Hurricane Ian
Released: November 16, 2022
NHERI DesignSafe Project ID: PRJ-3709

PRELIMINARY VIRTUAL RECONNAISSANCE REPORT (PVRR)

Image Source: Wilfredo Lee, AP

Virtual Assessment Structural Team (VAST) Lead: Maria D. Cortes Delgado, University of Puerto Rico-Mayagüez	
Virtual Assessment Structural Team (VAST) Authors (in alphabetical order)	
Prateek Arora, New York University Luis Ceferino, New York University Haitham A. Ibrahim, Florida International University Denis Istrati, University of Nevada Reno	Dorothy Reed, University of Washington David Roueche, Auburn University Amir Safiey, Auburn University Tori Tomiczek, US Naval Academy Ioannis Zisis, Florida International University
PVRR Editors (in alphabetical order)	
Mohammad Alam, University of Notre Dame Tracy Kijewski-Correa, University of Notre Dame	David O. Prevatt, University of Florida Ian Robertson, University of Hawaii at Manoa

PREFACE

The National Science Foundation (NSF) awarded an EAGER grant (CMMI 1841667) to a consortium of universities to form the Structural Extreme Events Reconnaissance (StEER) Network (see https://www.steer.network for more details). StEER was renewed through a second award (CMMI 2103550) to further enhance its operational model and develop new capabilities for more efficient and impactful post-event reconnaissance. StEER builds societal resilience by generating new knowledge on the performance of the built environment through impactful post-disaster reconnaissance disseminated to affected communities. StEER achieves this vision by: (1) deepening structural engineers' capacity for post-event reconnaissance by promoting community-driven standards, best practices, and training, as well as their understanding of the effect of natural hazards on society; (2) coordination leveraging its distributed network of members and partners for early, efficient and impactful responses to disasters; and (3) collaboration that broadly engages communities of research, practice and policy to accelerate learning from disasters.

Under the banner of the Natural Hazards Engineering Research Infrastructure (NHERI) CONVERGE node, StEER works closely with the wider Extreme Events Reconnaissance consortium to promote interdisciplinary disaster reconnaissance and research. The consortium includes the Geotechnical Extreme Events Reconnaissance (GEER) Association and the networks for Interdisciplinary Science and Engineering Extreme Events Research (ISEEER), Nearshore Extreme Event Reconnaissance (NEER), Operations and Systems Engineering Extreme Events Research (OSEEER), Social Science Extreme Events Research (SSEER), and Sustainable Material Management Extreme Events Reconnaissance (SUMMEER), as well as the NHERI RAPID equipment facility, the NHERI Network Coordination Office (NCO), and NHERI DesignSafe CI, curation site for all StEER products.

While the StEER network currently consists of the three primary nodes located at the University of Notre Dame (Coordinating Node), University of Florida (Southeast Regional Node), and University of California, Berkeley (Pacific Regional Node), StEER is currently expanding its network of regional nodes worldwide to enable swift and high quality responses to major disasters globally.

StEER's founding organizational structure includes a governance layer comprised of core leadership with Associate Directors for each of the primary hazards as well as cross-cutting areas of Assessment Technologies and Data Standards, led by the following individuals:

- **Tracy Kijewski-Correa (PI),** University of Notre Dame, serves as StEER Director responsible for overseeing the design and operationalization of the network and representing StEER in the NHERI Converge Leadership Corps.
- **Khalid Mosalam (co-PI),** University of California, Berkeley, serves as StEER Associate Director for Seismic Hazards, serving as primary liaison to the Earthquake Engineering community.
- **David O. Prevatt (co-PI),** University of Florida, serves as StEER Associate Director for Wind Hazards, serving as primary liaison to the Wind Engineering community.
- **Ian Robertson (co-PI),** University of Hawai'i at Manoa, serves as StEER Associate Director for Coastal Hazards, serving as a primary liaison to the coastal engineering community and ensuring a robust capacity for multi-hazard assessments.
- **David Roueche (co-PI),** Auburn University, serves as StEER Associate Director for Data Standards, ensuring StEER processes deliver reliable and standardized reconnaissance data suitable for re-use by the community.

This core leadership team works closely with StEER Research Associates, Data Librarians and its Student Administrator in event responses, in consultation with its Advisory Boards for Coastal, Seismic and Wind Hazards.

ATTRIBUTION GUIDANCE

Reference to PVRR Analyses, Discussions or Recommendations

Reference to the analyses, discussions or recommendations within this report should be cited using the full citation information and DOI from DesignSafe (these are available at https://www.steer.network/products).

Citing Images from this PVRR

Images in this report are taken from public sources. Each figure caption specifies the source; re-use of the image should cite that source directly. Note that public sources might still have copyright issues and depending on the use case, the user may need to secure additional permissions/rights from the original copyright owner.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. CMMI 2103550. Any opinions, findings, and conclusions or recommendations expressed in this material are those of StEER and do not necessarily reflect the views of the National Science Foundation. All authors and editors listed on the cover page participate as volunteer professionals. Thus, any opinions, findings, and conclusions or recommendations expressed herein are those of the individual contributors and do not necessarily reflect the views of their employer or other institutions and organizations with which they affiliate.

Special thanks also go to our Student Administrator, Ella, for monitoring outage/access and restoration data used in this report. StEER further extends its appreciation to all those individuals who contributed case studies to the media repository.

The sharing of videos, damage reports and briefings via Slack by the entire NHERI community was tremendously helpful and much appreciated. StEER recognizes the efforts of the DesignSafe CI team who continuously supported and responded to StEER's emerging needs.

For a full listing of all StEER products (briefings, reports and datasets) please visit the StEER website: https://www.steer.network/products

TABLE OF CONTENTS

PREFACE 2

ATTRIBUTION GUIDANCE 2

Reference to PVRR Analyses, Discussions or Recommendations 3

Citing Images from this PVRR 3

ACKNOWLEDGMENTS 4

TABLE OF CONTENTS 5

Common Terms & Acronyms 6

EXECUTIVE SUMMARY 8

1. Introduction 8

1.1. Loss of Life and Injuries 9

1.2. Official Response 9

1.3. Report Scope 11

2. Hazard Characteristics 11

2.1. Meteorological Background 11

2.2. Wind Field 13

2.3. Storm Surge and Coastal Flooding 14

2.4. Rainfall and Inland Flooding 17

2.5. Tornadoes 18

2.6. Comparative Case: Hurricane Charley (2004) 19

3. Local Codes and Construction Practices 20

4. Building Performance 22

5. Infrastructure Performance 25

5.1. Power Outages & Restoration 26

5.2. Transportation Disruptions & Restoration 28

5.3. Telecommunications 32

6. Coastal Protective Systems Performance 33

7. Recommended Response Strategy 33

Appendix A. Loss Estimates 37

Appendix B. Evacuation Orders 38

Appendix C. Hazard Observations 39

References 41

Common Terms & Acronyms

Acronym	General Terms	Brief Description
--	DesignSafe	Data Repository
--	DesignSafe-CI	Academic Organization within NHERI
ASCE	American Society of Civil Engineers	Professional Organization
BOCA	Building Officials and Code Administrators	Code Body
CC-BY	Creative Commons Attribution License	Code/Standard
CESMD	Center for Engineering Strong Motion Data	Federal/State Agency
CI	Cyberinfrastructure	Research Asset
CLPE	Critical Load Path Elements	StEER Term
CMU	Concrete Masonry Unit	Building Material
DOI	Digital Object Identifier	Common Term
EF	Enhanced Fujita	Intensity Measure
EF	Equipment Facility	Academic Organization within NHERI
FAA	Federal Aviation Administration	Federal Agency
FAQ	Frequently Asked Questions	Common Term
FEMA	Federal Emergency Management Agency	Federal Agency
GEER	Geotechnical Extreme Events Reconnaissance	Academic Organization within NHERI
GSA	Government Services Administration	Federal Agency
IBC	International Building Code	Code/Standard
ICC	International Code Council	Code Body
IRC	International Residential Code	Code/Standard
ISEEER	Interdisciplinary Science and Engineering Extreme Events Research	Academic Organization within NHERI
NBC	National Building Code	Code/Standard
NEER	Nearshore Extreme Event Reconnaissance	Academic Organization within NHERI
NHERI	Natural Hazards Engineering Research Infrastructure	Academic Organization within NHERI
NIST	National Institute of Standards and Technology	Federal Agency

NOAA	National Oceanic and Atmospheric Administration	Federal Agency
NSF	National Science Foundation	Federal Agency
NWS	National Weather Service	Federal Agency
OSEEER	Operations and Systems Engineering Extreme Events Research	Academic Organization within NHERI
PEER	Pacific Earthquake Engineering Research center	Academic Organization Focusing on Earthquake Hazard
RAPID	RAPID Grant	Funding Mechanism
RAPID-EF	RAPID Experimental Facility	Academic Organization within NHERI
SPC	Storm Prediction Center	Federal Agency
SSEER	Social Science Extreme Events Research	Academic Organization within NHERI
StEER	Structural Extreme Events Reconnaissance network	Academic Organization within NHERI
SUMMEER	SUstainable Material Management Extreme Events Reconnaissance	Academic Organization within NHERI
USGS	United States Geological Survey	Federal Agency

EXECUTIVE SUMMARY

Eighteen years after Hurricane Charley made landfall in 2004, Hurricane Ian made landfall in nearly the same location, also as a Category 4 hurricane. Unlike Hurricane Charley (2004), water more so than wind was the impetus behind the disaster that unfolded. Despite being a below-design-level wind event, the large windfield drove a powerful storm surge as much as 13 ft high (relative to the NAVD8 vertical datum) in the barrier islands of Sanibel, Ft. Myers Beach, and Bonita Beach. Flooding was extensive along not only the Florida coast, but also well inland into low-lying areas as far north as Duval County and the storm's second landfall site in South Carolina. As such, Hurricane Ian will likely be one of the costliest landfalling hurricanes of all time in the US, claiming over 100 lives.

The impacts from Hurricane Ian were most severe in the barrier islands from the combination of storm surge and high winds, with many buildings completely washed away, and others left to deal with significant scour and eroded foundations. Several mobile/manufactured home parks on the barrier islands fared particularly poorly, offering little to no protection to anyone unfortunate enough to shelter in them. The damage was not restricted to buildings, as the causeways out to the barrier islands were washed away in multiple locations. In contrast, wind damage from Hurricane Ian appears less severe overall relative to other Category 4 storms, perhaps due to a combination of actual wind intensity being less than Category 4 at the surface at landfall, and the improvements in building construction that have occurred since Hurricane Charley struck 18 years earlier. It is notable that extensive losses were in part driven by decades-long construction boom of residential structures in Ft. Myers and Cape Coral since the 1950s and 1960s, expanding communities and neighborhoods encroaching upon vulnerable coastlines. Beyond serving as an important event to validate current and evolving standards for coastal construction, Hurricane Ian provides a clarion call to reconsider the ramifications of Florida's coastal development under changing climate.

This **Preliminary Virtual Reconnaissance Report (PVRR)** is the primary product of the StEER Level 1 response to Hurricane Ian, intended to:

1. provide an overview of Hurricane Ian, particularly relating to wind and storm surge hazards and their impact on the built environment,
2. establish the regulatory environment and construction practices in the affected area,
3. synthesize preliminary reports of damage to buildings and other infrastructure, and
4. provide recommendations which include:
    - Performance of Elevated Buildings Subjected to Coastal Hazards
    - Characterization and Prediction of Coastal Hazards
    - Performance of Nature-Based Protective Systems
    - Performance of Infrastructure Under Coastal Hazards
    - Performance of Power Infrastructure Under Combined Hazards

Serving as a synthesis document, the PVRR is accompanied by a Media Repository providing a rich collection of georeferenced visual evidence cataloged by infrastructure class. Interested readers may also consult the accompanying Outage/Restoration Database for a chronology of disruption/outage/restoration data for power, telecommunications, and transportation networks.

1. Introduction

Hurricane Ian made landfall near Cayo Costa, FL as a Category 4 hurricane according to the National Hurricane Center, with peak sustained wind speeds over water estimated at 150 mph (NHC 2022a), a minimum surface pressure of 940 mb, and preliminary storm surge inundation measurements of 13 ft relative to NAVD88 (USGS, 2022). The results were catastrophic in terms of both damage to infrastructure and loss of human life on the densely-populated west coast of Florida, particularly in the barrier islands off Ft. Myers and Cape Coral. Tragically, preliminary numbers available at the time of this report confirm that Ian has caused over 100 fatalities in Florida, the highest direct loss of life in any hurricane landfalling in Florida since the 1935 Labor Day hurricane. The fatalities are primarily associated with the heavy storm-surge that struck the barrier islands of Sanibel, Ft. Myers Beach, and Bonita Beach. Wind damage was generally less severe, but widespread roof cover loss and other building envelope damage will drive economic losses. Extensive inland flooding due to heavy rainfall was reported across Florida and into the Carolinas as Ian made a second landfall there.

Hurricane Ian will likely be one of the costliest landfalling hurricanes of all time in the US, despite it being a below-design wind event. Risk modelers estimated wind and coastal storm surge losses of $40-$74 billion (see Appendix A). These estimates do not include losses due to inland flooding covered by the National Flood Insurance Program (NFIP) and uninsured losses, which are likely to be high given the extensive inland flooding and low percentage of homes with flood insurance in these areas.

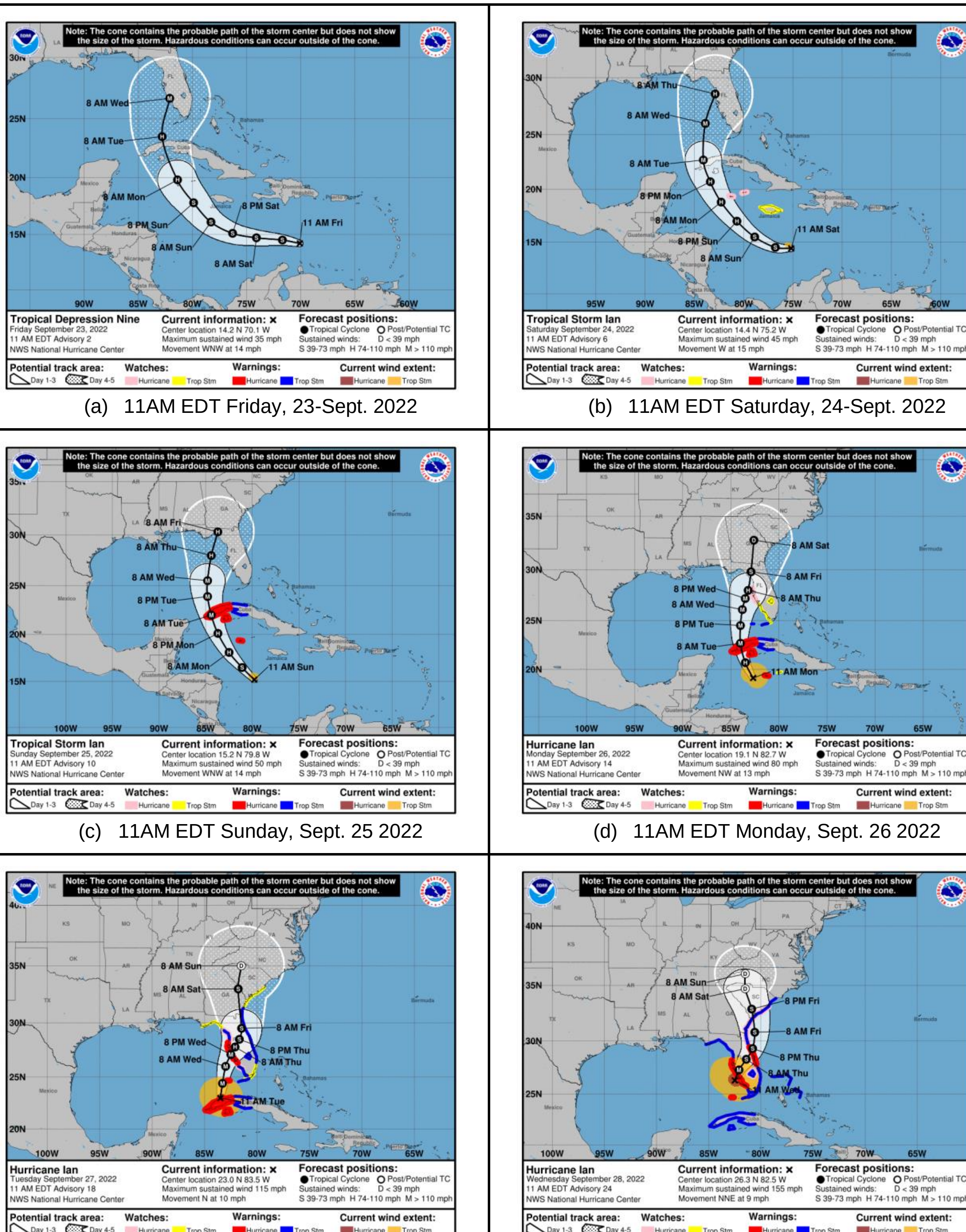
While making landfall in the same location as Hurricane Charley did 18 years earlier, with similar peak sustained wind speeds, damage from Charley was primarily driven by high winds concentrated within a fairly narrow band of this relatively small hurricane. In contrast, Ian was a larger storm and as a result drove a much higher storm surge that was upwards of 13 ft above NAVD88 based on preliminary measurements. The surge impacted regions with high population densities housed in both elevated and on-grade residential structures, including mobile and manufactured home parks, along hundreds of miles of canals and coastal frontage in Cape Coral, Ft. Myers, and nearby barrier islands. Despite the lessons on wind mitigation learned from Hurricane Charley 18 years earlier, these communities were ill-prepared for the storm surge and flooding produced by Hurricane Ian, highlighting vulnerabilities that likely exist in many similar communities along coastlines around the US.

1.1. Loss of Life and Injuries

The storm-related death toll from Hurricane Ian was 125 as of November 10, 2022. The death toll included 119 storm-related fatalities in Florida (FDME, 2022), five in North Carolina, and one in Virginia (Smith et al. 2022). At the time of this report, official numbers were not yet available differentiating between direct and indirect fatalities. The majority of the deaths (57) were reported in Lee County, FL, and an estimated 60% were caused by drowning (WKYC, 2022). The historical context of these numbers remains to be quantified once official direct and indirect fatalities are available. For a preliminary comparison, Hurricane Irma (2017) caused 11 direct deaths and 115 indirect deaths (Issa, 2018). Hurricane Michael (2018) caused 8 direct deaths and 43 indirect deaths (Beven et al. 2019). Hurricane Andrew (1992) caused 15 direct deaths and 29 indirect (Combs et al. 1996).

1.2. Official Response

The earliest forecasts of Hurricane Ian targeted the gulf coast of Florida (Fig. 1.1). As time progressed, the forecast track shifted from the Ft. Myers region (Advisory 2, 11AM EDT Sept. 23rd) to the Big Bend (Advisory 10, 11AM EDT Sept. 25), before trending south with all subsequent forecasts towards the Tampa region (Advisory 14, 11 AM EDT Sept. 26) and eventually Punta Gorda (Advisory 22, 5 AM EDT Sept. 28), which was approximately where Hurricane Ian made landfall.



(a) 11AM EDT Friday, 23-Sept. 2022

(b) 11AM EDT Saturday, 24-Sept. 2022

(c) 11AM EDT Sunday, Sept. 25 2022

(d) 11AM EDT Monday, Sept. 26 2022

(e) 11AM EDT Tuesday, Sept. 27 2022

(f) 11AM EDT Wednesday, Sept. 28 2022

Figure 1.1. Progression of forecast graphics from the National Hurricane Center between September 23-28, 2022. The first evacuation order for Lee County was issued at 7AM EDT on September 27, 2022. Source: [NHC](NHC).

Lee County, the scene of the heaviest impacts, was under a Tropical Storm Warning by 5 PM EDT on Sept. 26th, and a Hurricane Warning by 8 AM EDT on Sept. 27th. The first evacuation order for Lee County (Zone A) was issued at 7 AM EDT on Sept. 27th, approximately 32 hours prior to landfall, and 13 hours prior to the most likely time of the arrival of Tropical Storm force winds (>39 mph) in the Ft. Myers region, as predicted by the National Hurricane Center. Evacuation orders for Zone B of Lee County were issued at 8:30 AM EDT, and for Zone C, covering up to several miles inland, at around 2 PM EDT. See Appendix B for summary of evacuation orders by geography.

At the state level, Governor DeSantis issued a State of Emergency for many of the southern and central peninsular counties in Florida on September 23, 2022 under Executive Order 22-218 (DeSantis, 2022a). The State of Emergency was extended statewide on September 24, 2022 under Executive Order 22-219 (DeSantis, 2022b).

1.3. Report Scope

Hurricane Ian came ashore as a powerful Category 4 hurricane as estimated by the National Hurricane Center, with the large wind field driving catastrophic storm surge levels into densely populated regions of the west coast of Florida. As such, this **Preliminary Virtual Reconnaissance Report (PVRR)** is the primary product of the StEER Level 1 response to Hurricane Ian, intended to:

1. overview of Hurricane Ian, particularly relating to wind and storm surge hazards and their impact on the built environment,
2. establish the regulatory environment and construction practices in the affected area,
3. synthesize preliminary reports of damage to buildings and other infrastructure, and
4. provide recommendations for continued study of this event by StEER and the wider engineering reconnaissance community.

2. Hazard Characteristics

2.1 Meteorological Background

Tropical storm Ian formed over the Central Caribbean Sea on September 23, 2022 with the NHC reporting the possibility of hurricane conditions in the Cayman Islands; a hurricane warning was issued for the Grand Cayman Islands within a day and extended to the Cuban provinces of Isla de Juventud, Pinar del Rio, and Artemisa over the next 24 hours (Fig. 2.1a). Ian was officially classified as a Hurricane on Sept. 26, 2022, with the first hurricane warning for the US issued on the same day. The hurricane warning included the areas from Englewood to the Anclote River, including Tampa Bay, as well as the Dry Tortugas (Fig. 2.1b).

In the next 2 days, Hurricane Ian continued its initially NNW and then NNE path, with rapid strengthening, eventually making landfall on September 28, 2022 near Cayo Costa, Florida, as a Category 4 hurricane (Fig. 2.2). At the time of landfall, the Category 4 hurricane was moving forward (NNE or 15 deg.) at approximately 9 mph, with maximum sustained wind speeds of 150 mph and a minimum central pressure of 940 MB (Fig. 2.3). Shortly after, the NHC reported a wind gusts of 124 mph (200 km/h) at Punta Gorda airport and 128 mph (177 km/h) at a station in Grove City, FL (NHC, 2022b). Based on the landfall reported data, Hurricane Ian is now tied with Hurricane Charley (2004) in terms of landfall intensity on the west coast of the Florida Peninsula. Ian’s mainland Florida landfall occurred approximately 1.5 hrs later, just south of Punta Gorda near Pirate Harbor, with a maximum sustained wind speed of 145 mph and a minimum central pressure of 942 MB.

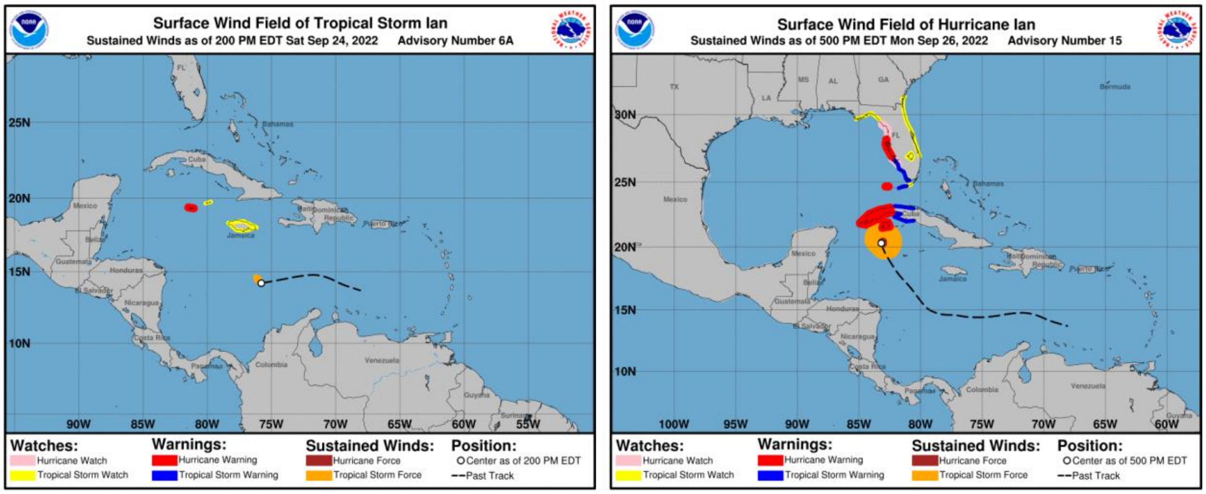


Figure 2.1. Initial wind field and first hurricane warning graphic for (a) Grand Cayman Islands and (b) Tampa Bay region and Dry Tortugas (Source: NHC/NOAA).

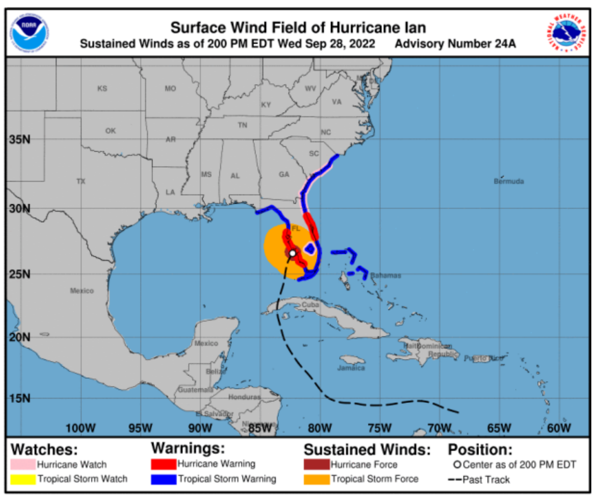


Figure 2.2 Hurricane Ian's path before reaching Florida's West Coast (Source: NHC/NOAA).

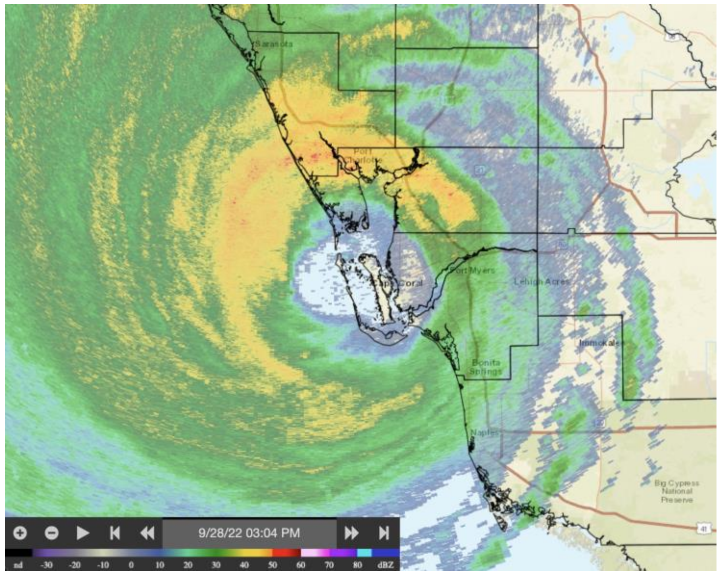


Figure 2.3 Satellite image right before Hurricane Ian made landfall near Cayo Costa, Florida as a Category 4 hurricane (Source: NHC via Twitter).

2.2 Wind Field

Hurricane Ian was categorized as a Category 4 hurricane at landfall (131-155 mph 1-minute sustained winds at 10 m above ground level in open terrain), but surface wind observations published at the time of this report do not corroborate this designation. Appendix C (Table C1) summarizes a collection of surface observations primarily from Automated Surface Observing Systems (ASOS), mobile pre-deployed research towers from the University of Florida and the University of Illinois at Urbana-Champaign, and the WeatherFlow HurrNet and ProNet mesonets. The highest reported gust was 134 mph (3-s gust averaging time, 10 m height, open exposure) by the Punta Gorda Airport ASOS at 4:15pm local time, when winds were out of the east. A Grove City, FL WeatherFlow HurrNet station reported a 130 mph gust from the north at 65 ft AGL over open exposure, which would reduce to ~120 mph at standard meteorological reporting conditions using the Simiu and Scanlan (2003) gust conversion method. Outside of the landfall region, wind gusts between 60 and 85 mph were observed along the east coast of Florida and between Charleston and Myrtle Beach, SC, where Hurricane Ian made landfall for the second time as a Category 1 hurricane.

As illustrated in Figure 2.4, the estimated wind field for Hurricane Ian produced by ARA, conditioned to the surface observations, indicate observed wind speeds were at most 80% of design levels near the Punta Gorda airport. Peak wind loads would thus be ~64% of design levels for a typical building with a 700-year Mean Recurrence Interval (MRI) based on ASCE 7-16.

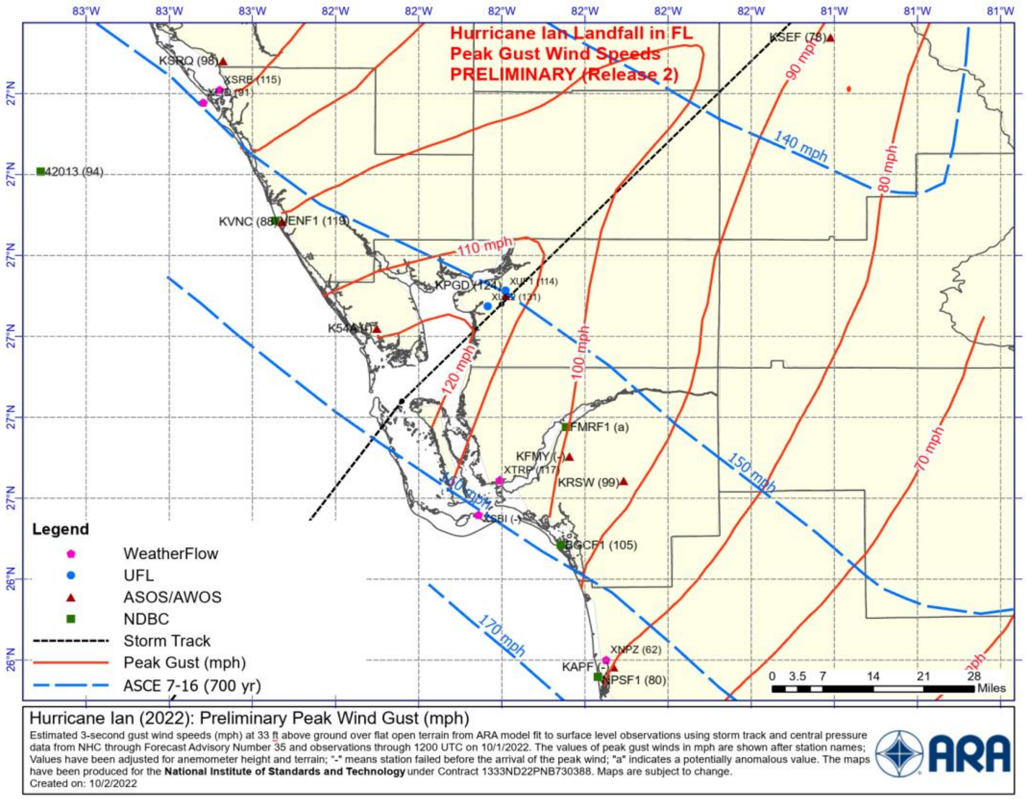


Figure 2.4. Preliminary estimate of 3-second wind gusts (Data Source: ARA, Release 2) with notable surface observations (standardized) and design wind speed contours from ASCE 7-16 for 700-yr MRI.

2.3 Storm Surge and Coastal Flooding

Hurricane Ian generated a significant storm surge causing severe coastal flooding from Port Charlotte to the Upper Florida Keys. Hurricane Ian's size, fueled by the warm waters of the Gulf of Mexico and its slow forward propagation up Florida's Gulf Coast influenced the severity of the surge. Hurricane Ian generated maximum water elevations of over 3 m (10 ft) above mean sea level (MSL) near Fort Myers and Cape Coral. Significant storm tides were also observed in Marco Island and the Upper Florida Keys. Figure 2.5a shows modeled maximum water surface elevations for South Florida output by the ADCIRC Surge Guidance System from Coastal Emergency Risks Assessment (CERA). Following its impacts in Florida, Hurricane Ian made another landfall south of Georgetown, SC on the afternoon of September 30 as a Category 1 storm. Figure 2.5b provides ADCIRC projections for maximum water surface elevations along the Georgia, South Carolina, and North Carolina Coasts provided by CERA.

Nearby tide buoys similarly recorded impacts of the hurricane on tides and water levels. Figure 2.6 shows water levels in meters recorded with respect to MSL at NOAA stations located at (a) East Bay, near the City of Tampa, (b) Port Manatee, near the mouth of Tampa Bay, (c) Fort Myers, and (d) Naples. The hurricane caused a negative storm tide in Tampa Bay, with water levels receding to -2 m (6.5 ft) with respect to MSL at East Bay (Fig. 2.6). The storm tides recorded at the Fort Myers and Naples locations were significant, with peak water levels (referenced to MSL) reaching 2.42 m (8 ft) at the Fort Myers station. Peak water levels at the Naples station reached 2.26 m (7.41 ft) with respect to MSL before the buoy malfunctioned.

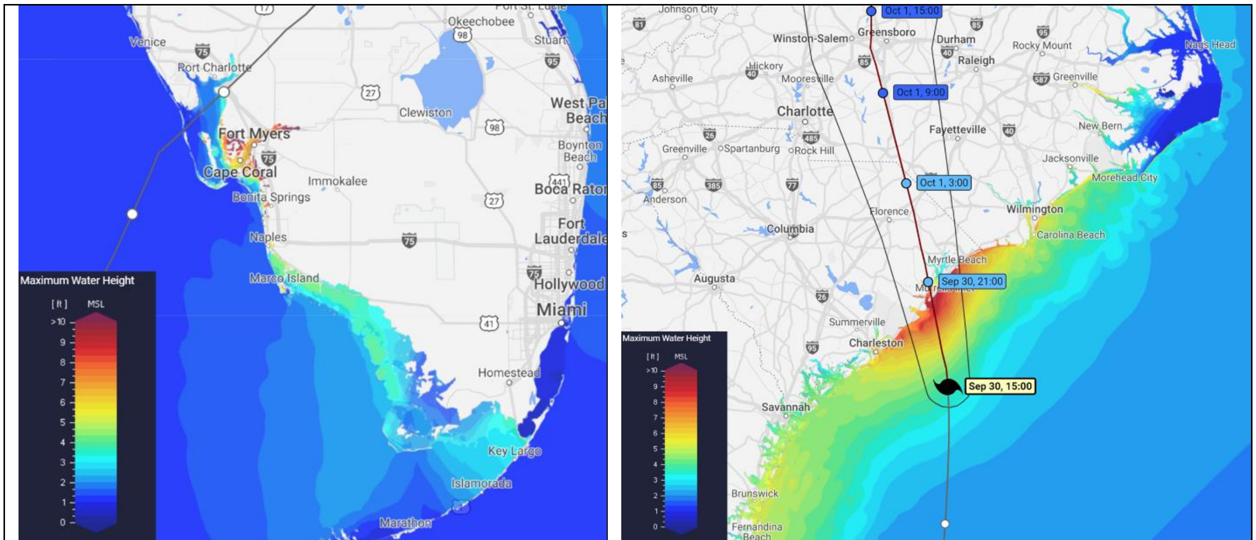


Figure 2.5. (a) Maximum water height above MSL in South Florida, and (b) water surface elevations along the Georgia, South Carolina, and North Carolina Coasts based on ADCIRC Surge Guidance System from Coastal Emergency Risks Assessment (CERA). Heights are shown in ft with respect to MSL (Source: CERA).

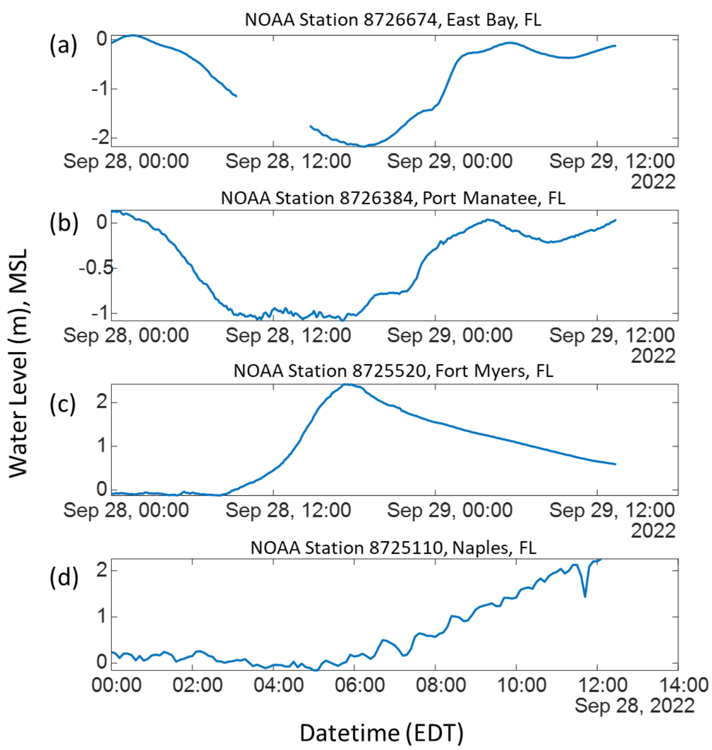


Figure 2.6. Preliminary water levels (m) during Hurricane Ian from 28-29 September, 2022 referenced to MSL at NOAA Stations (a) 8726674, East Bay, FL near City of Tampa; (b) 8726384, Port Manatee, FL near mouth of Tampa Bay; (c) 8725520, Fort Myers, FL; and (d) 8725110, Naples, FL (Data Source: NOAA Tides and Currents).

The storm surge generated by Hurricane Ian was accompanied by riding waves; offshore waves reached 3.4 m (11 ft) during the storm at the NDBC Station, in Egmont Channel Entrance, FL, offshore of Tampa Bay in 12 m (40 ft) water depth. USGS FLWC 17A measured waves of approximately 4 ft atop a storm tide that reached a filtered height of 13 ft above NAVD88 (Figure 2.7) in Sanibel. Surge and riding waves are associated with the significant coastal damages observed along the barrier islands of Fort Myers Beach, Sanibel and Captiva, as described in Sections 4 to 6.

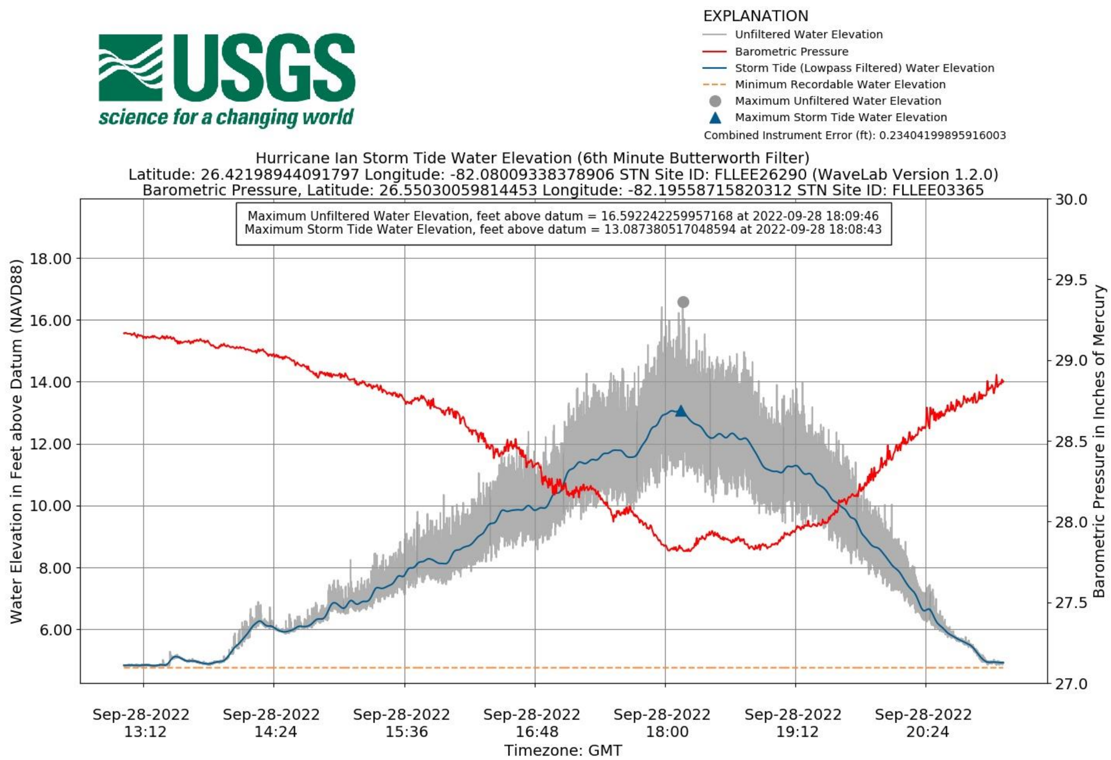


Figure 2.7. Hurricane Ian storm tide water elevation measured at the USGS FLWC 17A (GPS: 26.422, -82.080) (Source: USGS Flood Event Viewer).

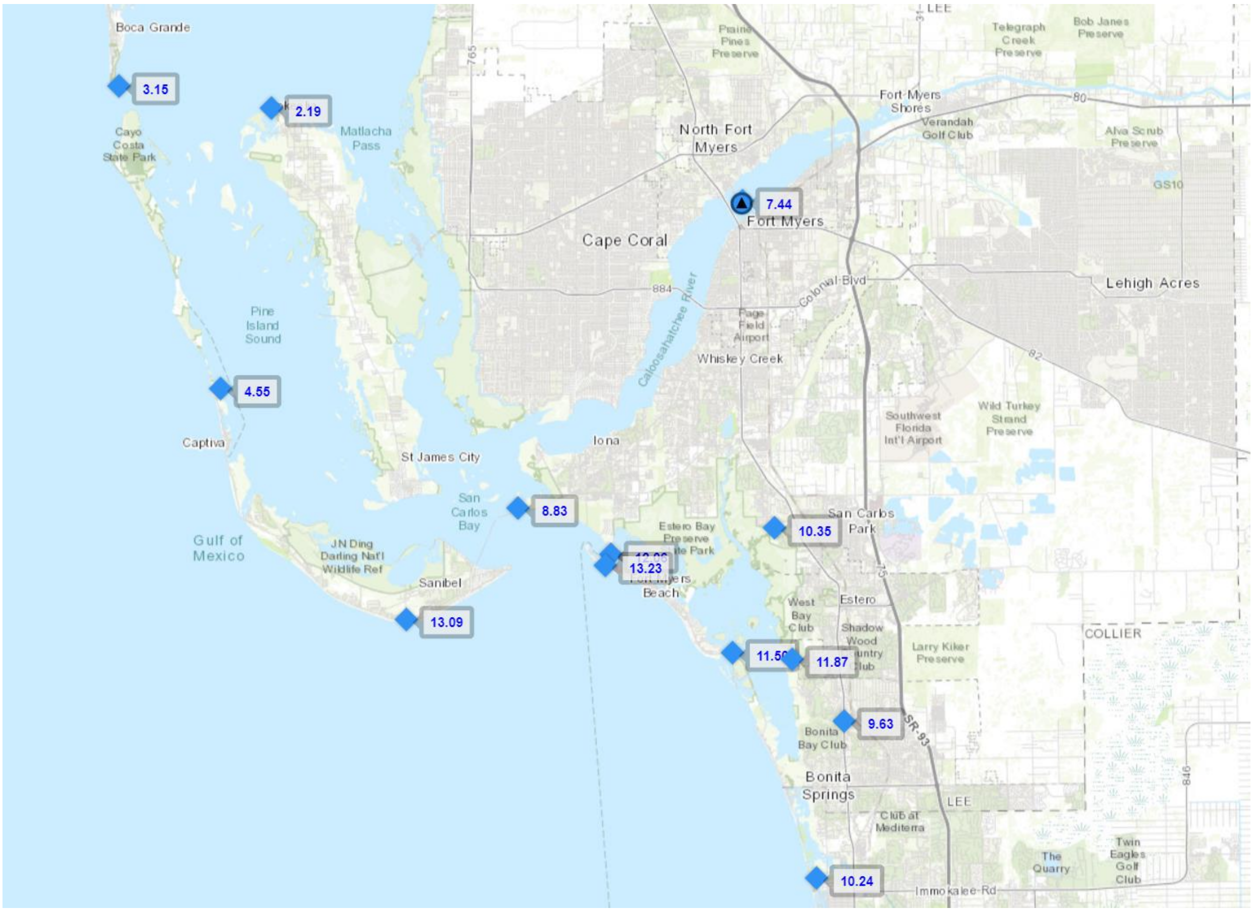


Figure 2.8. High water marks observed in the landfall region. Units are feet and vertical datum is NAVD88 (Source: USGS 2022).

2.4 Rainfall and Inland Flooding

Hurricane Ian dropped heavy rainfall across the state of Florida, as shown in Figure 2.9. Fritz and Miller (2022) reported several locations experiencing a 1000-year (0.001 annual exceedance probability) rainfall event, including Placida (>15 inches in 12 hours) and Lake Wales (almost 17 inches in 24 hours). Appendix C reports locations across Florida for which Ian-induced rainfall totals exceeded 10 inches (Argueta, 2022). Heavy rainfall caused inland flooding across Florida, with flash flood warnings issued for Orange, Osceola, Seminole, Brevard and Volusia counties (Fritz and Miller, 2022). These rainfall totals can be attributed to several factors, including the storm's slow forward progression and large size and warming air temperatures that allow air to hold more water vapor (Van Oldenborgh et al., 2017).

Following landfall in South Carolina, remnants of Hurricane Ian also produced significant rainfall across the mid-Atlantic states of South Carolina, North Carolina, and parts of Virginia and Maryland.

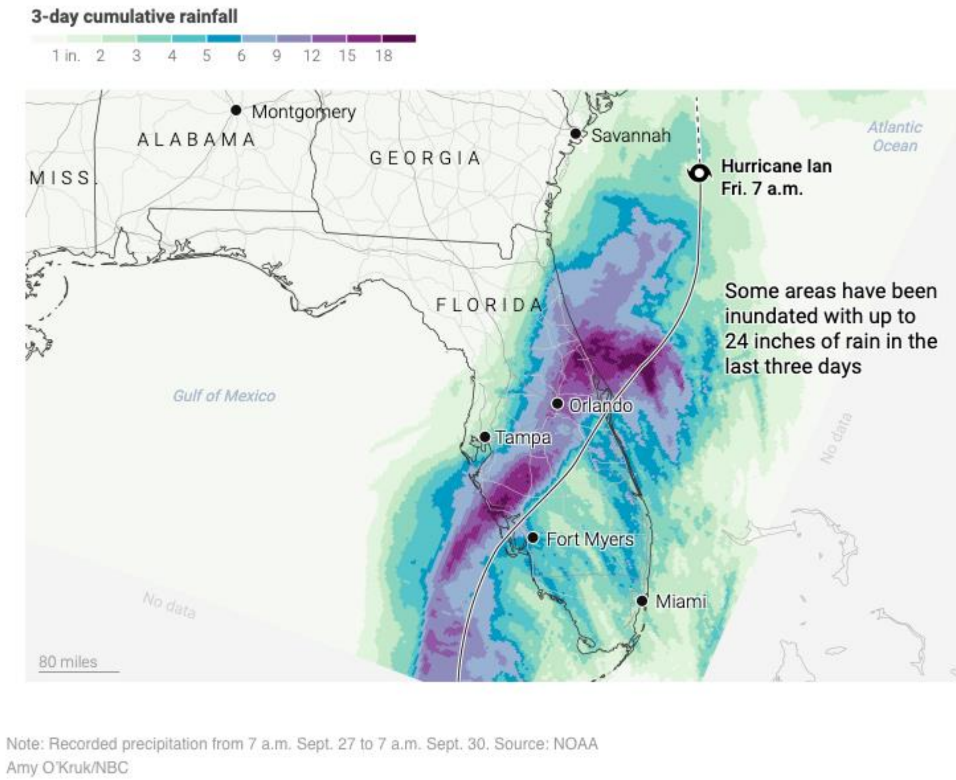


Figure 2.9. Rainfall totals in from Hurricane Ian (Data Source: NOAA; Map Source: Amy O'Kruk).

2.5 Tornadoes

According to the National Weather Service (NWS), there were 139 Tornado Warnings from September 27 to September 30 in Florida, with locations displayed in Figure 2.10. The Storm Prediction Center issued 12 tornado reports in Florida with 11 being on September 27. As of September 30, the Center reported one tornado at Holden Beach, Brunswick County, North Carolina. According to the Public Information Statement of NWS, Miami, FL, these warnings had confirmed at least seven tornadoes with rankings of EF0, EF1, or EF-2 based on the Enhanced Fujita Scale (as of September 30, 2022). Appendix C provides further details on these reported tornadoes. It should be noted that 2 injuries and damage at the Florida Atlantic University Campus were reported as a result of the 130 mph estimated peak wind speed of the EF2 tornado in Boca Raton.

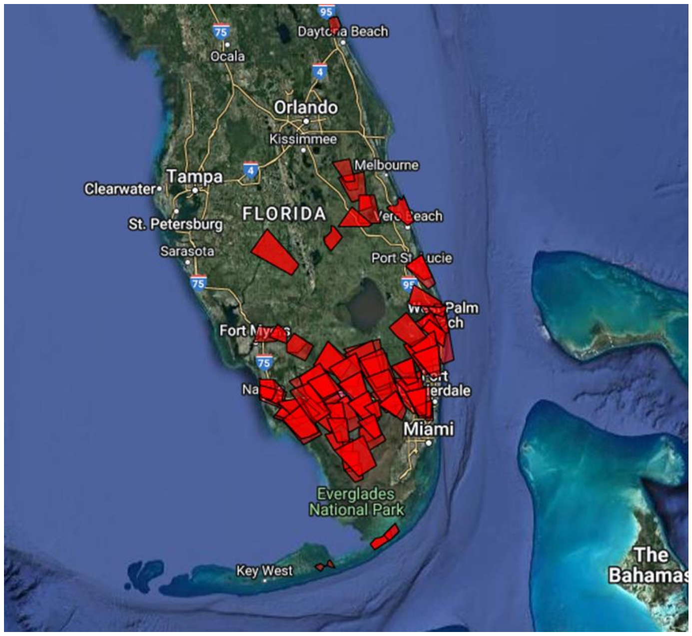


Figure 2.10. NWS issued 139 warnings for tornadoes for 27-30 September 2022. (Source: [Iowa State University Mesonet](#))

2.6 Comparative Case: Hurricane Charley (2004)

Hurricane Ian (2022) has many similarities to Hurricane Charley (2004), including having an almost identical landfall location (Cayo Costa, FL), having the same Category 4 rating at landfall, and having identical or nearly identical maximum sustained wind (150 mph in both) and minimum pressure estimates at landfall (NCEI, 2004). However, the two storms had very different hazard characteristics as summarized by Table 2.1 and Figure 2.11.

Table 2.1. Comparison of Charley and Ian

	Charley (2004)	Ian (2022)
Minimum Pressure	941 mb	940 mb
Peak Official Wind Gust (Punta Gorda Airport)	112 mph* (Right Eyewall)	124 mph (Center Eyewall)
Radius of Maximum Winds	6.9 mi	17 mi
Extent of 100 mph gusts	30 mi	35 mi
Dominant Hazard(s)	Wind	Surge, rainfall
*prematurely failed; peak effects possibly not captured (FEMA, 2005)		

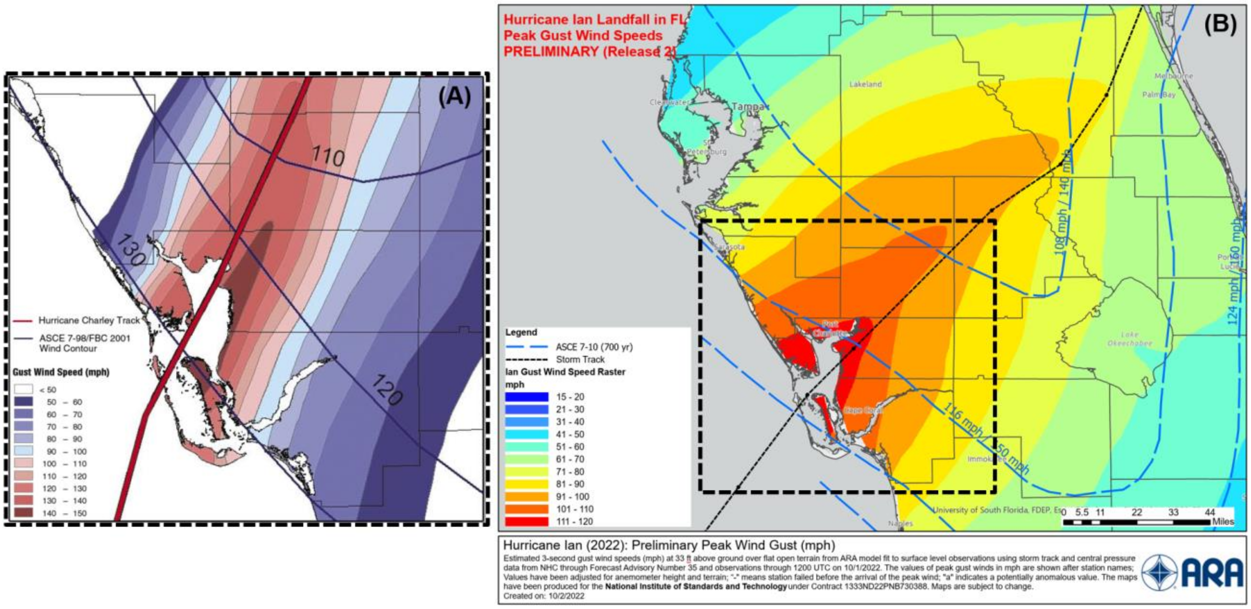


Figure 2.11. Comparison of estimated wind field maps produced by ARA for (a) Hurricane Charley (2004) and (b) Hurricane Ian (2022). The extent of the map in (a) is shown in the dashed outline in (b). The ASCE 7-10 contour labels shown in (b) give both the estimated ASCE 7-05 equivalent design wind speed (50-year return period) and the ASCE 7-10 design wind speed (700-year return period). Map (a) is sourced from FEMA (2005).

3. Local Codes and Construction Practices

Florida relies on two codes to regulate most building construction: (1) the Florida Residential Code and (2) the Florida Building Code. While the Florida Residential Code provides regulations and guidance for the construction of one and two-family dwellings, the Florida Building Code addresses all other permanent buildings and structures. The Florida Building Code released in 2010 was primarily based on the 2009 International Building Code. The 2009 International Building Code did not incorporate the specifications of ASCE 7-10 at that time. From 2012, the ASCE 7-10 served as the foundation of the Florida Building Code. According to the latest version of Florida Building Code, wind loads on buildings must be calculated using Chapters 26-30 of ASCE 7. See Table 3.1 for the history of code adoption in the landfall region. Design wind speeds should be determined from the maps given in Figures 1609.3(1), 1609.3(2), and 1609.3(3) of the 2017 Florida Building Code, Sixth Edition. Fig. 3.1 illustrates the design wind speeds from ASCE 7-16 Risk Category 2 structures (700-yr mean reoccurrence interval) the landfall region.

Mobile and manufactured[1] home regulations in Florida are managed by the Florida Department of Highway Safety and Motor Vehicles and provided in Rule 15C-1.0102 of the Florida Administrative Code. Counties may have more stringent standards. The regulations require compliance with manufacturer installation standards unless otherwise noted in Rule 15C. Design provisions refer to the HUD Wind Zone regions for mobile and manufactured homes, in which

[1] "Mobile/Manufactured Home" means a structure, transportable in one (1) or more sections, which is eight body feet (8') or more in width, greater than four hundred (400') square feet and which is built on an integral chassis and designed to be used as a dwelling when connected to the required utilities and includes the plumbing, heating, air conditioning and electrical systems contained herein.

coastal regions of south and central Florida fall under Wind Zone III. Storm surge loads are not included in the anchorage requirements or superstructure design based on the HUD manufactured home installation standard (HUD, 2022).

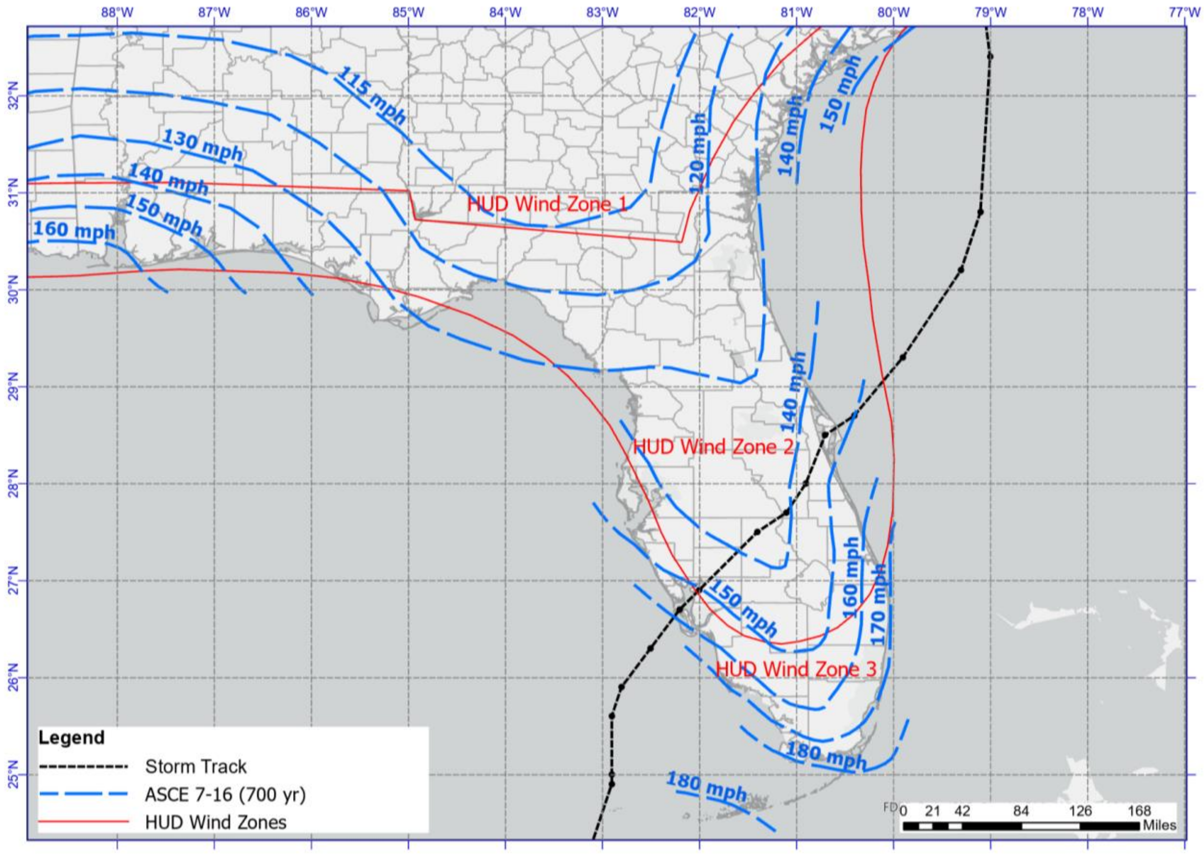


Figure 3.1. Design wind speeds in Florida for ASCE 7-16 Risk Category II buildings (blue) and HUD-regulated buildings (red) (Source: ATC Hazards by Location).

Hurricane Charley's impacts in 2004 spurred several changes to the Florida Building Code, summarized as follows (Dixon, 2009):

- Improved requirements for wood to masonry wall interfaces
- Improved requirements for roof tile attachment
- Adoption of standards that rated asphalt shingles based on wind speed resistance
- Requirement to improve roof deck nailing when reroofing existing buildings
- Adoption of wind pressure criteria for soffits
- Adoption of requirements for labeling of windows, garage doors, and shutters for wind pressure.

Table 3.1. History of building codes and wind design standards for Punta Gorda, FL

Code Edition	Effective Date	ASCE Reference	Design Wind Speed (mph)[a]	ASD Wind Load Factor	Lateral Design Pressure (psf)[b]
1997 SBC	Pre-2002	ASCE 7-98	120	1	26
2001 FBC	Mar-02	ASCE 7-98	120	1	33.9
2004 FBC	Oct-05	ASCE 7-02	120	1	33.9
2007 FBC	Mar-09	ASCE 7-05	120	1	33.9
2010 FBC	Mar-12	ASCE 7-10	150	0.6	31.8
2014 FBC	Jun-15	ASCE 7-10	150	0.6	31.8
2017 FBC	Dec-2017	ASCE 7-10	150	0.6	31.8
2020 FBC	Jan-2021	ASCE 7-10	150	0.6	31.8

[a] Design wind speeds are 3-second gusts in open terrain at 10 m height above ground level, but correspond to a 50 yr MRI in ASCE 7-98/02/05 and a 700 year MRI in ASCE 7-10.
[b] Lateral design pressure is defined as $P = 0.00256*(V_{design})^2*LF$, where V_{design} is the design wind speed, and LF is the ASD wind load factor.

The FL Coastal Construction Control Line (CCCL) is another important part of Florida's regulatory environment and was first implemented in the late 1970s, with the most recent updates in Lee County implemented in 1991. The CCCL delineates that area of the beach-dune system that is expected to be subject to severe fluctuation resulting from a 100-year storm event. The 100-year storm elevation requirements for habitable structures located seaward of the coastal construction control line ensure that the lowest horizontal structural member of the building is placed at an elevation above the predicted breaking wave crest, termed the 100-year storm elevation. All major structures are required to be designed to resist the predicted forces associated with a 100-year storm event. On Sanibel Island, the CCCL approximately aligns with Gulf Blvd, and in Fort Myers Beach, CCCL closely follows Estero Blvd. Base Flood Elevations are highly variable seaward of the CCCL on both islands, with Base Flood Elevations between 15 and 17 feet at the coastline in most areas.

4. Building Performance

Tables 4.1 and 4.2 provide a synthesis of the typical performance of buildings in this event, respectively organized by occupancy and geography. The subsections that follow present notable case studies. Readers may consult the imagery compiled in the accompanying Media Repository, curated with this report in DesignSafe, to access a richer collection of georeferenced visual evidence cataloged by occupancy.

Table 4.1. Summary of Building Performance by Occupancy

Single-Family Residential Buildings	Single-family housing performance was variable, with exposure to surge hazard being a primary driver of structural failures. Such damage was primarily restricted to the barrier islands (e.g., Sanibel, Fort Myers Beach, Bonita Springs), where many homes were completely washed away and many others lost breakaway walls. Mobile/manufactured housing and RV parks were the most susceptible to the damage as they lacked the elevation and lateral force resisting systems necessary to resist any significant storm surge-induced loads. Wind damage was primarily limited to building envelopes in site-built homes, and even that was isolated based on the imagery available at the time of this report. More severe damage, including structural failures, were observed in some mobile/manufactured housing and RV parks in Fort Myers, FL. Many single-family residential buildings constructed using slab-on-grade were also exposed to significant inland flooding.
Multi-Family Residential Buildings	Hotels built on the shorelines incurred damages, mostly in the form of damage to the cladding and windows and washout of equipment and walls at the ground floor. A few wood-frame multi-family residential structures on or along the causeways to the barrier islands experienced significant structural damage, including complete roof structure failure and wall collapse, but such damage was atypical. Roof cover loss was widespread. Several multi-family units in Delray Beach, FL suffered structural damage from a cyclone-induced tornado rated EF3 by the National Weather Service.
Commercial Buildings	Many restaurants and other commercial facilities located on the shorelines were damaged due to high winds and storm surge, including multiple buildings completely washed away. Wind-only damage was generally restricted to minor roof cover and wall cladding loss, but such damage extended as far inland as Orlando, where one of the rides at Universal Studios Theme Park lost a portion of the wall siding.
Healthcare/Medical Facilities	Direct impacts to hospitals and indirect impacts to supporting infrastructure forced 642 patients to be evacuated from 6 health care facilities in Charlotte, Lee, Sarasota, Orange, and Volusia Counties (FL Gov, 2022). HCA Florida Fawcett Hospital in Port Charlotte experienced surge-induced flooding in the ground floor emergency room and partial loss of the built-up roof. Hospitals in the impacted area suffered severe staffing shortages due to displaced workers (FHA, 2022).
Schools	Wind damage to schools appears to be minor, with damage reports focusing on roof cover loss and damage to appurtenant structures. The surge and flood impacts were more severe, particularly in Lee County. Fort Myers Beach Elementary, The Sanibel School, and Pine Island

	Elementary all experienced significant flooding, with high water marks documented near the top of the ground level door at Fort Myers Beach Elementary (Speck, 2022).
Government Facilities	No observations available for this building class at the time of this report.
Mobile/Manufactured Homes	Mobile/manufactured homes (MH) suffered widespread damage from wind, surge, and inland flooding. Multiple MH parks on or near the barrier islands were washed away. Away from the wave action, structural damage from wind was common, but not uniform. Many MH, even what appeared to be older (pre-1994) homes, within the area of highest impacts experienced no structural damage. Cladding damage and damage to attachments (e.g., porch overhangs) was frequently observed.
Critical Facilities	Several critical facilities experienced significant flooding, but no reports of significant structural damage have been found.
Historical Buildings	Venice Theater, a historic building in Venice, FL, experienced severe damage to its roof and part of its exterior wall, with only the structural framing remaining. No other reports have been obtained at the time of this report.
Religious Institutions	Roof cover loss and flooding was frequently observed in churches, but no reports of structural damage have been found. Several religious facilities are located on the barrier islands and appear to still be structurally functional based on review of aerial imagery, but the full damage extent is not known at this time.

Table 4.2. Summary of Building Performance by Geography

Barrier Islands near Landfall (Sanibel, Pine Island, Fort Myers Beach, Bonita Beach).	The worst damage is observed in this region, but performance overall is highly variable. Many structures built at ground level, primarily those exposed to wave action, were completely washed away but this damage is not uniform as many also remain standing, albeit with significant interior damage and contents loss. Many elevated structures remain standing and show little evidence of exterior structural damage beyond removal of breakaway walls.
Coastal Urban Regions (Cape Coral, Ft. Myers, Port Charlotte, Punta Gorda)	Interior damage due to flooding is likely extensive in areas closer to the coast, but most site-built structures do not show any visible exterior damage. Visible damage is almost exclusively limited to roof cover, wall cladding, and attached signs or facades. Damage appears to be somewhat more frequent in Port Charlotte than in Cape Coral and Ft. Myers based on the preliminary review of aerial imagery and other public data sources.

Inland Regions	Only isolated reports of wind damage to the building envelope have been reported in the inland communities. Flooding was widespread, however, and likely affected many buildings. Also multiple cyclone-induced tornadoes were reported, in some cases causing severe structural damage.
Florida East Coasts	Isolated reports of minor damage to buildings in this region are available.

5. Infrastructure Performance

Tables 5.1 and 5.2 provide a synthesis of the typical performance of other infrastructure classes in this event, respectively organized by class and geography. The subsections that follow present notable case studies. Readers may consult the imagery compiled in the accompanying Media Repository, curated with this report in DesignSafe, to access a richer collection of georeferenced visual evidence cataloged by infrastructure class. Interested readers may also consult the Outage/Restoration Database, curated with this report in DesignSafe, for a chronology of disruption/outage/restoration data for power, telecommunications, and transportation networks.

Table 5.1. Summary of Performance by Infrastructure Class

Power Infrastructure	Power infrastructure was more critically damaged in southwest Florida near the landfall area, causing power outages for several days. Many power poles and other infrastructure in the worst-impacted areas were observed to be still standing, but will require significant repairs.
Airports	There were minor damages to airport facilities, including Sarasota-Bradenton International Airport and Venice (Florida) Municipal Airport. Several metal hangar buildings were observed with structural damage, but no widespread structural failures were observed.
Roads & Bridges	In contrast to past major hurricanes like Hurricane Katrina, there was almost no damage to bridge superstructures and to their connections to the substructure, which is encouraging. On the other hand, it was revealed that the weak component was the approach slab, which failed at different locations, both on the coast (due to surge, waves) and far from the coast (due to inland flooding). Moreover, extreme coastal erosion near transportation infrastructure led to scour and different damage levels to roads and pavements, including differential settlements caused by the removal of the soil below the road, and the washout of pavements.
Other Lifelines	Telecommunications infrastructure primarily in southwest Florida was not functional following the storm due to loss of power, flooded generators, and in at least one case, the collapse of a cellular tower. Damage to water, wastewater, and other lifelines is not available at this time.

Port Facilities	Damage to port facilities was limited to piers and seawalls damaged by storm surge in Florida.
Agricultural	Structural damage to agriculture facilities was limited to only a few isolated cases. Overall agricultural impact of Hurricane Ian was much larger however, particularly for the citrus industry, due to wind damage to crops.

Table 5.2. Summary of Infrastructure Performance by Geography

Barrier Islands near Landfall (Sanibel, Pine Island, Fort Myers Beach, Bonita Beach).	Power infrastructure was critically damaged, causing power outages for several days. A collapsed cell tower was observed in Boca Grande, FL. Access bridges to the islands and port facilities were severely damaged. A section of Pine Island road near Matlacha Pass road partially collapsed. The Sanibel Island causeway was washed out. The coastal roads of Sanibel Island were flooded. The iconic pier was extensively damaged, and floating docks were twisted at Fort Myers. Power lines were typically supported by concrete poles that from preliminary observations seem to have performed well overall.
Coastal Urban Regions (Cape Coral, Ft. Myers, Port Charlotte, Punta Gorda)	Power infrastructure was critically damaged, causing power outages for several days. Port facilities and marinas were considerably damaged. There were slight damages to airport facilities, including Venice Municipal Airport and Sarasota-Bradenton International Airport.
Inland Regions	Power infrastructure was considerably damaged, causing power outages for several days. In central Florida, falling trees caused damage to the power transmission lines. There are reports of damages to agricultural facilities. A levee was in danger of failing in the Hidden River area, threatening even more extensive flooding in the region.
Florida East Coast	Isolated damage to power infrastructure caused power outages for several days. In Daytona Beach, there was extensive damage to the seawalls.
Carolinas	Isolated damage to power infrastructure, notably downed power lines.

5.1 Power Outages & Restoration

The strong hurricane winds associated with Hurricane Ian caused widespread power outages in Florida, recording peak outages of 2,697,372 on September 29th at 3PM (Florida Public Service Commission, 2022). Charlotte, Desoto, Hardee, Lee, and Sarasota counties in Florida had more than 80% of consumers without power (Fig. 5.1). Lee, Charlotte, and De Soto counties took almost nine days to restore power to 80% of consumers. Meanwhile, North Carolina had power outages of more than 358,000 (Dean, K. Cataudella, K., 2022); South Carolina had more than 180,000 power outages (Mejia, J., 2022), and Virginia had more than 100,000 power outages (Flickinger, G., 2022). As of October 3, 2022, Florida had 1.2 million outages; North Carolina had 294,000 outages; Virginia had 77,000 outages, and South Carolina had 47,000 outages (Poweroutage.us,, 2022).

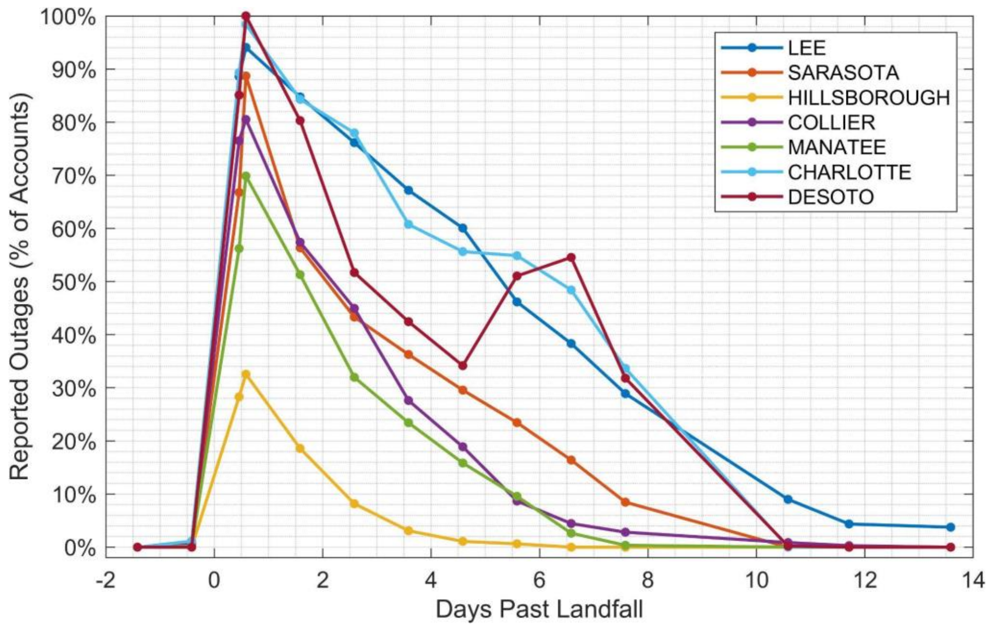


Figure 5.1. Power outages in select Florida counties as a function of time. Landfall occurred at around 4pm on September 28. (Data source: Florida Public Service Commission (2022)).

Power Case Study: Solar Panels

Many households in Florida have adopted solar panels as a source of energy. There have been a total of 155,383 solar panel installations in Florida (Yu et al. 2018), out of which 90.7% (140,265) are residential installations, and 9.3% (15118) are commercial installations. Over 90% of the solar panels have been installed since 2017.

Solar panels can provide access to continuous power supply when a hurricane damages the primary grid, as exemplified in Hurricane Ian by Babcock Ranch, a community located 12 miles northeast of Fort Myers. The community has 700,000 solar panels, which continuously provided electricity for 2,000 households throughout Hurricane Ian's passage. These solar panels showed good structural performance with no damage (Ramirez, R., 2022), albeit under below-design wind speeds (90-100 mph according to the ARA wind field estimate).

Beyond Babcock Ranch, however, aerial imagery from NOAA revealed damage to roof solar panels in areas that observed higher peak wind gusts. A preliminary assessment conducted in multiple neighborhoods in Cape Coral and Fort Myers identified 30 rooftop panel installations with severe damage (Fig. CS.5.1). An example of typical damage is shown in Fig. CS.5.2. Field inspections can reveal less visible damage to the panels (Burgess & Goodman, 2018; Ceferino et al., 2022), identify specific failure mechanisms (e.g., cracks and local failures in the rack, panel connection, or roof attachment), and evaluate the impacts on continuous power access and building functionality.

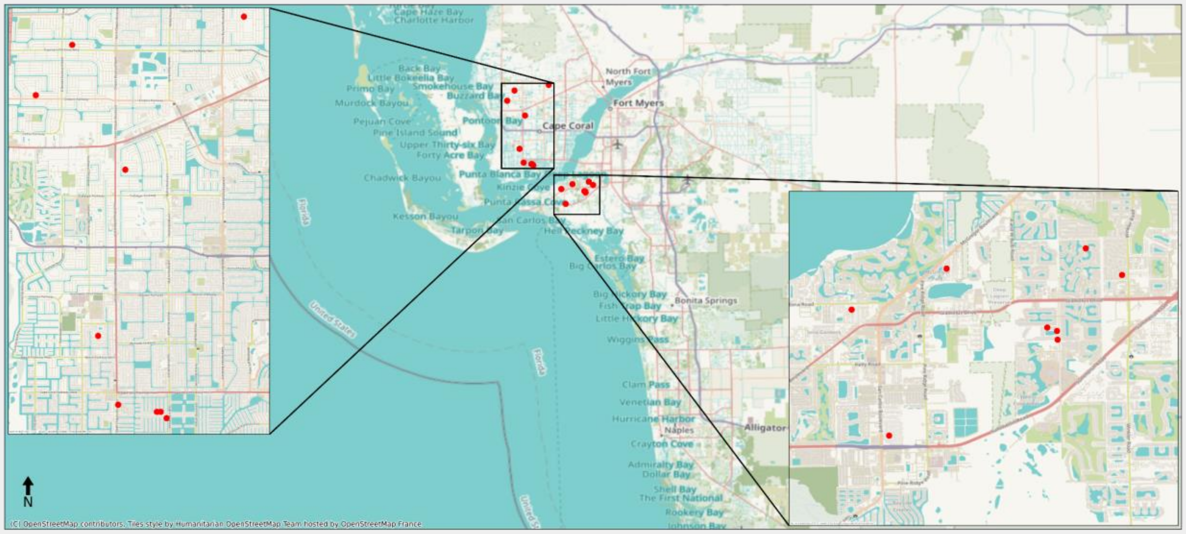


Figure CS5.1. Locations with damaged solar panels in Cape Coral and Fort Myers shown with red dots. Damage was visually inspected from NOAA's aerial imagery after Hurricane Ian.

Figure CS5.2. Evidence of roof solar panel damage by comparing (left) a damaged panel visible in the post-storm NOAA imagery, and (right) pre-event imagery showing the undamaged panel.

5.2 Transportation Disruptions & Restoration

Figure 5.2 summarizes the progression of road closures during the landfall of Hurricane Ian, initiating with coastal roadways and causeways in Lee County inundated by storm surge, which in several cases caused structural damage. This includes all the bridges to Pine Island (Gallman, 2022), the roadway connecting Captiva and Sanibel Islands, the Sanibel Causeway connecting Sanibel Island to Fort Myers (Levy, 2022), the Big Hickory Bridge, and Little Hickory Bridge (fl511.com). Damage was also observed to coastal highways in Fort Myers, with the most characteristic case being McGregor Blvd. The most common pattern of failure was the severe coastal erosion near the causeways and roads that led to scour and partial damage (e.g., differential settlements) or washout of pavements and causeways, and the damage to approach slabs, as shown in Figure 5.3.

As Hurricane Ian moved towards the northwest, causing intense precipitation with long durations, inland transportation networks of central and northwest Florida were disrupted due to rainfall-induced flooding (Fig. 5.2). For example, roadways and bridges were closed due to submergence by the inland flooding in Arcadia where the Peace river reached record breaking levels, at Manatee Sarasota County Line. Although many inland roads and bridges survived the flooding, some witnessed major damage, such as SR-37 at Manatee Polk County, experienced wash outs, while other locations experienced scour of roads and culverts (Wicks, 2022). Despite the extensive damage to several bridges and roadways in coastal and inland areas, the Florida Department of Transportation was able to quickly restore access to barrier islands, e.g., Pine Island causeway was reopened in under 3 days (Yablonski, 2022).

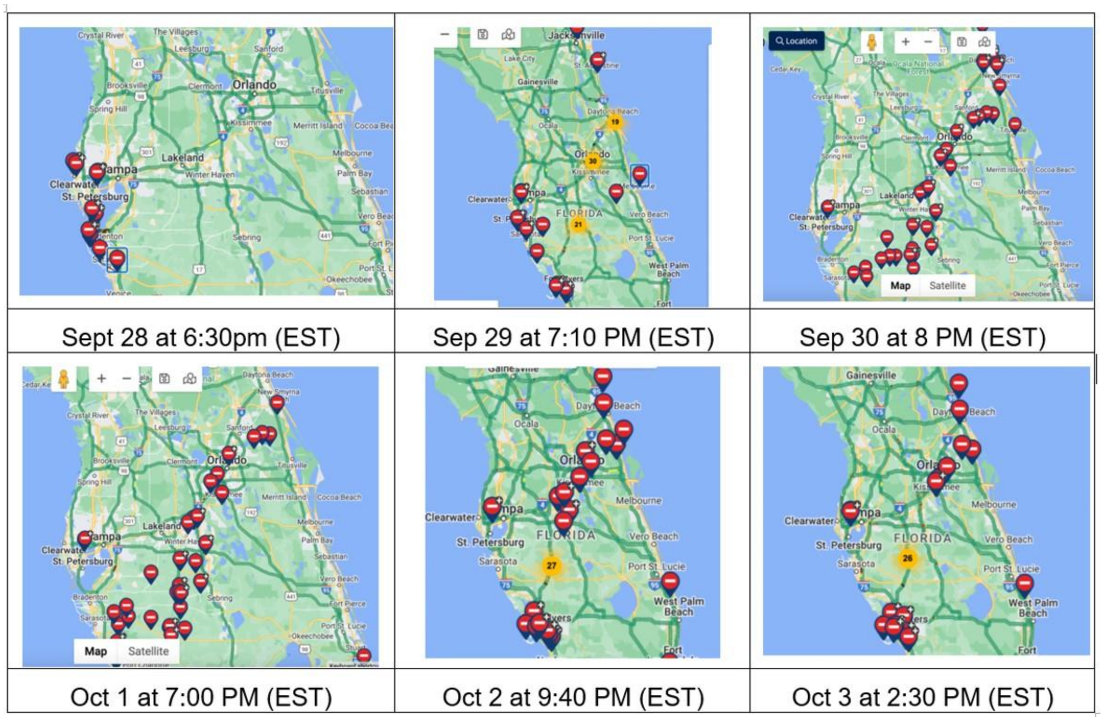


Figure 5.2. Road closures after the arrival of Hurricane Ian in Florida (Source: fl511.com).

Figure 5.3. Observed damage coastal roadways, including (a) the McGregor Blvd in Fort Myers (source: NOAA Hurricane Ian Imagery), and (b), (c) the Pine Island Rd (Source: ABC news (2022) and Levy (2022) respectively).

Transportation Case Study: Sanibel Causeway

A notable case is the failure of the Sanibel Causeway, experiencing three different types of damage at different locations (see Fig. CS.5.3). The Sanibel Causeway consists of three bridges (A, B, C) and two islands (Causeway Island Park A, B) as shown in Fig. CS.5.3. Interestingly, in contrast to past hurricanes (e.g. Hurricane Katrina) that had uplifted bridge superstructures in multiple locations of the Gulf Coast Region, in this case the superstructures and their connections to the substructure (piers) were intact and the damage occurred at the approach slab of both Bridge A (on the mainland side) and Bridge B (on the south side). In both cases the approach slab was elevated (same elevation with the bridge span) and was supported on backfill material that was protected by wing-walls consisting of modular panels restrained by soil anchors embedded in the compacted fill. These panels were exposed to lateral loads from the surge and the waves. Since there is no observed erosion of the area in the vicinity of the wing-walls, it could be hypothesized that the lateral hydrodynamic loads made some of the panels unstable, which exposed the backfill material to hydrodynamic actions and scour. Once the backfill material started undergoing scour, the vertical pressures that were applied by the backfill on the slab and helped keep the slab in place were reduced, essentially leading to a simply supported slab.

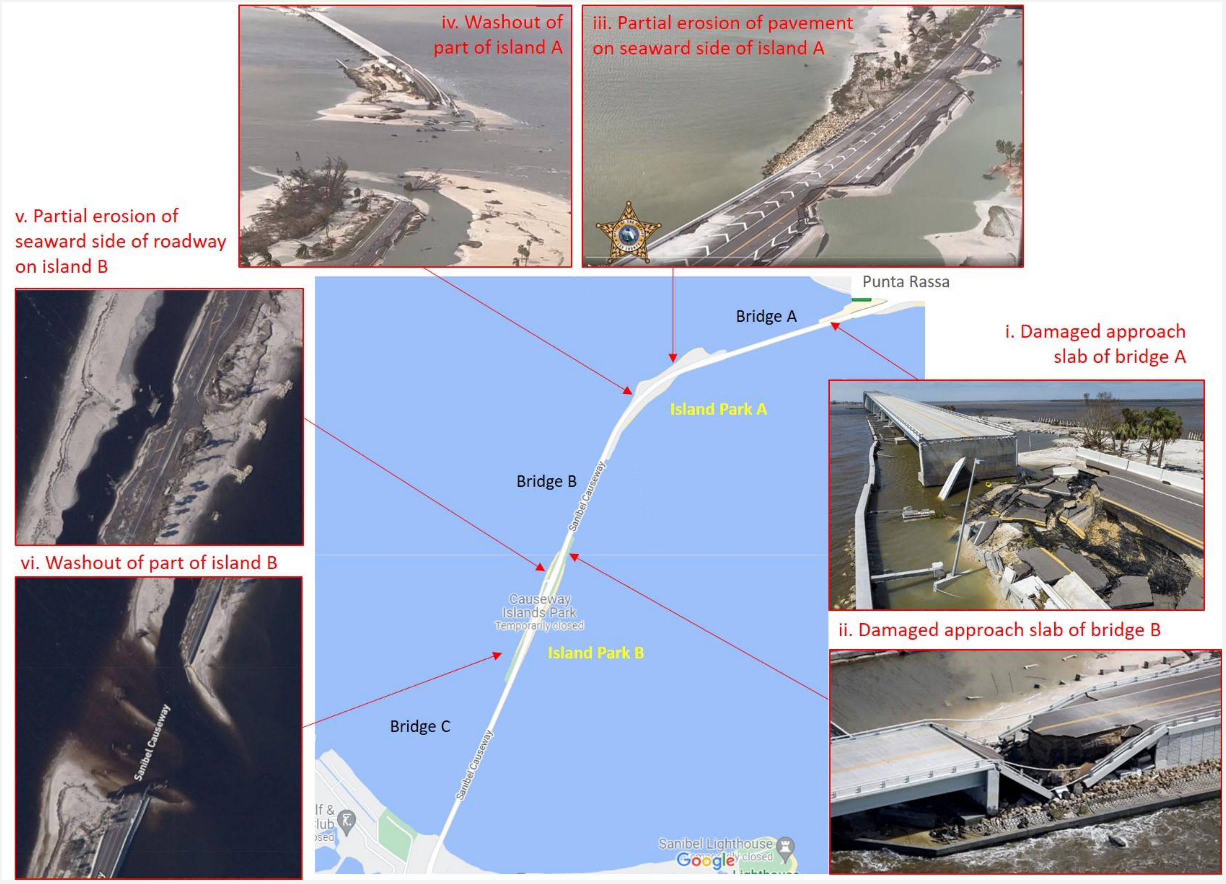


Figure CS.5.3. Observed damage to Sanibel Causeway, including damage to approach slabs of bridge A (Source: Lasey (2022) and B (Source: Brackett and Wesner Childs, 2022), erosion and washout of island A (Source: Lee County Sheriff's Office) and erosion of island B (Source: NOAA Hurricane Ian Imagery).

Two other types of damage were also observed in the Sanibel Causeway, particularly 'at the two islands. The first type was the partial damage of the pavements on the seaward side, which was caused by the erosion of the soil below the roads, and the second type was the total washout of the road with the island below it (see Fig. CS.5.3). Interestingly, for both island A and B, the first type of damage occurred towards the north side of the island and the second type (total washout) occurred towards the south end. As shown in Figure CS.5.4, for island A at the location where a total washout was observed, the road was very close to the shore, which means that it could be exposed to surge and direct impact from the waves. On the other hand, at the location with partial damage and scour of the pavement, the road was located further from the shore. This would consequently imply that while in the former case the road would be subjected to hydrodynamic effects (e.g., scour) immediately after the instant at which the surge and waves reached the elevation of the road, in the latter case the road would be subjected to the same effects only after the sandy beach (on the seaward side) would have been eroded. Apart from this hypothetical explanation, other potential reasons that could have contributed to the different levels of damage are (i) differences in road elevations, (ii) directionality effects which may be important in the case of skewed bridge superstructures subjected to extreme waves (e.g., Istrati and Buckle, 2021), (iii) differences in bathymetry, or (iv) other reasons not evident at this point.

Figure CS.5.4. Selected locations of Causeway Island Park A before Hurricane Ian (modified from Google Maps).

5.3 Telecommunications

Hurricane Ian caused damages to the telecommunication systems of Florida and South Carolina. The west coast of Florida and the Ft. Myers area are the most heavily impacted regions. The Federal Communications Commission (FCC) reported that cell service outages dropped from 65.0% to around 5.0% between September 29, 2022 and October 10, 2022 (Fig. 5.4a). The total number of wireline/cable users affected in Florida dropped from around 320,000 users to around 110,000 users between October 1, 2022 and October 20, 2022 (Fig. 5.4b). As documented in the accompanying media repository, the collapse of a cell tower in Boca Grande, FL, on a business impacted both the telecommunication system and the adjacent building.

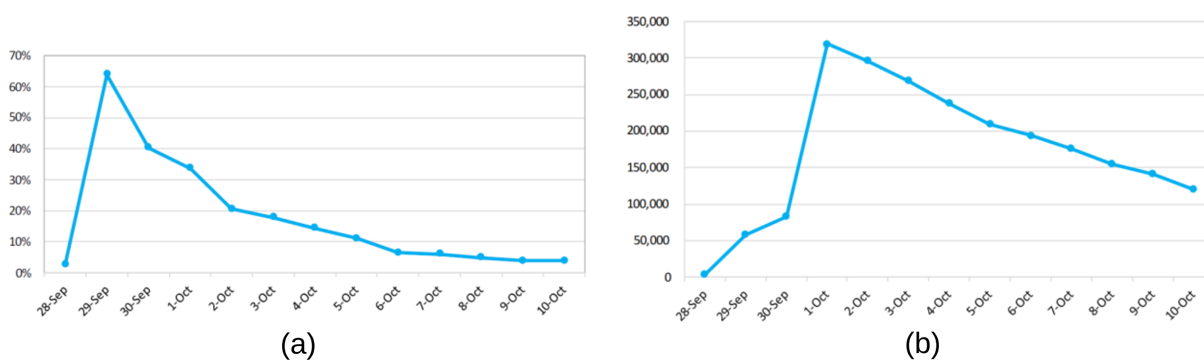


Figure 5.4. Percent of cell sites out of service (Source: FCC Hurricane Ian status reports) and (b) total number of wireline/cable users affected in the landfall region by date (Source: FCC Hurricane Ian status reports) in the landfall region by date.

6. Coastal Protective Systems Performance

Seawall collapses were reported along the Atlantic coastline of Florida at Daytona Beach Shores (Burbank, 2022), damaging surrounding facilities like pool decks and boardwalks. The seawall appeared to be lightly reinforced precast concrete with a height of around 10 ft and thickness of approximately 8 in. Poor connection between the seawall on the foundation played a prominent role in the collapse of the seawall. See the accompanying Media Repository for images of this failure. A levee in Hidden River in Sarasota County, FL, was also breached, causing severe localized flooding (Clowe, 2022). According to the National Levee Database, the Hidden River levee is a 1.98 mile embankment levee along the Myakka River that protects about 20 buildings along Hidden River Rd.

7. Recommended Response Strategy

Based on the information gathered for this Preliminary Virtual Reconnaissance Report (PVRR), StEER offers the following recommendations for further study:

Topic #1: Performance of Elevated Buildings Subjected to Coastal Hazards

1. Gather evidence to quantify uplift (buoyancy and hydrodynamic) forces acting on the floor slabs of elevated buildings due to storm surge and wave action, reviewed in the context of the ASCE 7-22 Chapter 6 Tsunami Loads and Effects and the soon to be released Supplement 3 of ASCE 7-22 Chapter 5 on Flood Loads.
2. Document performance of breakaway walls and other surge damage mitigation measures used in coastal buildings.
3. Document performance of mechanical, electrical, and plumbing (MEP) systems (e.g., plumbing, electrical, HVAC) in maintaining and restoring functionality in line with performance goals.
4. Document evidence of scour and overall performance of foundations and in-situ geotechnical conditions.
5. Document types of floating debris, evidence of impacts and damming of floating debris against structural components that may lead to increased hydrodynamic loads.

Topic #2: Characterization and Prediction of Coastal Hazards

1. Capture field measurements of the depth of inundation, wave heights, flow velocity and debris fields around structures in populated coastlines affected by storm surge.
2. Use these observations to validate and improve existing storm surge models that extend to flow overland to: (1) characterize hazard intensity in support of Topic #1, (2) model debris transport and impact, including source and characteristics of the debris, velocity, and damming effects, (3) capture effects of channeling and sheltering effects due to interaction with built environments, and (4) enable rapid inundation forecasting for emergency management purposes.
3. Continue to advance capabilities to model compound flooding that captures the interaction between storm surge and rainfall-induced inland flooding.
4. Continue to promote the development of risk-consistent storm surge hazard maps that establish an appropriate mean recurrence interval for the design of coastal structures, including examination of the appropriateness of the 100-year floodplain.

Topic #3: Performance of Nature-Based Protective Systems

1. Conduct longitudinal studies to document damage to and recovery of the nature-based protective systems across a gradient of hazard intensities to quantify the fragility of such systems.
2. Document the impacts of the nature-based protective systems in reducing flow velocity, wave heights, and other specific hazard measures and thereby mitigating damage to coastal communities. Sanibel Island may be a particularly rich area for focused study.

Topic #4: Performance of Infrastructure Under Coastal Hazards

1. Conduct in-depth investigations on the performance of coastal infrastructure, focusing on notable case studies such as bridges/roadways serving the affected barrier islands, to enhance understanding of hazard loading and failure mechanisms of critical coastal roadways and other infrastructure. Studies should characterize (i) hydrodynamic loads, (ii) scouring processes, and (iii) anticipated damage levels under different scenarios to inform the development of more resilient protective measures.
2. Project long-term impacts of coastal hazards on transportation infrastructure and causeway islands, including how sea level rise, increasing storm frequency/intensity, and coastal morphology may change future threats. Studies should explore coastal erosion processes in relation to (a) the direction of the storm surge and wave propagation, (b) the distance of the road from the shore, and (c) the duration of road exposure to storm surge, waves and scour.

Topic #5: Performance of Power Infrastructure under Combined Hazards

1. Quantify physical infrastructure failure probabilities and performance of backup power systems used for other lifelines over areas facing coastal and inland flooding, framed within the context of design hazard levels and overall community resilience objectives.
2. Document the performance of renewable energy sources and systems such as solar panels to enable continuous or immediate functionality, including successes and failures to inform evolving ASCE 7 provisions for resilient design of these systems.

While not within the direct purview of StEER and the structural engineering community it serves, this hurricane has illuminated the following research needs in related fields of study:

Topic #6: Data synthesis and processing

1. Create machine-augmented visualization and automated processing tools to swiftly synthesize the vast amounts of geospatial data generated by Hurricane Ian (and other storm events) in support of any of the above topics. Capabilities should include methods for feature extraction as well as feature evolution over longitudinally-collected datasets.
2. Create a web-based clearinghouse for Hurricane Ian (similar to EERI Clearinghouses for earthquakes) to catalog the data generated by multiple agencies and organizations collecting hazard and impact data, beginning with the data shared on #hurricane-ian-2022 Slack channel. Identification of a responsible agency will further ensure that this model can be long-term supported and replicated for future hurricanes and even for legacy events.

Topic #7: Effects of Hurricane Ian on Risk Perception, Preparedness and Mitigation

1. Despite the successes of the Florida Building Code in delivering resilient new construction, devastating losses in construction that pre-dates these codes warrants human subjects research to determine what defines acceptable performance of coastal residential

buildings and the messaging/incentives that can drive voluntary retrofit and/or managed retreat.
2. Significant loss of life in this event suggests a need to understand how evacuation sequencing, risk communication, and risk perception influenced fatal shelter-in-place decisions, as well as potential challenges in evacuating elderly/vulnerable populations without vehicles over short evacuation timelines.

Based on the criteria summarized in Table 8.1, and supported by the preliminary observations outlined in this report, StEER's response to this event escalated to Level 2 on September 29, 2022 with panoramic imaging of affected areas. This response was later escalated to Level 3 on October 14, 2022 fielding Level 3 and 4 StEER members and a Level 2 trainee to collect high water marks, performance assessments, and unmanned aerial surveys in collaboration with the NHERI RAPID Facility. StEER is continuing to coordinate with other agencies and responding organizations to further develop its FAST strategy. This strategy and assembled assets and products will be made available at https://www.steer.network/hurricane-ian as they are released.

Table 8.1. Summary of Escalation Criteria

Activation Level	Hazard	Exposure	Feasibility
Level 2	*Unique Hazard characteristics* ● Unusual coastal or compound flooding characteristics for the impacted region	*Infrastructure of interest* ● Highly vulnerable structures with severe damage or collapse ● Highly engineered structures with lower damage	*Resources* ● Availability/interest of members in the impacted region ● Availability of sufficient support from regional nodes ● Availability of imaging hardware *Access and safety* ● Driving access to affected areas *Collaboration Potential* ● Other EER's deployment (GEER, NEER) ● FEMA pre-MAT
Level 3	*Unique Hazard characteristics* ● Some aspects of the event exceed code requirements or expected performance ● Site-specific hazards require up-close evaluation, e.g., evidence of high water marks	*Infrastructure of interest* ● Performance/failures observed requires direct access to load path or other details to ascertain causes, e.g., damages caused by uplift effects ● Identification of multiple structures suitable for in-depth forensic investigation	*Resources* ● Up-close access to targeted structures is anticipated ● Availability/interest of members with logistics plan to travel to site

		• Extent of damage (greater than localized Level 2 event) requiring multiple field teams or multiple field visits	

Appendix A. Loss Estimates

Table A.1. Predicted economic losses due to Hurricane Ian

Source	Loss	Details
Fitch Ratings (Artemis.bm 2022)	$25 billion to $40 billion	Insured losses from wind and storm surge
CoreLogic (CoreLogic 2022)	$41B-$70B	Insured wind losses of $23-$35 billion Insured flood losses of $8-$18 billion Uninsured flood losses $10-$17 billion
KatRisk (KatRisk 2022)	$46 billion +/- $16 billion	Insured wind losses: $24.1 billion +/- $13.8 billion Insured storm surge losses: $17.8 billion +/- $7.1 billion Insured inland flooding losses: $4.4 billion +/- $1.6 billion
Verisk (Verisk 2022)	$42 billion to $47 billion	Insured wind losses of $38-$51 billion Insured surge losses of $3-$5.5 billion (excludes NFIP losses)
RMS (RMS 2022)	$53 billion to $74 billion	Insured wind losses of $46-$67 billion Insured surge losses of $6+ billion Insured inland flooding losses of $1+ billion (excludes NFIP losses of $10 billion)
Karen Clark & Company	$63 billion	Total insured loss, excluding NFIP losses.

Appendix B. Evacuation Orders

Table B.1. Summary of mandatory evacuation orders by county (Source: Feito, 2022).

County	Time of First Evacuation Order	Extent of Evacuation Order
Lee	Sept. 27 at 9 a.m.	Zones A and B
Charlotte	Sept. 26 at 3:30 p.m.	Zone A, all residents living on Don Pedro Island, Knight Island (Palm Island), Little Gasparilla Island, Gasparilla Island and Manasota Key, and all residents in mobile homes and trailers
Collier	Sept. 27 at 5 p.m.	Immediate coastal areas, west and south of US Highway 41/Tamiami Trail, in low-lying flood-prone areas and mobile homes
Hillsborough	Sept. 26 at 2 p.m.	Zone A, Zone B, and mobile and manufactured homes, Recommended.
Manatee	Sept. 27 at 8 a.m.	Zones A and B
Pinellas	Sept. 26 and 27 at 6 p.m.	Zone A at 6 p.m.
Hernando	Sept. 27 at 9 a.m.	Zones A, B, and C
Levy	Sept. 27 at 4 p.m.	Coastal, RV, mobile home, and low-lying residents.
Pasco	Sept. 27 at 10 a.m	Zone A, manufactured, mobile, and RV home residents, low-lying or flood-prone homes, and mandatory.
Citrus	Sept. 27 at 6 p.m.	Zone A
Putnam	Sept. 27 at 6 p.m.	Residents of low-lying and flood-prone areas and mobile homes

Appendix C. Hazard Observations

Table C.1. Locations in Florida experiencing rainfall totals >10 inches during Hurricane Ian as of 10:34 am EDT on 30 SEP 2022

Station	**Network**	**Latitude**	**Longitude**	**Anemometer Height (m)**	**Terrain**	**Peak Gust (mph)**
KPGD	ASOS	26.92	-81.99	10	Open/ Suburban	134
KRSW	ASOS	26.54	-81.76	10	Open /Suburban	98
KSRQ	ASOS	27.4	-82.56	10	Open/ Suburban	85
BGCF1	USF/COMPS	26.404	-81.881	17.3	Marine	108
UF-T1	University of Florida	26.9279	-81.9919	10	Suburban	114
UF-T2	University of Florida	26.8957	-82.0279	10	Open/ Suburban	115
UIUC-T1	University of Illinois at Urbana-Champaign	27.7118	-82.2837	4.5	Open/ Suburban	58
UIUC-T2	University of Illinois at Urbana-Champaign	27.6416	-82.5262	4.5	Open/ Suburban	50
Naples Zoo	WeatherFlow / HurrNet	26.1674	-81.7903	10	Suburban	62
Tarpon Pt	WeatherFlow / HurrNet	26.5373	-82.0036	10	Marine/ Suburban	118
Desoto-Orange	WeatherFlow / HurrNet	26.6748	-81.7683	15.24	Suburban	78
Grove City	WeatherFlow / HurrNet	26.9013	-82.3145	19.812	Suburban/ Open	130

Charlotte Harbor YC	WeatherFlow / HurrNet	26.959	-82.0804	10	Suburban/ Marine	104
Venice Beach	NDBC/C-Man	27.0725	-82.4528	11	Marine	102

Table C.2. Locations in Florida experiencing rainfall totals >10 inches during Hurricane Ian as of 10:34 am EDT on 30 SEP 2022 (data from Stutler, 2022)

Location	County	Total Rainfall (in)
Lehigh Acres	Lee	14.42
Titusville	Brevard	14.07
Merritt Island	Brevard	10.69
Union Park	Orange	16.69
Orlando	Orange	14.37
Pine Castle	Orange	13.89
Aloma	Orange	12.46
Azalea Park	Orange	11.90
Bithlo	Orange	11.58
Campbell	Osceola	15.65
Pine Grove	Osceola	12.86
St. Cloud	Osceola	11.67

Table C.3. Details of the reported tornadoes by the National Weather Service (Data Source: Iowa State University Mesonet)

No	Location	Starting Date	Rating	Estimated Peak Wind
1	North Perry Airport, Broward County	09/27	EF1	94 mph
2	2 SSW Hollywood, Broward County	09/27	EF0	80 mph
3	1 NW Boca Raton, Palm Beach County	09/27	EF2	130 mph
4	3 SW Wellington, Palm Beach County	09/27	EF1	95 mph
5	2 NNE Lion Country Safari Park, Palm Beach County	09/27	EF1	100 mph
6	1 ESE Moore Haven, Glades County	09/28	EF0	85 mph
7	1 WSW Ocean Ridge, Palm Beach County	09/28	EF0	76 mph

References

ABC news (2022) “Hurricane Ian leaves a path of destruction.” https://abcnews.go.com/US/photos/hurricane-ian-strikes-florida-coast-90637762/image-pine-island-florida-90839337

Bloomberg, Twitter (2022), https://twitter.com/business/status/1575516623137812480

Beven II, J. L., Berg, R., and Hagen, A. (2019) *Tropical Cyclone Report: Hurricane Michael (AL142018)*. NOAA and National Weather Service. (https://www.nhc.noaa.gov/data/tcr/AL142018_Michael.pdf)

Borenstein, S. (2022) “Study finds that climate change added 10% to Ian's rainfall.” US. News, Sep 29, 2022. https://www.usnews.com/news/news/articles/2022-09-29/study-finds-that-climate-change-added-10-to-ians-rainfall .

Brackett, R. and Childs, J. W. (2022) “Hurricane Ian: At Least Four Dead In Southwest Florida; Hundreds Of Rescues Across The State.” The Weather Channel. Oct 1, 2022. https://weather.com/storms/hurricane/news/2022-09-29-hurricane-ian-florida-live-updates-thursday-impacts.

Burbank, J. (2022) “Pictures: erosion from hurricane Ian guts Volusia beaches.” *Orlando Sentinel*. Oct 5, 2022. https://www.orlandosentinel.com/visuals/os-beach-erosion-volusia-county-hurricane-ian-20221003-wfyze7xx2zfyppoj5tamfouuxq-photogallery.html.

Burgess, C., & Goodman, J. (2018). Solar Under Storm. Select Best Practices for Resilient Ground-Mount PV Systems with Hurricane Exposure. https://www.rmi.org/wp-content/uploads/2018/06/Islands_SolarUnderStorm_Report_digitalJune122018.pdf

Ceferino, L., Lin, N., & Xi, D. (Accepted for publication). Bayesian Updating of Solar Panel Fragility Curves and Implications of Higher Panel Strength for Solar Generation Resilience. Reliability Engineering & System Safety. https://doi.org/10.31224/osf.io/dv7s3

Clowe, S. (2022) “Sarasota County community affected by levee break cleaning up after Hurricane Ian.” WTSP. Oct 29, 2022. https://www.wtsp.com/article/news/local/sarasotacounty/sarasota-county-community-levee-break-cleaning-up-hurricane-ian/67-8c2a4ac4-94ee-4811-81cb-463509963953.

Combs, D. L., Parrish, R. G., McNabb, S. J., and Davis, J. H. (1996) “Deaths related to Hurricane Andrew in Florida and Louisiana, 1992,” *International Journal Epidemiology*, Vol. 25, No. 3, 537–544. doi: https://doi.org/10.1093/ije/25.3.537

Dean, K. Cataudella, K. (2022) “358,000+ without power in NC as Post-Tropical Cyclone Ian moves inland”, https://www.newsobserver.com/news/weather/hurricane/article266608621.html

DeSantis, R. (2022a) “State of Florida office of the governor executive order number 22-218 (emergency management-tropical depression nine).” *FMCSA*. Sep 24, 2022.

https://www.fmcsa.dot.gov/emergency/state-florida-office-governor-executive-order-number-22-218-emergency-management-tropical.

DeSantis, R. (2022b) “State of Florida Office of the Governor Executive Order Number 22-219 (Emergency Management-Tropical Depression Nine) | FMCSA.” Accessed November 1, 2022. https://www.flgov.com/wp-content/uploads/2022/09/EO-22-219-TS-Ian.pdf

Duke Energy, Twitter (2022a), https://twitter.com/DukeEnergy/status/1576177142236323846

Duke Energy, Twitter (2022b), https://twitter.com/DukeEnergy/status/1576177142236323846

Evans, S. (2022) “Hurricane Ian industry loss estimated up to $40bn by Fitch - Artemis.bm.” artemis, Sep 30, 2022 https://www.artemis.bm/news/hurricane-ian-industry-loss-estimated-up-to-40bn-by-fitch/.

Feito, M. (2022) “Here are all the evacuations ordered for Hurricane Ian.” WUSF Public Media. September 26, 2022. https://wusfnews.wusf.usf.edu/weather/2022-09-26/here-are-all-the-evacuations-ordered-for-hurricane-ian

Florida Public Service Commission. “Hurricane Season Power Outage Reports”, http://www.psc.state.fl.us/Home/HurricaneReport

Flickinger, G. (2022) “100,000 Virginia customers lose power due to Ian”, https://wset.com/weather/weather-extra/100000-virginia-customers-lose-power-due-hurricane-ian-tropical-storm-force-electric-service-lost-power-scattered-trees-down-windy-october-1-2022

FCC. (2022a) “FCC activates disaster reporting in Florida for Hurricane Ian.” *Federal Communications Commission*. Sep 27, 2022. https://www.fcc.gov/document/fcc-activates-disaster-reporting-florida-hurricane-ian.

FCC. (2022b) “Hurricane Ian Communications Status Report - October 10, 2022.” *Federal Communications Commission*. Oct 1, 2022. https://www.fcc.gov/document/hurricane-ian-communications-status-report-october-10-2022.

FEMA (2005) *FEMA 488 - Mitigation assessment team report hurricane Charley in Florida observations, recommendations, and technical guidance*. FEMA. https://www.fema.gov/sites/default/files/2020-08/fema488_mat_report_hurricane_charley_fl.pdf

FL511. (2022) “Florida's official source for real-time traffic information.” https://fl511.com/

Gallman, S. (2022) “All bridges to Pine Island, Florida, have failed, county official says”, *CNN,* https://edition.cnn.com/us/live-news/hurricane-ian-florida-updates-09-29-22/h_bd73eb6f49df6fa13a265a4e63712fcb

HUD: Department of Housing and Urban Development. (2021) *Part 3280—Manufactured Home Construction and Safety Standards*. Federal Register. https://www.ecfr.gov/current/title-24/subtitle-B/chapter-XX/part-3280

Issa, A., Ramadugu, K., Mulay, P., Hamilton, J., Siegel, V., Harrison, C., Campbell, C., M., Blackmore, C., Bayleyegn, T., and Boehmer, T. (2017) "Deaths Related to Hurricane Irma — Florida, Georgia, and North Carolina, September 4–October 10, 2017," *Morbidity and Mortality Weekly Report*, Vol. 67, No. 30, 829-832. doi: http://dx.doi.org/10.15585/mmwr.mm6730a5external icon

Istrati, D., and Buckle, I.G. (2021) *Tsunami Loads on Straight and Skewed Bridges–Part 2: Numerical Investigation and Design Recommendations*. Oregon Dept. of Transportation. (https://rosap.ntl.bts.gov/view/dot/55947)

Lasey, D. (2022) "Work begins to assess damage caused by hurricane Ian." *ENR Southeast*. Sep 29, 2022. https://www.enr.com/articles/54909-work-begins-to-assess-damage-caused-by-hurricane-ian.

Lee County. (2022) "Sanibel causeway bridge." *Lee County*. https://www.leegov.com/dot/tolls/lw_facilities/san.

Lee County Sheriff's Office. (2022) *Twitter*. Sep 29, 2022. https://twitter.com/SheriffLeeFL/status/1575529164899340289?ref_src=twsrc%5Etfw%7Ctwcamp%5Etweetembed%7Ctwterm%5E1575529164899340289%7Ctwgr%5Ec744cc79412fa1861636521c5f73c046725a7529%7Ctwcon%5Es1_&ref_url=https%3A%2F%2Fwww.fox13news.com%2Fweather%2Fhurricane-ian-storm-surge-damage-fort-myers-naples-southwest-florida

Levy, D. (2022) "Photos: Hurricane Ian destruction in Matlacha." *The News-Press*. https://eu.news-press.com/picture-gallery/news/2022/09/30/hurricane-ian-photos-destruction-matlacha/8140101001/.

Mejia, J. (2022) "Power outages due to Hurricane Ian experienced in the state", https://www.abccolumbia.com/2022/09/30/power-outages-due-to-hurricane-ian-experienced-in-the-state/

NHC (2022a) "Hurricane Ian discussion number 25." *National Hurricane Center Forecast Discussions*. Sep 28, 2022. https://www.nhc.noaa.gov/archive/2022/al09/al092022.discus.025.shtml? .

NHC (2022b) "Hurricane Ian Advisory Number 25." *National Hurricane Center Forecast Advisories*. Sep 28, 2022. https://www.nhc.noaa.gov/archive/2022/al09/al092022.public.025.shtml?.

NOAA (2022) "Hurricane Ian Imagery." https://storms.ngs.noaa.gov/storms/ian/index.html#17/26.46651/-82.02909.

NOAA (2004) "August 2004 tropical cyclones report." *National Hurricane Center Forecast Advisories*. National Centers for Environmental Information. Nov 10, 2022. https://www.ncei.noaa.gov/access/monitoring/monthly-report/tropical-cyclones/200408.

Ramirez , R. (2022) "This 100% solar community endured Hurricane Ian with no loss of power and minimal damage", https://www.cnn.com/2022/10/02/us/solar-babcock-ranch-florida-hurricane-ian-climate/index.htm.

RMS (2022) "RMS estimates US$67 billion in insured losses from hurricane Ian." RMS, Oct 7, 2022. https://www.rms.com/newsroom/press-releases/press-detail/2022-10-07/rms-estimates-us67-billion-in-insured-losses-from-hurricane-ian.

Smith, M., Robels, F., Fawcett, E. and Sasani, A. (2022). Many of Hurricane Ian's Victims were Older Adults Who Drowned. https://www.nytimes.com/2022/10/07/us/hurricane-ian-victims-drowned.html

USGS. 2022. "Flood Event Viewer: 2022 Ian." Accessed November 12, 2022. https://stn.wim.usgs.gov/fev/#2022Ian.

Verisk (2022) "Verisk estimates industry insured losses for hurricane Ian." Verisk, Oct 3, 2022. https://www.verisk.com/newsroom/verisk-estimates-industry-insured-losses-for-hurricane-ian/.

van Oldenborgh, G. J., van der Wie, K., Sebastian, A., Singh, R., Arrighi, J., Otto, F., Haustein, K., Li, S., Vecchi, G., and Cullen, H. (2017) "Attribution of extreme rainfall from Hurricane Harvey, August 2017," *Environmental Research Letters*, Vol. 12, No. 12. doi: https://doi.org/10.1088/1748-9326/aa9ef2.

Wicks, N. (2022). "Farmers assessing Hurricane's Ian damage to crops, equipment." *Agri-Pluse.* Oct 1, 2022. https://www.agri-pulse.com/articles/18318-hurricane-ians-damage-to-farms-still-being-assessed.

Wolfe, E., Cladwell, T., McCleary, K., Sangal, A., Vogt, A., Chowdhury, M., Hammond, E. and O'Murchú, S.F. (2022) "September 29, 2022 hurricane Ian updates." *CNN*. Sep 30, 2022. https://edition.cnn.com/us/live-news/hurricane-ian-florida-updates-09-29-22/h_bd73eb6f49df6fa13a265a4e63712fcb.

Xiang, T. and Istrati, D. (2021) "Assessment of extreme wave impact on coastal decks with different geometries via the arbitrary Lagrangian-Eulerian method," *Journal of Marine Science and Engineering*, Vol. 9, No. 12, doi: https://doi.org/10.3390/jmse9121342.

Yablonski, S. (2022). "Road to recovery: Temporary bridge restores lifeline to Florida's Pine Island cut off by Hurricane Ian", https://www.foxweather.com/extreme-weather/pine-island-bridge-fdot-hurricane-ian-florida-lee-county

Yu, J. Wang, Z. Majumdar, A. Rajagopal, R. (2018) "DeepSolar: A Machine Learning Framework to Efficiently Construct a Solar Deployment Database in the United States," *Joule,* Volume 2, Issue 12, Pages 2605-2617, ISSN 2542-4351, https://doi.org/10.1016/j.joule.2018.11.021