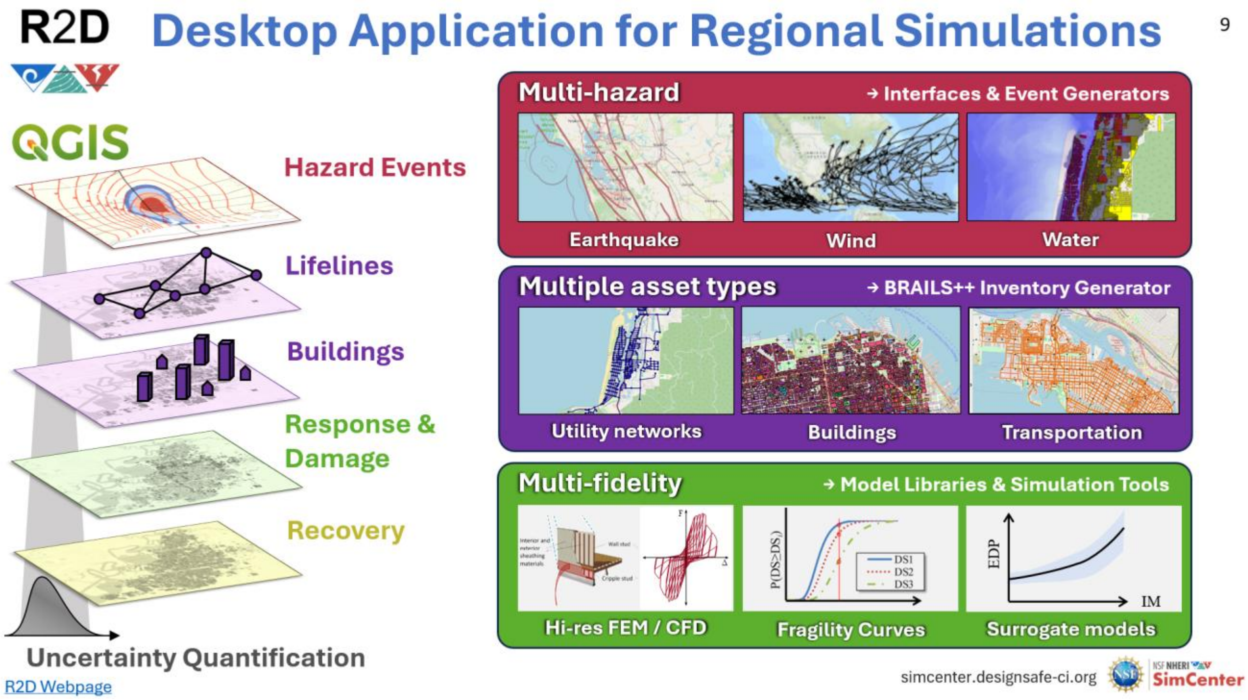

Figure 8. Regional simulations of natural hazard events using the SimCenter.

8.6. Lightning Presentation #6: “Measurement and Modeling Damage Across Scales” by Dan Cox

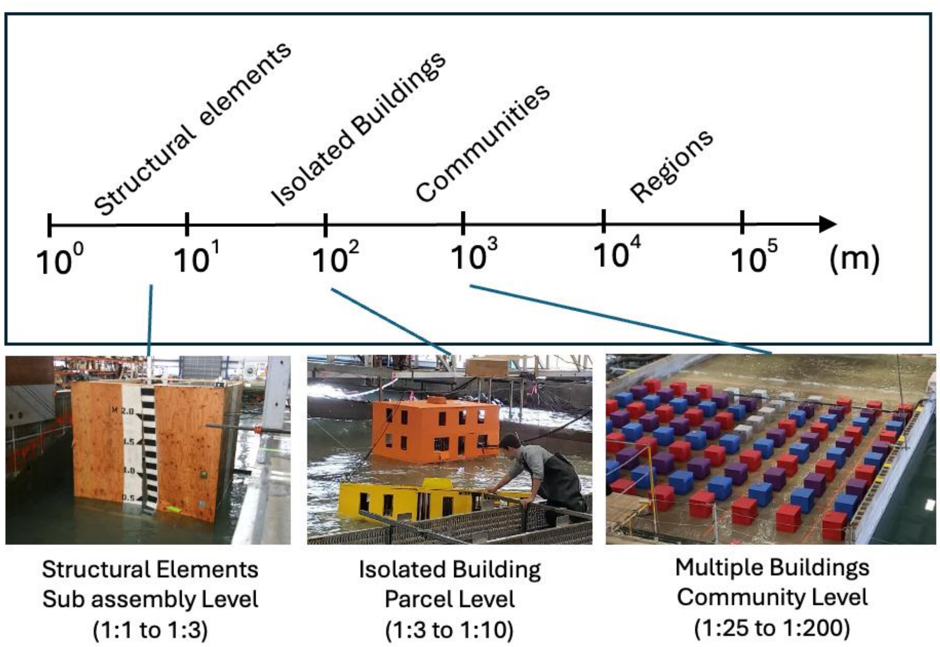

Figure 9. Example experimental testing for various spatial scales

8.7. Breakout Discussion

This session was aimed at developing specific strategies for the advancement of measurement science. As such, breakout discussions for this session were prompted first to identify the theme which was being addressed. Following the discussion of a strategy, participants were then asked to consider or evaluate the effort and impact that such a strategy might have. Many of the identified strategies require longitudinal research and sustained funding to produce consistent, high-quality data. This requires support from the public and decision makers by reframing and emphasizing economic and safety benefits from committing to community resilience research.

8.7.1. Strategies for Understanding Primary Hazards

Strategies for the measurement of primary hazards includes the development of more robust instrumentation accompanied by and in service of increased data collection and monitoring.

- Increased temporal resolutions and duration of wind and wave measurements to capture fluctuations.
- Explore un-manned or long-range alternative solutions to sensor placement and other instrument deployments (e.g., drones) to avoid or greatly reduce personnel exposure and reduce mobilization times.
- There have been instances where instrumentation has been stolen, lost, or damaged by the event. To reduce the magnitude of losses, financially or of data, it is of interest to develop and use low-cost sensors.
- Calibrate and test instrumentation during smaller scale events.
- Integration of machine learning or artificial intelligence methods to conduct image-based analyses. This requires a baseline training dataset.
- Utilize expanded data collection of wind and surge to validate and further improve interaction models.
- Archive storm hindcasts and alternative model runs (e.g., predictions several hours prior to landfall) for local-scale modeling and for predictive impacts.

8.7.2. Strategies for Understanding Secondary/Cascading Hazards

Strategies associated with secondary or cascading hazards were focused around both improved measurements and mitigation for future scenarios.

- Integration of natural (e.g., mangroves, dunes) and hybrid strategies (e.g., natural features covering or staggered with seawalls) for coastal protection. This requires first the investigation of their performance either in situ or in experimental and numerical campaigns in order to optimize and standardize practice in the field.

- Develop better measurements to estimate the impacts of currents, particularly during water recession when flows carve out channels in the beaches.
- Improve risk modeling that evaluated debris pathways and impacts on structures including during storm retreat.
- Evaluate performance of structural components (e.g., ability to resist uplift forces) influence of orientation of breakaway walls.

8.7.3. Strategies for Understanding Hazard Impacts

Strategies for understanding and reducing hazard impacts are largely centered around increasing participation across different groups and developing the means for communicating potential, ongoing, and final work.

- Coordination across agencies, stakeholders, and researchers at multiple scales would help reduce redundancies but also requires the creation and use of standardized field data formats, collection protocols, and performance metrics.
- The collected data should be archived and available to be utilized as development of a test-bed for additional works.
- Engage with communities to communicate the benefits of mitigation investments and incentivize participation. This participation could include being hosts of sensors in return for insurance discounts or improved recovery tools. Communication with communities may include showing comparative outcomes based on previous and preliminary research.

9. Session #5: From Strategies to Action Plans

Session #5 is the culmination of the previous sessions where workshop participants were seated at six Tables (A-F) tasked with developing action plans for selected strategies from the previous discussions and presentations. Discussions at the various sub-groups addressed topics such as in-situ measurements of water ingress (Table A) and of building response to wind and water hazards (Table B), of hazard modeling and products (Table C), of translating research into practice (Table D), of expanding fragility libraries to address modeling needs (Table E), and of the development of a next-generation hurricane testbed (Table F).

9.1. Table A: In-Situ Measurements of Water Ingress

Participants discussed the issue of water ingress and strategies for measuring the impacts. The majority of economic losses in hurricanes is caused by water ingress and the ensuing damage to interior contents. Water has many pathways into a building during a hurricane, including the following:

- Through the direct action of storm surge and/or waves
- Through an unsealed roof deck if the roof cover has sustained damage
- Through the soffits, which are often permeable and/or damaged
- Through windows or doors when the combination of wind pressure and rain drives water through gaps in the component assemblies
- Through windows or doors when these components have been damaged by wind-borne debris or wind pressure
- Through inland flooding induced by heavy rain or tidal surges

Participants recognized that obtaining information on water ingress is particularly difficult because it is invasive to communities due to the need to access the interior of structures, and because it is highly time sensitive if high quality measurements are needed. To address the need, participants discussed several possible strategies for measuring or estimating interior water damage, mostly focusing on strategies related to surveying impacted communities, deploying in-situ sensors of some kind, and utilizing remote sensing (e.g., aerial imagery, surface-level, vehicle-mounted panoramas) and are listed in Table 9-1.

Table 9-1. Strategies and considerations for in-situ measurements at the Rodanthe testbed

Strategy	Pros	Cons
Community Surveys Methods may include structured interviews with impacted populations, online survey instruments, on-site solicitations in impacted communities.	● Can be targeted to specific communities of interest where known impacts occurred ● Highly adaptable - can range from broad yes/no impact surveys to detailed interviews and interior inspections ● Can snowball once initial contacts are made, leveraging realty management companies and others as partners ● Can be broadened to also include related topics such as exterior damage, decision-making, recovery, etc	● It is very difficult to make connections post-disaster due to long-term stressors, population displacement, community fatigue, etc. ● Self-reported impacts can have high uncertainty ● Post-processing and standardization can be challenging depending on survey methods ● On-site surveys in communities are time-consuming - difficult to obtain large sample sizes
Remote Sensing Using aerial or ground-based imagery, both in the visible and infrared spectrum, to estimate or measure water ingress through residual moisture in building components, debris piles, etc.	● Minimally invasive to the affected communities ● Widespread coverage possible within affected communities at relatively low cost ● Broader use cases of the data beyond just water ingress estimation (e.g., tracking recovery) ● Relatively easy to consistently replicate methods across multiple events	● Highly time sensitive - e.g., must capture debris piles after they have been put out to the road but before removal by debris management companies ● Post-processing the imagery into structured data is time-consuming ● Difficult to distinguish different types of water-damaged components in debris piles ● Difficult to capture the source of the water ingress
In-Situ Sensors Pre-deployed sensors (e.g., moisture detection, mold detection) in buildings that collect physical measurements of water ingress or water ingress effects	● Can be beneficial to building owner at all times for maintenance, i.e., SmartHome concepts ● Less invasive post-event so long as sensor data is wirelessly transmitted ● Provides physical measurements that can be analyzed and optimized through experiments	● Need high coverage to maximize likelihood of useful data ● Sensor technology needs further development to create an optimal package ● More expensive unless populations see value and community-driven uptake occurs ● Privacy concerns ● Unclear how well sensors can accurately measure holistic water ingress and impacts

9.2. Table B: In-Situ Measurements - Wind Hazards, Water Hazards, Building Response (Rodanthe Testbed)

Participants in this session focused on the Rodanthe Testbed, an in-situ opportunity to instrument and observe the failure of houses in Rodanthe, North Carolina. Specifically, participants were asked to consider the following: what are we measuring, how are we measuring, and why or what do we want to learn? Phases of consideration can be subdivided between (1) initial actions before and in the early stages of the experiment and (2) once the house collapses.

Initial action includes determining foundation stability from wave loads, characterizing velocities, deploying scour sensors and more. Action items for this phase may include verification of pile depth so that the structure can be modeled even if simplifications are made to the design. When the building disintegrates, floating debris is generated which can further be measured at least visually. This last component is currently an area of uncertainty in the codes. The methods to capture and measure these phases and considerations includes largely the photography and videoing of the events at different angles and with different focal points. Herein, issues for consideration include how to ensure permanent or continuous power sources and storage for capturing these feeds over the necessary period. Additional instrumentation may include accelerometers, tilt meters, pressure sensors, and more but these also require considerations for things such as channel limitations or the small impact speeds of debris in oscillating flows. Altogether, participants looked to integrate novel approaches to making measurements based on previous work and techniques while maintaining safe practices (Table 9-2).

Table 9-2. Strategies and considerations for in-situ measurements at the Rodanthe testbed

Strategy	Considerations
Have sensors when, not if, the buildings collapse. Including instrumentation of the piers.	Considerations for continuous long term sensor deployment are associated with logistics of permitting and instrumentation types: ● Permanent or continuous power is useful and would likely reduce the budget compared to intermittent battery replacement ● Continuous measurements and unpredictability of time of failure mean there is a need for capturing imagery at night. Maybe use near-infrared camera that shines on target area ● Less invasive fixtures are easier to market, so what instrumentation is permanently affixed to the structure and where can we adapt (e.g., ratchet straps)
Use Sentinel, a state-of-of-the-art monitoring station that can be operated in and measure extreme conditions, to capture data.	Can be useful independently (instrument package is useful whether its attached to a sentinel pole or a utility pole) ● Deployed on existing infrastructure means wind and water sensors would likely be separated (i.e. water sensors on home piles and wind sensors further inland) ● Deployed between houses requires clearances when they fall over and/or generate debris

9.3. Table C: Hazard Modeling, Part 1 - Advancing the Flood Hazard Models to Local Scale and Part 2 - From Hazard Models to Hazard Maps

Existing surge and wave modeling approaches seem to overall be doing a good job of capturing the peak water levels at the shoreline. However, impacts at the building scale are dependent on local scales that are currently not captured by the regional models. Participants in this session discussed strategies for bringing regional scale models down to smaller, local scales so that features such as shielding effects and local topography (channels and berms) can be included in capturing impacts. Regional-scale models perform well, but local-scale predictions are more variable, as demonstrated by underpredictions of high-water marks during Hurricane Ian. Mechanisms and impacts that might better be captured through the developments of these local scale models are: flow velocity, wave energy and spectra, and other effects that govern building loads, scour and erosion, and other impacts. The findings from this work would contribute greatly to the development of hazard maps

The following considerations were discussed during this session, some accompanied by strategies and action plans:

- Buildings and surface friction are not well represented in current models, affecting accuracy.
- The channel algorithm in ADCIRC helps model compound flooding and inland flow, but automating grid creation remains a challenge.
- Coupling XBeach results with ADCIRC could improve wave and morphodynamic modeling.
- Rainfall can be included in ADCIRC, but assigning dry land values and compound flooding directions is difficult.
- Additionally, switching to a finite-volume approach could improve rainfall modeling.
- Hurricane Ian provides a rich dataset for refining hazard models, but more wave data is needed for better hazard mapping.
- SST synthetic storm translation, funded by FEMA, is a promising technique for improving storm modeling.
- Coupling multiple models is the best approach, as some existing models are outdated.
- Community engagement may be more effective than relying solely on agencies for resilience planning.

9.4. Table D: Translating Research (Experimental, In-Situ, Numerical) into Existing Standards

This session addressed some key concepts, knowledge gaps, and proposed solutions identified by participants that would contribute to improving standards. To begin, participants identified the importance of characterizing hazards specifically through the development of better maps which may show exposure category, velocities, wake effects, and flow accelerations. These are meant to not only demonstrate the impact the hazards will have but also to cross compare pre- and post-standard conditions. The impacts of these hazards would include components such as forces. Currently some data exists for upward forces and equivalent static loads but more is needed especially for enclosed spaces. Additional areas of research of interest include debris that may be generated from these hazards. Considerations for a pre-standard for debris may be coupled with additional research on debris source, destination, and damming loads. The interactions between wind and flood loads currently does not have much guidance and may have opposing designs that correspond to differing hazards (e.g., homes on stilts with cross bracing may contribute to debris damming). Though standards are generally effective for new construction, this session also addressed the importance of retrofitting to ensure existing buildings may be better aligned with existing standards. Table 9-3 lays out a summarized version of the strategies that may be useful for translating research to practice.

Table 9-3. Summary of strategies developed to address needs in translating research to practice

Gaps in Understanding	Strategies or Action Plans
Hazard Mapping Mapping that captures potential hazard risks and can be used for comparative analysis.	● Consider and communicate exposure categories ● Create pre-standard mapping as a baseline for which simulations may be compared ● Include visualizations of velocities, wake effects, flow accelerations
Forces Exploration of hydrodynamic forces on structures requires additional data.	● Evaluate upward forces especially for enclosed spaces and balconies ● Coordinate with engineers designing seawalls to better understand equivalent static loading ● Guidance needed on combined loading (e.g., wind and flood) and study trade-offs
Debris Pre-standards may be needed for debris but the movements and loading are still unknown.	● Continue studying debris behavior (sources, paths, and impacts) ● Damming effects in particular are of high impact and interest
Structural Design The use of components and cladding as well as breakaway walls and their behaviors under storm conditions.	● Continue innovation of breakaway walls, especially for masonry ● Build off of work on components and cladding currently conducted by IBHS and develop construction documents ● Account for shielding ● For existing buildings consider retrofit options ● Develop a joint ASCE/SEI-NIST workshop for industry and include: Home builders; Flood industries; Material; AISC; masonry; Carbon fiber. ICMA – county/city managers association; ICC

9.5. Table E: Expanding Fragility Libraries for Improved Modeling of Wind and Water Impacts

In this session, participants discussed the expansion of fragility functions, an essential tool to modeling community resilience. The seismic community has well established methods for generating fragility functions, and extensive libraries of fragility functions across a diversity of building types and component types. Fragility libraries for hurricane loading, including both wind and water impacts, are relatively minimal. The Hazus Hurricane fragilities are over 20 years old now, and have not been updated to reflect the latest wind tunnel modeling and building archetypes and materials, and lack open-source tools for generating the fragilities. IN-CORE (The Interdependent Networked Community Resilience Modeling Environment) and the NHERI SimCenter have more recently developed fragility libraries, but there is a lack of consensus in the existing methodologies (e.g., IN-CORE wind fragilities lack internal pressure updating as building components fail), fragility libraries for wind and water loading combined are lacking, and fragility libraries for both wind and water independently are still relatively sparse.

Participants discussed fragilities within the context of functionality and network analyses which may leverage IN-CORE as a framework for this broader community resilience modeling. Of note was also the process of mapping archetypes and retrofit strategies to individual communities and the uncertainties inherent to that process; these propagate to the downstream impacts. Other programs of note were the USACE uses of Beach FX for investigating primary structure impacts which utilizes fragility models that are updated through new storms though downstream impacts aren't considered. The USACE is also working on the Coastal Hazard Analysis and Risk Toolkit.

The following strategies were discussed to better capture wind and water impacts through building out fragility libraries:

- We need an initial baseline/library for what is available for different infrastructures. Similar work has been done in earthquake engineering.
- Select a building type and show different approaches to develop fragility curves.
- Compare methods for developing proper multi-hazard fragility functions. What are the best approaches to using new data to develop new fragility functions? What is the level of complexity for each method?
- Develop a standard damage assessment method to gather data for future events to be used later as input for developing a multi-hazard fragility function.
- Identify essential parameters that must be included in multi-hazard fragility functions, such as distance from shoreline, wave height, built year, and foundation type. We need to leverage the Hurricane Ian database.
- We need to move forward with developing multi-hazard fragility functions of other infrastructure, such as the transportation system.
- Developing fragility function for different components such as breakaway walls leveraging available data.

- Ensure that the developed fragility functions (the method) are consistent with the functional recovery framework for the community.
- Develop damage scale/state for different building occupancies (e.g., multi-story buildings) so these can be fed into fragility functionality development.
- We need to include structure-soil interaction to look at the foundation failure. There has been some ongoing research in this field (https://www.cive.uh.edu/faculty/kalliontzis)
- Aging and deterioration need to factor in fragility functions. Also, what about the repeating events? For example, time-dependent fragility functions for coastal damage assessment.

9.6. Table F: Next-Generation Hurricane Testbed Design

This session discussed the need for and design of next-generation hurricane testbeds to facilitate long-term goals of understanding and advancing community hazard resilience. Participants noted that the idea of hurricane testbeds is not new, but there needs to be a common definition and design for holistic hurricane testbeds that can be used across the many disciplines involved since disciplines often have narrow existing concepts of testbeds that can be quite different from that of other disciplines (Enderami et al. 2022) [12]. For example, the NOAA Weather Program Office established the Hurricane and Ocean Testbed (AOML, 2022) [13], which it defines as a physical and virtual collaboration space for researchers and forecasters to integrate research into improved forecasts of hurricane intensity. This concept differs from the NIST Center of Excellence IN-CORE and the NSF NHERI SimCenter testbeds, which are digital representations of real or virtual communities that include buildings, infrastructure systems, terrain, community functions, and more for which models of hazards can be used to evaluate impacts and resiliency. The participants of this breakout discussion envisioned a concept more similar to the IN-CORE and NHERI SimCenter testbeds, whereby each testbed represents a community or collection of communities impacted by a specific event (e.g., Cape Coral, Sanibel, Fort Myers, and Fort Myers Beach during Hurricane Ian in 2022). This next-generation hurricane testbed should include the data that define the hazard, the exposure, and the vulnerability (physical and social) using consistent data formatting and standards across multiple events.

Participants spent the majority of the session discussing the end goal, core elements, and action plan of these proposed next-generation testbeds. The key discussion points within each of these focus areas are summarized in Table 9-4.

Table 9-4. Summary of key discussion points related to next-generation hurricane testbeds

End Goals:	Core Elements:	Action Plan:
• Platform for understanding total community hazard resilience • Repository of cross-disciplinary data that is temporally and spatially defined, easily accessible, and supports analysis and model validation • Long-term sustainability • Consistent testbed design and structure across different communities and events	• In-situ measurements with confidence levels or uncertainty estimation and necessary metadata • Pre-event exposure data, such as building footprints and attributes, physical infrastructure, LiDAR • Data representing performance observations from remote and on-site reconnaissance efforts, such as post-event LiDAR, aerial and surface-level imagery, and building-scale performance assessments • Longitudinal data defining recovery • Hub and node approach for integration of modeling and validation efforts	• Data inventory for recent events (e.g., Hurricane Ian (2022)) • Identify gaps and data needs for robust modeling (hazard, impacts, recovery) and validation of community resilience • Examine past testbed efforts, both US-based and international, to identify best practices • Engage stakeholders across government agencies, academia, and private industry early to foster buy-in and collaborative design and participation • Develop robust cross-disciplinary data integration (both physical and modeled) frameworks • Develop optimal data archival structure and long-term maintenance strategies to maximize lifespan • Begin with Hurricane Ian (2022) as a test case

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Appendix A. List of Participants

Table A-1. In Person Participants

First	Last	Affiliation
Shafiq	Alam	University of Hawaii
Mehrshad	Amini	University of Rhode Island
Aaron	Anton	Oregon State University
Josette	Audi	University of Rhode Island
Chris	Bender	Taylor Engineering
Stefano	Biondi	University of Florida
Graham	Brasic	Jezniac Group
Jennifer	Bridge	University of Florida
Tanya	Brown-Giammanco	National Institute of Standards and Technology
Dave	Butry	National Institute of Standards and Technology
Joel	Cline	National Institute of Standards and Technology
Dan	Cox	Oregon State University
Shane	Crawford	University of Alabama
Chris	Daly	Florida Gulf Coast University
Trung	Do	University of South Alabama
Pedro	Fernandez-Caban	Florida State University
Mewcha	Gebremedhin	Florida Gulf Coast University
James	Kaihatu	Texas A&M University
Marc	Levitan	National Institute of Standards and Technology
Rick	Luettich	University of North Carolina
John	Madden	CDMSmith
Amina	Meselhe	Oregon State University
Wesam	Mohamed	University of Illinois
Jo	Muller	Florida Gulf Coast University
Omar	Nofal	Florida Int. University
Jamie	Padgett	Rice University
Brian	Phillips	University of Florida
David	Prevatt	University of Florida
Tim	Reinhold	
Spencer	Rogers	North Carolina Sea Grant (retired)
David	Roueche	Auburn University

Don	Scott	Don Scott Consulting
Don	Slinn	National Institute of Standards and Technology
Jane	Smith	University of Florida
Seneshaw	Tsegaye	Florida Gulf Coast University
Mike	Uduebor	Florida Gulf Coast University
David	Webb	National Institute of Standards and Technology
Johannes	Westerink	Notre Dame University

Table A-2. Virtual Contributors[a]

First	Last	Affiliation
Jenna	Brown	US Geological Survey
Frank	Lombardo	University of Illinois
Jean-Paul	Pinelli	Florida Institute of Technology
Tom	Smith	TLSmith Consulting Inc.

[a] Did not attend workshop but contributed to report

Appendix B. Agenda

Location: The Water School, Florida Gulf Coast University, Room 138

Detailed Agenda:

Table B-1. Day 1: Monday, March 17, 2025

Time	Activity	Details
8:30 am	Check-in	Coffee, pastry provided
9:00 am	Plenary	Self-introductions (all)
		Overview and Workshop Goals (Tanya Brown-Giammanco, Dan Cox, David Roueche)
9:15 am	Session 1	Wind and Flood Hazard Presentations (Rick Luettich, Brian Philips, Jim Kaihatu, 10 min each)
9:45 am		Table discussion (45 min)
10:30 am		Group report out (15 min)
10:45 am	Break	Coffee provided
11:00 am	Session 2	Wind and Flood Cascading Hazard Presentations (Jane Smith, Jamie Padgett, David Webb; 10 min each)
11:30 am		Table discussion (30 min)
12:00 pm		Group report out (15 min)
12:15 pm	Lunch	Provided
12:45 pm		Measurements and Modeling of Hx Ian, Helen, and Milton (Chris Daly, 30 min)
1:15 pm	Session 3	Wind and Flood Impact Presentations (Shafiq Alam, Mehrshad Amin; 10 min each)
1:45 pm		Table discussion (45 min)
2:30 pm		Group report out (15 min)
2:45 pm	Break	Snacks provided
3:00 pm	Session 4	Strategies to Improve Measurement Science Presentations, Part 1 (Jennifer Bridge, David Roueche, Marc Levitan; 5 min each)
3:15 pm		Table discussion (30 min)
3:45 pm		Group report out (15 min)
4:00 pm		Strategies to Improve Measurement Science Presentations, Part 2 (Graham Brasic, Adam Zsarnoczay, Dan Cox, 5 min each)
4:15 pm		Table discussion (30 min)
4:45 pm		Group report out (15 min)
5:00 pm	Summary	Day 1 Summary (Dan Cox, David Roueche)
5:15 pm	Adjourn	
6:30 pm	Dinner	Ford’s Garage Estero (10801 Corkscrew Rd, Estero, FL)

Table B-2. Day 2: Tuesday, March 18, 2025

Time	Activity	Details
8:15 am	Check in	Coffee, pastry provided
8:30 am	Plenary	Day 1 Recap and Day 2 Goals (David Roueche, Dan Cox)
9:00 am	Session 5	Action plan (Part 1)
9:15 am		Table discussion (30 min)
9:45 am		Group report out (15 min)
10:00 am		General discussion (15 min)
10:15 am	Break	Coffee provided
10:30 am	Session 6	Action plan (Part 2)
10:45 am		Table discussion (30 min)
11:15 am		Group report out (15 min)
11:30 am		General discussion (15 min)
11:45 am	Summary	Day 2 summary
12:00 pm	Lunch/Tour	Box provided, Depart for tour
1:00 pm	Tour	Optional post-workshop tour, Fort Myers Beach recovery (van provided)
5:00 pm	Conclude	(van returns to hotel; dinner on your own)