Investigating Storm Resilience of United States Coast Guard Fixed Aids to Navigation Structures

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Technical Report

APL-UW TR 2306

November 2023

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Acknowledgments

The author thanks Dr. Jim Thomson at the University of Washington Applied Physics Laboratory for his guidance and assistance during this independent study project. In addition, the author thanks Mr. James Spilsbury of the USCG Research and Development Center for making this project possible by assisting with initial idea development and coordinating with various Coast Guard stakeholders. Mr. Dave Merrill of CG-NAV, Ms. Amilynn Adams of the USCG Geospatial Working Group, and Professor Rick Luettich at the University of North Carolina all provided datasets that were critical to the project. The author acknowledges Mr. Merrill and members of the USCG Waterways Operations Product Line team for their knowledge and advice early in the project while developing a vision for the study.

EXECUTIVE SUMMARY

Hurricanes along the United States Gulf and East coasts are becoming more intense, slower moving, and costlier than ever as the world's climate warms. The United States Coast Guard (USCG), which operates and maintains the nation's Aids to Navigation (ATON) system, is experiencing increasing ATON infrastructure damage after each storm. This project investigates how the USCG can apply modeled hurricane data to best understand the environmental conditions that various ATON structure types are most vulnerable to in a storm. The project uses Hurricane Ian in 2022 as a case study and focuses on structures consisting of a single pile. The distributions of maximum wind speed, wave height, and water elevation experienced at locations of aids that failed during the storm were compared to the distributions of the same parameters at aids that did not experience any issues. The study found that discrepant single-pile ATON had a higher probability of having experienced high wind speed and wave height during Hurricane Ian than non-discrepant ATON, while no difference was observed between the distribution of water elevation at discrepant versus non-discrepant ATON. Thus, high wind speeds and wave heights are likely drivers of damage to single-pile ATON during major storms, but higher water level is not. More importantly, these results show that modeled hurricane data is useful to reveal vulnerabilities in USCG infrastructure. If the USCG applies these methods to analyze different structure types, categories of storms, and discrepancy types (e.g., structural failure, missing dayboard, extinguished light, etc.), the resulting conclusions may reveal probabilistic trends of discrepancies that will aid both short-term equipment preparation and long-term strategic and financial planning ahead of a hurricane season, improving the service's resiliency towards future storms.

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1. INTRODUCTION

On the Gulf and East coasts of the United States, hurricanes are becoming more intense, slower moving, and costlier than ever as the climate changes (*Center for Climate and Energy Solutions*, 2023). The nation must consider whether its current critical infrastructure can withstand these and future storms. The United States Coast Guard (USCG), which operates and maintains maritime Aids to Navigation (ATON) to enable the safe passage of commerce within and across the nation's borders, is addressing this pressing issue.

The USCG Commandant published the service's first Climate Framework in early 2023, detailing its goal for future efforts to enhance its overall resiliency towards climate change (*Commandant*, 2023). The document establishes three "Lines of Effort" for strategic planning that emphasize the need for innovation, adaptability, and collaboration, the first of which directs the USCG to "build climate resiliency into [its] workforce, infrastructure, and assets." Actions necessary to achieve this objective include research on the actual impacts of climate change to USCG infrastructure and vulnerability identification, with the expectation that the future will bring more frequent and intense weather emergencies. Fixed ATON structures are damaged frequently during major storm events, highlighting the importance of understanding the implications that more frequent storms will have on ATON resources.

This project contributes towards this effort by investigating how the USCG can apply modeled storm and hurricane data to best understand which fixed ATON structures are most vulnerable during storm events and likely to be damaged or fail completely, resulting in an ATON discrepancy (e.g., not functioning properly as a navigational aid). Major damage to fixed ATON structures is generally more difficult, costly, and time-intensive to repair or replace (e.g., driving piles, structural repairs, etc.) than to a floating navigation aid. Therefore, the goal of this project is to identify storm conditions that cause these issues, which will assist future projects seeking to design more resilient structures and in turn save time, money, and lessen risk exposure for personnel.

2. BACKGROUND

Aids to Navigation

The USCG oversees the construction, maintenance, and operation of the United States Aids to Navigation (ATON) System, a collection of visual, audible, and electronic signals that mark the nation's navigable waters (33 CFR 62). ATON utilize an arrangement of colors, shapes, numbers, and light characteristics on a variety of floating or fixed infrastructure to delineate the location of safe water or hazards within a waterway (*USCG District 13*, 2018). With over 50,000 federal aids nationwide, the ATON system plays a crucial role in facilitating the safe passage of 90% of the nation's imports and exports, resulting in $4.6 trillion of economic activity annually (*Commandant*, 2018).

According to the USCG's *ATON Structures Manual*, there are more than 22,000 fixed ATON structures in the United States, almost half of all federal aids (*USCG*, 2005). The structures are classified as major or minor; a major structure consists of a complex, unique design tailored to the constraints of a specific location, whereas a minor structure is a simple design, typically made of piles, that is easily repeated at various locations (**Fig. 1**). Major structures are often large and require years of site analysis, technical design, and collaboration between USCG Civil Engineering Units and government contractors before construction begins. Minor structures are smaller and can be constructed quickly, without the need for specific site analysis, following a standard procedure performed by USCG units such as inland construction tenders or Aids to Navigation Teams (ANT).

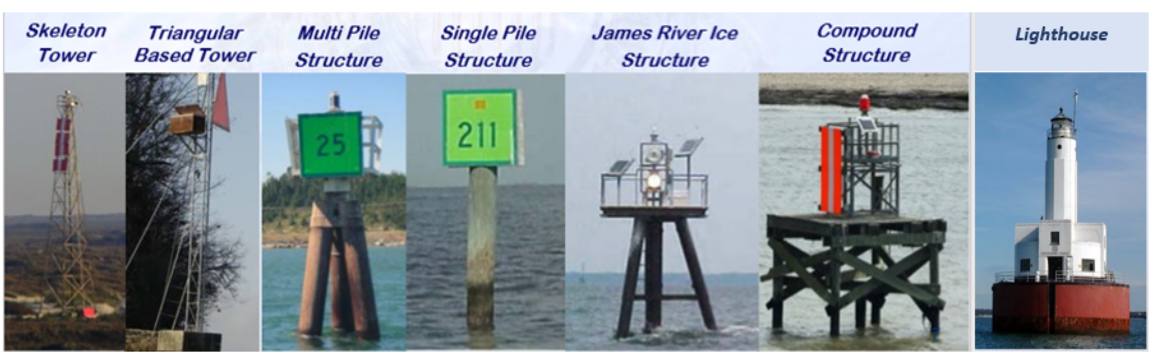

Figure 1. *Types of fixed ATON structures out of 14 different types and hundreds of unique configurations. (Source: NATON School presentation)*

This project focuses on minor structures, which make up most of the USCG's fixed ATON, especially on the U.S. Gulf and East coasts (*USCG*, 2005). Minor structures, frequently consisting of a single wood, steel, or concrete-filled pile (**Fig. 2**), are designed with a variety of factors in mind, including expected loading, weather, site considerations, and operational requirements. They are designed to endure up to a 10-year storm and are considered discrepant if the structure fails or if the aid is exhibiting no signals or improper characteristics. The latter could manifest in the form of a missing or damaged dayboard, an extinguished light, a malfunctioning sound signal, etc. These issues all pose a hazard to recreational and commercial mariners alike, who will lack correct navigation information. Thus, following a storm, the USCG must work prudently to restore aids to their proper function, requiring time and resources. Fixed ATON structures often remain discrepant for longer durations than floating aids, because buoys can be replaced by temporary units that display similar characteristics to the original, whereas a damaged structure must be reconstructed and cannot be replaced with a buoy.

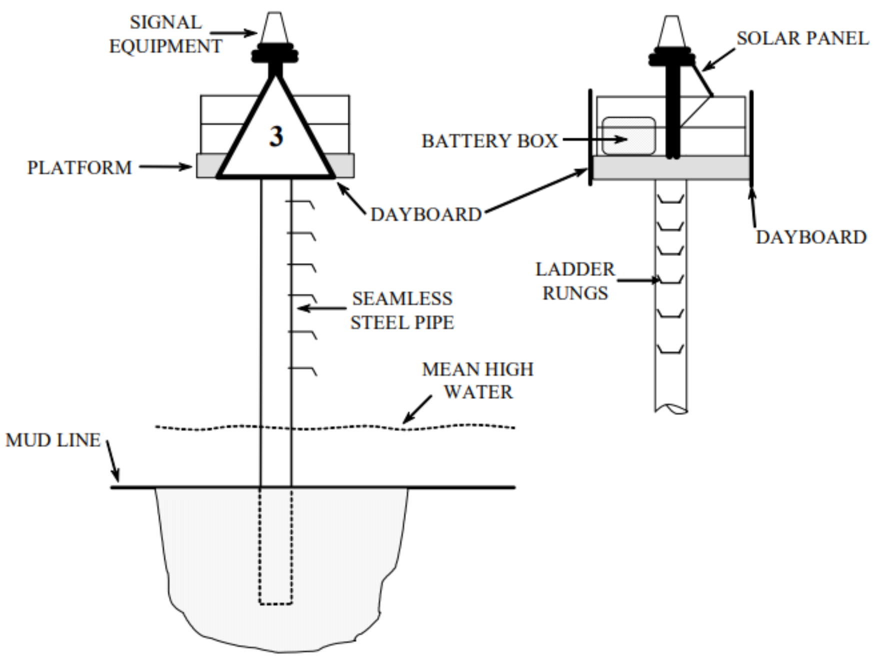

Figure 2. *Single-pile steel structure supporting a light and dayboard.*

Several technologies innovated by the USCG have increased the resiliency of the ATON system in response to major storms. The most successful is the Automatic Identification System (AIS) to transmit virtual ATON (AIS-ATON) in place of buoys and structures damaged or destroyed in a storm, which is an efficient, albeit temporary, method of providing mariners with navigational information when the usual visual aids have been compromised (*U.S. Committee on the Marine Transportation System*

Resilience Integrated Action Team, 2018). These AIS-ATON are broadcast as AIS messages from a shoreside location and display on the radars or charting systems of ships in the virtual aid's vicinity, so vessel pilots can reference their ship's position to the AIS-ATON location on their screen and be informed of a channel's boundaries or hazardous water (*NOAA Office of Coast Survey*, n.d.). Additionally, AIS-ATON technology helps USCG units transiting a waterway identify actual ATON that are missing or off station, which proved crucial to enabling an early reopening of the Port of Corpus Christi, Texas, following Hurricane Harvey in 2017. It can even be activated prior to a storm's occurrence to further expedite the restoration of a waterway's operations in the aftermath.

An innovation that would be useful for assessing the health of the ATON system following a storm is the implementation of an asset management system. Such a concept, proposed in detail by a United Kingdom company Catapult Connected Places, would utilize a central computer system and remote monitoring of beacons equipped with accelerometers, strain, and thickness gauges, and "smart" lights to monitor structural and signal performance of connected ATON structures (*White*, 2021). The tool would use gathered information to predict and be immediately aware of failures within the connected aids, enabling the quick dissemination of information to responding authorities and local mariners. It would also feature the ability to track environmental conditions during the time of failure and apply this information to machine learning to more accurately develop the prediction capability for discrepancies. The culmination of these metrics would minimize the need for reports or visual inspection of damage following a storm, allowing the USCG to prioritize the restoration of critical ATON to reopen a port.

Although AIS-ATON and asset management systems are immediately useful in the recovery phase after a hurricane, they would not be as necessary if ATON structures themselves were made more resilient. The USCG has investigated buoyant beacons as a possible solution. They resemble typical fixed structures, but are actually small towers connected to a float chamber that is tension moored to a sinker on the seafloor (*Pharos Marine Automatic Power*, n.d.). Unlike buoys, these configurations are not equipped with extra chain to rest on the seafloor, so they have smaller watch circles and therefore can mark channels with greater precision. Because the buoyant beacons are capable of heeling over until almost submerged and are not rigid like fixed beacons, they offer the same capabilities during normal weather conditions but may be more resilient under heavy weather. They can also be adapted to deeper water and more serious environmental conditions by varying the size and location of the buoyant section. However, buoyant beacon systems are both costly and difficult to install and service because they require an oversized sinker as part of the tension mooring and need the assistance of divers to be positioned accurately. Another option that may provide increased storm resilience is piles constructed from fiberglass reinforce polymer (FRP), which have already been implemented in recent ATON structure construction with positive feedback (*Benvenuto and O'Connor*, 2016). FRP piles have a projected design life of 75 to 100 years and offer a high strength-to-weight ratio, with one-fifth of the bending stiffness of steel so they offer elasticity towards the high impact loads experienced during major storms.

Hurricanes

A tropical cyclone is a large, rotating storm that forms over the warm waters within 25 degrees of latitude of the Equator, typically occurring between June and November. According to NASA, the formation of a tropical cyclone depends on the coincidence of four key environmental conditions: ocean water with a temperature of around 80°F or above, air with high humidity, low vertical wind shear (minimal difference between wind speed and direction at high and low elevations), and a pre-existing system of thunderstorms localized at a pressure disturbance (*Cobert*, 2022). When these conditions align, inflowing wind due to the low-pressure center and a vertical temperature gradient combine with the Coriolis force to create the storm's spin, resulting in the build-up of high winds and moisture accumulation (*Atlantic Oceanographic and Meteorological Laboratory*, 2023). Once developed, storms are driven by large scale circulation patterns and they either reach land, referred to as landfall, or they curve back out to sea. In either case, the tropical cyclones eventually dissipate from the added friction and abundance of dry air over land or cold water at sea. In North America, these storms are referred to as hurricanes when the sustained wind speed exceeds 64 kt. Beyond this threshold, hurricanes are classified on the Saffir–Simpson scale into five categories based on their maximum sustained wind speed, with Category 5 being the most intense.

Since the beginning of the 20th century and especially within the last few decades, researchers have observed an increase in the intensity of tropical cyclones around the globe (*C2ES*, 2023). With the onset of warmer sea surface temperatures due to human impact on the planet's climate, vertical temperature gradients within the mid latitudes have steepened, resulting in increased wind speeds and 10–15% greater precipitation in subsequent storms. As of July 2023, the average water surface temperature in the Gulf of Mexico was the highest on record, almost 2°F above the 1991–2020 average, which caused NOAA to revise their 2023 Atlantic Hurricane Season Outlook to include a greater number of expected major storms (*Chesnes and Prator*, 2023). This illustrates that although there is no evidence of a shift in the overall frequency of hurricanes, this environmental change has instigated an increase in the proportion of Category 4 and 5 storms (*Kossin et al.*, 2020), which are the most intense and cause the greatest damage.

Changes in the Earth's atmosphere, such as Arctic warming, are causing hurricanes to travel slower, exposing coastal communities to longer durations of high winds, precipitation, and storm surge. To compound matters, years of sea level rise has ripened the risk of severe coastal flooding, expanding the same coastal communities' vulnerability to storm surge. One study simulated Hurricane Katrina but with the sea level and climatic conditions from 1900 and compared it to the actual impact of 2005; they report that the actual flood elevations of 2005 were 15–60% higher than the 1900 simulation results, mainly due to the century of sea level rise (*Irish et al*., 2014). With no end to climate change in sight, we will likely continue to experience more severe storms that, when combined with our growing population and increasingly complex society, will cause unprecedented damage to our infrastructure unless we work to become more resilient.

In the USCG's 7th District, which encompasses most of Florida, Georgia, South Carolina, and Puerto Rico, no storm has caused more harm to infrastructure than Hurricane Ian, a category 5 storm that resulted in $112 billion of total damage (*Bucci et al*., 2023). The storm, which made landfall on Florida's southwestern coast on 28 September 2022, traveled northeast across the state causing unprecedented storm surge, extreme winds, and major freshwater flooding. Fort Meyers Beach, Florida, experienced a peak storm surge inundation level of 10–15 feet above ground level, while in Iona, a weather station documented a 94 kt sustained wind with gusts peaking at 122 kts. Just north of the landfall location in Cayo Costa, 26.95 inches of rain fell with most of the state averaging between 10 and 20 inches of rain. Hurricane Ian resulted in over 150 deaths and left over nine million without power, proving to be the costliest storm in Florida history as well as the third costliest in U.S. history. USCG ATON infrastructure was not exempt from the storm's impact, suffering over 510 total discrepancies to fixed and floating aids, 414 of which were minor structures consisting of a single pile (*Merrill*, 2023).

3. METHODS

A database of ATON discrepancies that occurred during Hurricane Ian was provided by CG-NAV-1 (Aids to Navigation and Positioning, Navigation and Timing Division at the USCG Office of Navigation Systems). Data were in the form of a spreadsheet exported from the Integrated Aids to Navigation Information System (I-ATONIS), a program used to track all pertinent information and logistics related to short-range ATON (*USCG*, 2010).

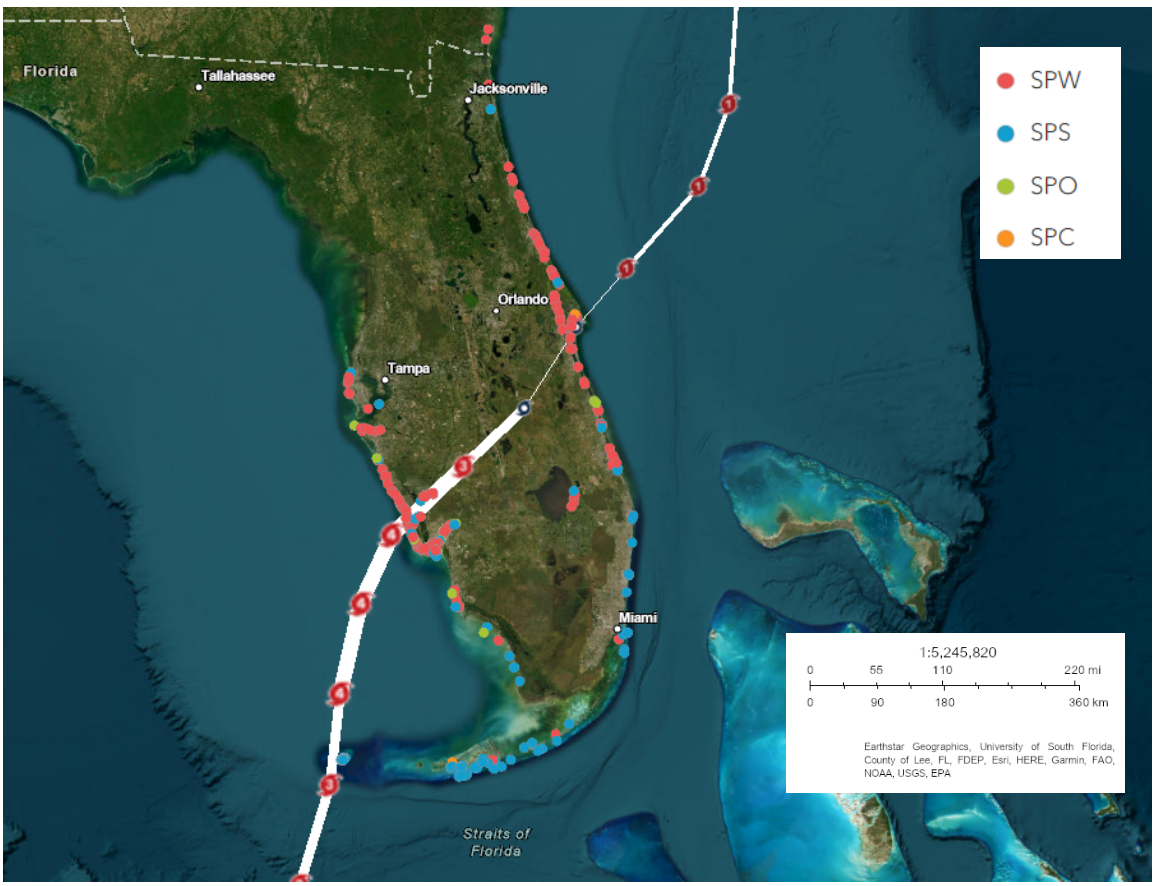

Figure 3. *Location of minor single-pile ATON structures, colored according to structure material, that went discrepant during Hurricane Ian's passage across Florida in relation to the storm's track. Materials: single-pile wood (SPW), single-pile steel (SPS), single pile made of material other than wood, concrete, or steel (SPO), and single-pile concrete (SPC).*

A GIS feature layer containing locations of all federal and private ATON was obtained from the USCG's Geospatial Working Group and was filtered to isolate the locations of ATON within District 7. From there, the layer was joined with the Hurricane

Ian discrepancy spreadsheet to identify the location of all the single-pile structures that went discrepant due to the storm (**Fig. 3**). There were 414 discrepant single-pile structures. The layer was also used to identify ATON in District 7 that did not become discrepant following Hurricane Ian. However, due to the limited information included in the original feature layer, the non-discrepant single-pile structures could not be isolated, so instead, the lights and daymarks were selected under the assumption that most of these were single-pile structures. While this may not be completely accurate, they would serve as a good approximation for comparing probability distributions of the various parameters. In total, 11,069 non-discrepant structures were selected.

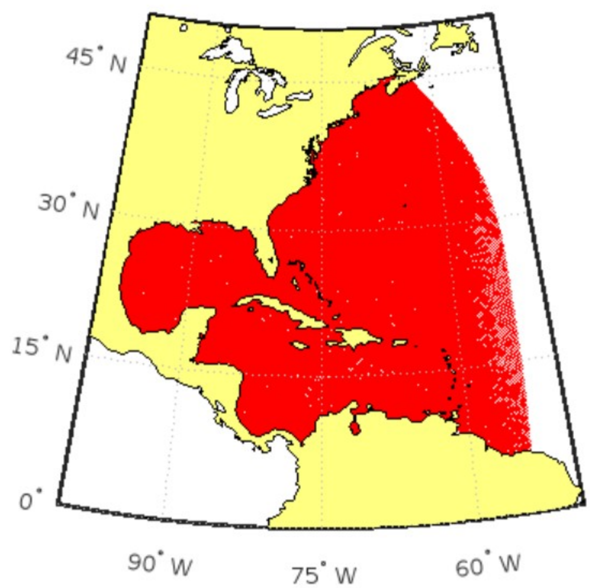

Figure 4. *Location of nodes (red) corresponding with modeled wind, wave height, and water elevation data for Hurricane Ian, primary covering the North American Gulf and East coasts, Caribbean, Central America, and the northern coast of South America.*

The DHS Coastal Resilience Center at the University of North Carolina provided Hurricane Ian model data for maximum winds, wave heights, and water elevation as netCDF files. The winds were a reanalysis produced by Ocean Weather, Inc. and modified in nearshore areas using a roughness algorithm from the Advanced Circulation (ADCIRC) model. Water levels and significant wave heights were computed using the coupled ADCIRC+SWAN models. **Figure 4** shows the location of the model nodes associated with available data. Using MATLAB, the three nearest model nodes to each of the ATON were located, both discrepant and non-discrepant. Two summary tables were created (one each for discrepant and non-discrepant) containing the aid and discrepancy (if applicable) information along with the wind, wave, and water elevation parameters associated with the three nearest nodes. For any ATON with a distance greater than one kilometer to its nearest node, the associated data were discarded because of the large variations in coastal processes that can occur even across a relatively short distance.

The summary tables were then utilized to examine and compare the distribution of the environmental conditions between the discrepant and non-discrepant ATON samples. For the purposes of analysis, due to the difference in sample size, both the discrepant and non-discrepant data sets were normalized with histograms to compare proportions.

4. RESULTS

Across parameters of maximum wind speed, wave height, and water elevation, there are apparent differences between the distributions corresponding with the discrepant ATON sample and the non-discrepant sample. Generally, there is a higher density of discrepant ATON in the higher values of wind speed and wave height, while in terms of water elevation, there is not a clear difference between the discrepant and non-discrepant distributions.

Four types of plots are shown for each environmental parameter: wind speed (**Fig. 5**), wave height (**Fig. 6**), and water elevation (**Fig. 7**). The first plot type, labeled (a), compares the probability distribution of the parameter values experienced during Hurricane Ian by ATON that went discrepant during the storm versus ATON that did not go discrepant. The next plot type (b) displays the cumulative distribution of the parameter for discrepant and non-discrepant ATON across increasing values of the parameter. The third plot type (c) shows the proportion of single-pile ATON that went discrepant in a given parameter bin out of all aids that experienced conditions that fall within that bin during Hurricane Ian, calculated by dividing the frequency of discrepancies within a bin by the total sum of discrepancies and non-discrepancies for that bin. This effectively normalizes the values in the probability distributions of plot type (a), such that any sampling bias in using conditions at the discrepancies is removed. The last plot type (d) shows the exceedance function in terms of each parameter for discrepant ATON, non-discrepant ATON, and a theoretical normal distribution based on the non-discrepant data. The confidence interval for the discrepant function was generated by a MATLAB function using Greenwood's formula.

Wind Speed

Figure 5 plots the distributions of Hurricane Ian maximum wind speeds experienced by discrepant and non-discrepant ATON. The highest density of discrepant ATON was in the 20–25-kt wind speed bin (**Fig. 5a**), making up about 0.23 of all discrepancies, while the highest density of non-discrepant ATON occurred in the 15–20-kt bin (**Fig. 5c**). In general, unimodal distributions (e.g., Raleigh, Chi-squared) of wind speeds are expected in natural, stochastic systems (*Ochi*, 1986). The non-discrepant distribution generally follows this expectation; it tapers off on either side of the 15–20-kt bin, though it does have a small peak of about 0.08 in the 30–35-kt bin. Contrarily, the discrepant distribution has a second peak, with the 35–40, 40–45, 45–50, and 50–55-kt bins each containing about 0.15 of the distribution. In addition, there are no occurrences of discrepancies experiencing 0–5-kt winds and a very low proportion of non-discrepancies experiencing 55–60-kt winds.

A comparison of the cumulative distribution of wind speeds for the discrepant sample and non-discrepant sample (**Fig. 5b**) shows the discrepant distribution with a relatively steady increase between each bin in contrast with the non-discrepant distribution, which increases sharply in the lower wind speed bins and levels off in the upper bins. Greater than half of the non-discrepant sample falls in the 15–20-kt bin or below, while the 50 percent threshold is not crossed until the 35–50-kt bin for the discrepant sample. The discrepant distribution does not approach one until the 50–55-kt bin, while the non-discrepant sample neared one in the 40–45-kt bin.

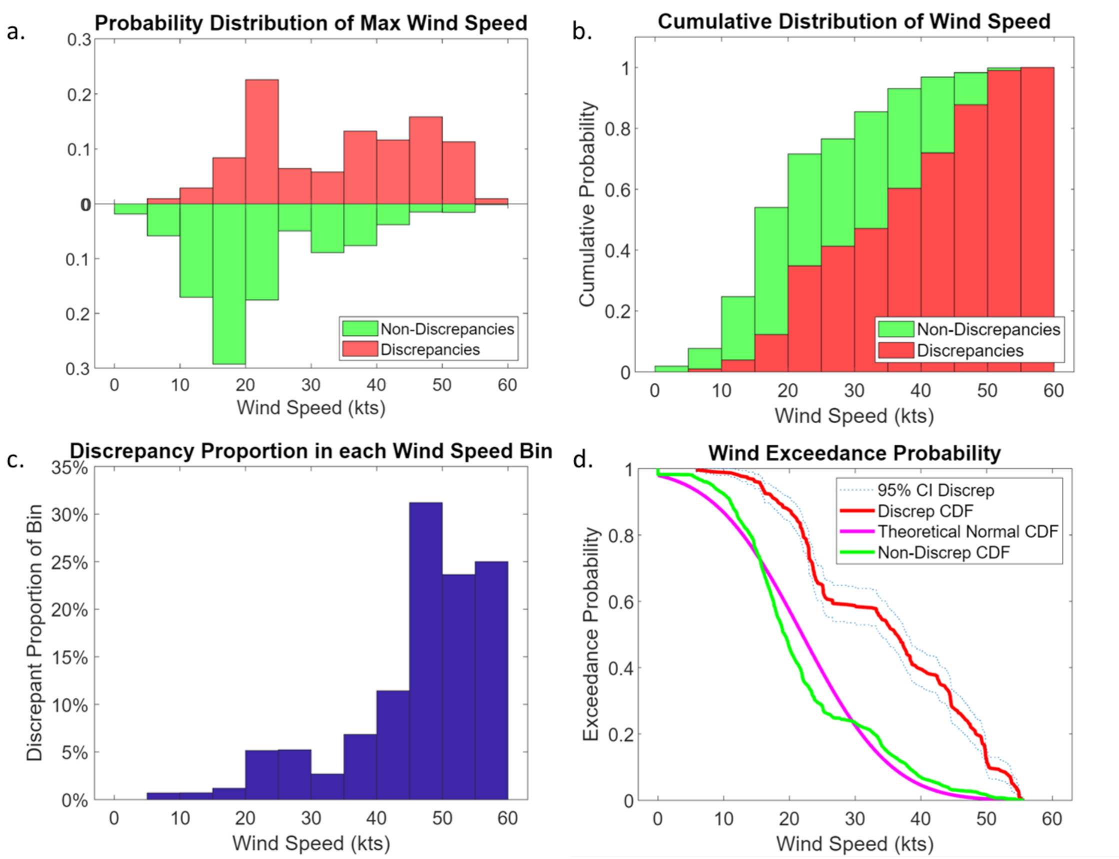

Figure 5*. Plots comparing Hurricane Ian maximum wind speeds experienced by discrepant single-pile ATON versus non-discrepant ATON.*

Figure 5c displays the fraction of discrepancies that occurred in each wind speed bin out of all single-pile ATON in District 7 that also experienced winds within the same bin. The proportion of discrepancies in each bin generally increases with increasing wind speed, peaking in the 45–50-kt bin and remaining near 25% in the 50–55 and 55–60-kt bins.

Figure 5d displays the empirical cumulative distribution functions (CDF) for wind speed associated with both the discrepant and non-discrepant samples on an exceedance probability plot, as well as a theoretical CDF based on the normal distribution around the non-discrepant sample mean and variance. For a given probability of exceedance, the discrepant sample ranges between 10 kts and almost 20 kts greater than the non-discrepant sample, with the largest difference occurring at wind speeds of 25–50 kts.

Overall, the wind results indicate that ATON are two to three times more likely to become discrepant when wind speeds exceed 25 kt. Further, the largest portion of discrepancies occur for wind speeds greater than 35 kt. Wind speed is a clear and critical factor in assessing the storm resilience of single-pile ATON.

Wave Height

Figure 6 plots the comparative distributions of Hurricane Ian maximum wave heights experienced by discrepant and non-discrepant ATON. **Figure 6a** shows the probability distribution of each sample, with the highest density of discrepant ATON in the 1–1.5-m wave height bin, making up about 0.3 of all discrepancies, while the highest density of non-discrepant ATON occurs in the 0–0.5-m bin and tapers off from there with increasing wave height. In terms of overall shape, the non-discrepant clearly favors the lowest wave height bins, while the discrepant sample has substantial concentrations out to the 2.5–3-m bin and numerous outliers to the 7–7.5-m bin. The cumulative distribution of wave height for both samples (**Fig. 6b**) shows that almost all the non-discrepant are below 2 m, while the discrepant distribution has notable contributions at 2–7 m.

Figure 6c displays the fraction of discrepancies that occurred in each wave height bin out of all single pile ATON in District 7 that also experienced wave heights within the same bin. The proportion of discrepancies in each bin generally increases with increasing wave height, with an initial peak occurring in the 2.5–3-m bin and then slightly tapering off. Neither sample had any ATON that experienced wave heights in the 4–4.5, 6–-6.5, and 6.5–7-m bins. However, all ATON that experienced wave heights in the 4.5–5 or 5–5.5 m bins went discrepant. In the 7–7.5 m bin, 60% of aids went discrepant.

Figure 6d displays the empirical CDFs for wave height associated with both the discrepant and non-discrepant samples on an exceedance probability plot, as well as a theoretical CDF based on the normal distribution around the non-discrepant sample mean and variance. For probabilities of exceedance between 1 and 0.1, the discrepant sample remains about 1 m greater than the non-discrepant sample, but below an exceedance probability of 0.1, the difference becomes about 2. The discrepant exceedance function does not approach 0 until 6 m, while the non-discrepant sample reaches 0 after a wave height near 2 m.

Overall, discrepancies are associated with wave heights greater than 2 m and are highly likely with wave heights greater than 4 m. The wave height results are not as well resolved as the wind speed results, because they are sparse at the extreme values.

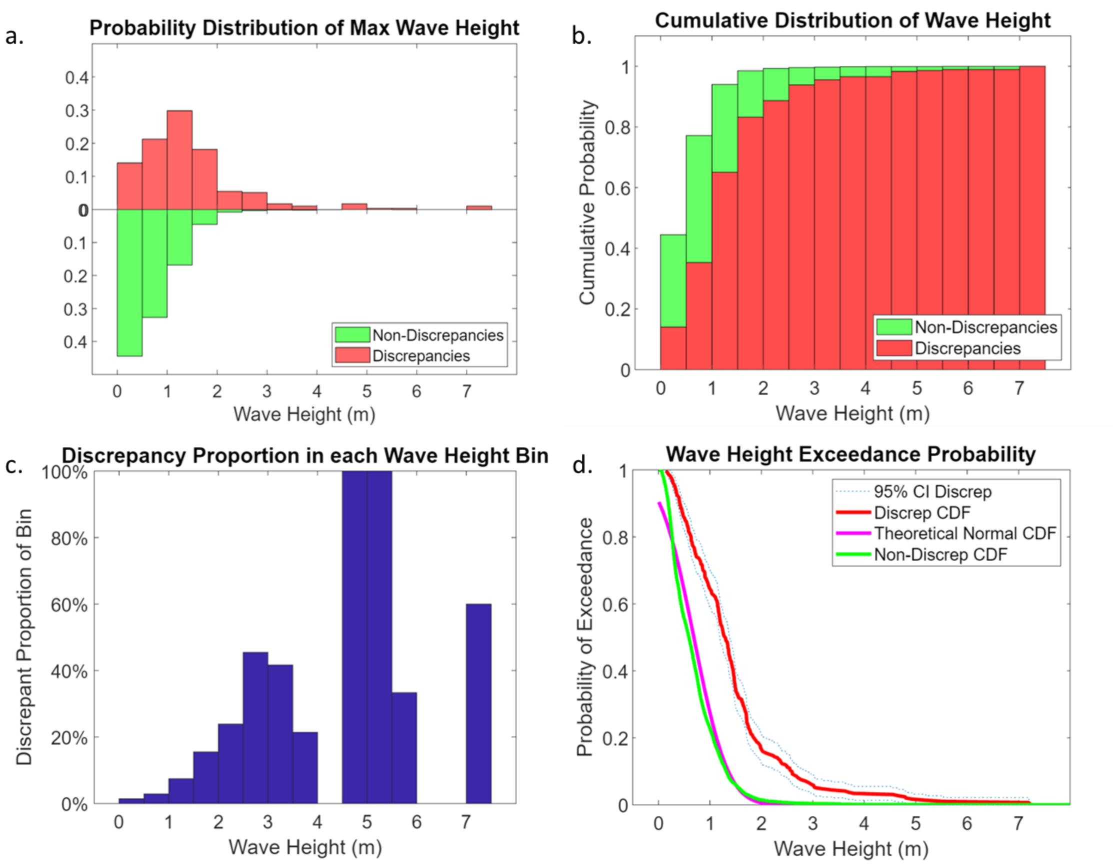

Figure 6. *Plots comparing Hurricane Ian maximum wave heights experienced by discrepant single-pile ATON versus non-discrepant ATON.*

Water Elevation

Figure 7 plots the comparative distributions of Hurricane Ian maximum water elevations experienced by discrepant and non-discrepant ATON. The highest density of both discrepant and non-discrepant ATON was in the 0.5–1-m water elevation bin with concentrations of around 0.3 and 0.5, respectively (**Fig. 7a**). The overall shapes of both distributions are similar, the only difference being that the discrepant sample has slightly greater weight towards the higher values of water elevation, with a secondary peak in the 2.5–3-m bin of about 0.15. The cumulative distributions (**Fig. 7b**) further illustrate these points.

Figure 7c displays the fraction of discrepancies that occurred in each water elevation bin out of all single-pile ATON in District 7 that also experienced water elevations within the same bin. There are no apparent patterns in this plot, with discrepancies accounting for 1–12% of all aids experiencing water elevations within that bin.

Figure 7d displays the empirical cumulative distribution functions (CDF) for water elevation associated with both the discrepant and non-discrepant samples on an exceedance probability plot, as well as a theoretical CDF based on the normal distribution around the non-discrepant sample mean and variance. There are no conclusive differences between these distributions, with only a slight deviation between the discrepant and non-discrepant sample in the 1–2-m range.

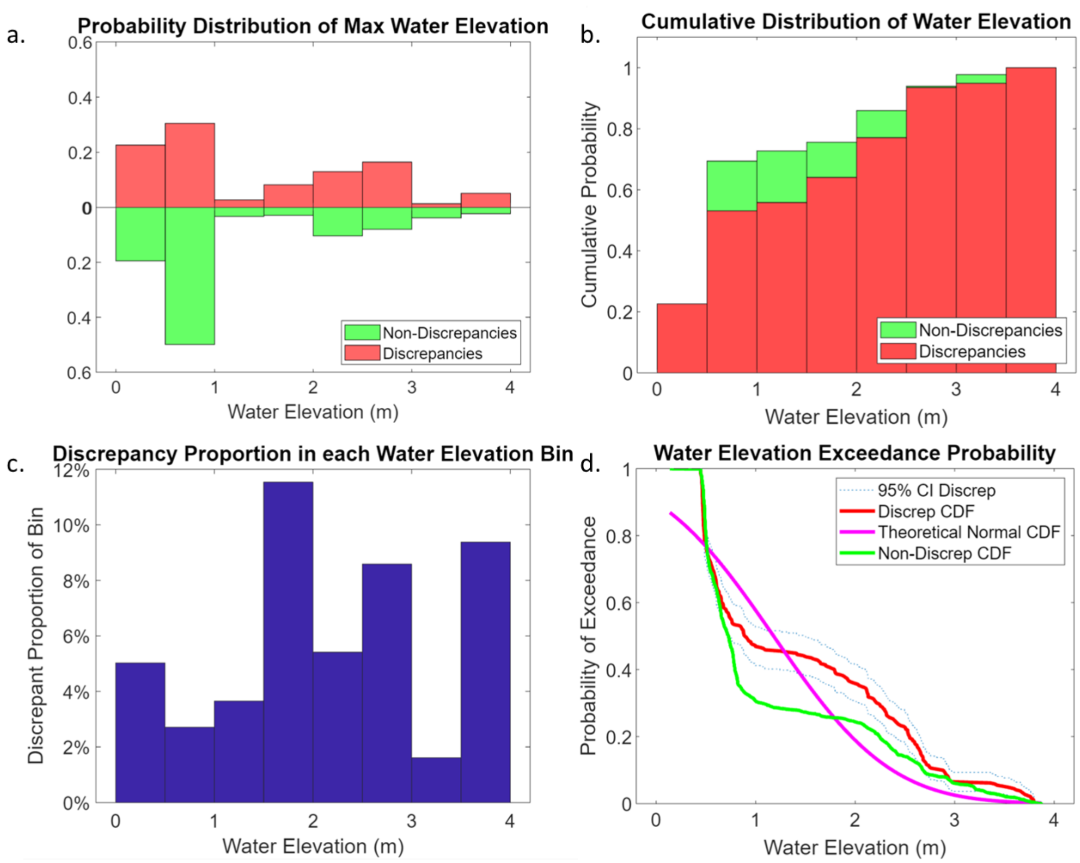

Figure 7. *Plots comparing Hurricane Ian maximum water elevations experienced by discrepant single-pile ATON versus non-discrepant ATON.*

5. DISCUSSION

When comparing the modeled storm conditions for Hurricane Ian associated with single-pile ATON that went discrepant versus the sample of non-discrepant ATON, both the probability distributions for wind speed and wave height of the discrepant sample appeared to differ from the distributions of the non-discrepant sample. Contrarily, the distributions of discrepant and non-discrepant ATON in terms of water elevation did not exhibit any strong difference. For wind speed and wave height, the discrepant distribution differed the most by having a stronger probability of occurrence in the mid- to upper values of both environmental parameters. For any given value of wind speed or wave height, the discrepant sample was more likely to have experienced or exceeded that value during Hurricane Ian.

Overall, these results indicate that high wind speeds or high wave heights are useful predictors of the likelihood of single-pile ATON in USCG District 7 becoming discrepant from a forecasted storm. The results also demonstrate that water elevation is not a significant factor in causing single-pile ATON structures to fail. Future studies should consider differences between discrepant and non-discrepant distributions based on a combined parameter of the sum of maximum wave height and maximum water level at an aid based on the assumption that greater wave energy at a higher elevation on the structure may be more destructive. This information can guide USCG ATON units in charge of servicing single-pile ATON structures because they may be able to look at a weather forecast and predict if they will have many discrepancies to correct following a storm. Additionally, this finding could be useful to USCG construction tenders and Civil Engineering Units as they design and construct future minor ATON structures so that they can prioritize wind and wave resistance within their plans, which will ultimately make these structures more resilient to future storms.

There are several assumptions in the methods that may influence these results. First, the non-discrepant single-pile structures could not be isolated directly, so minor lights and daymarks were filtered instead. Although this should have been sufficient for approximation because many of this type of ATON are made of single piles, this may have included a small number of structures of another type such as multiple pile or composite structures. Thus, because other types of structures may respond differently to storm conditions than single-pile structures, this was not a direct comparison and the results may have been impacted. Secondly, while assigning modeled environmental conditions to the aids, 1 km was used as the maximum distance between the model node and structure, which should be appropriate for estimating conditions in most circumstances, but it is possible that in some unique areas, coastal conditions may change drastically over a much smaller scale than 1 km.

It is important to consider that the environmental data used in this study were modeled using hindcasting, so at certain locations, it is likely that there were deviations between the modeled data and the actual conditions during Hurricane Ian. Additionally, while comparing the distributions of discrepant and non-discrepant ATON for each of the storm parameters, each was approached with the lens that the environmental factor worked independently to cause a structure to become discrepant, when it is a combination of many forces beyond the three considered in this study. Lastly, the results of this study only provide insight into how Hurricane Ian and other similar storms affect single-pile ATON in USCG District 7. Although the conclusions may hold true in other regions, this study did not attempt to investigate this.

Future research could utilize a similar methodology to investigate how different ATON structure types or categories are impacted by storms. This could include examining the different structures themselves or looking at broader categories such as lights versus daymarks. Another useful research pathway that the USCG could consider would be to look at the actual discrepancy type and how they are distributed relative to environmental conditions. For example, a significant issue such as complete structure failure to a more minor discrepancy such as missing or damaged dayboard might differ in how each is influenced by varying conditions. Finally, it would be extremely beneficial to investigate other historical storms, both in District 7 and in other regions, to see if results are consistent across space and time.

6. CONCLUSION

The time is more critical than ever for the United States Coast Guard to understand the vulnerabilities of its Aids to Navigation infrastructure, as tropical storms become more intense because of the world's changing climate. The goal of this study was to examine how the most widely used type of ATON structure is impacted by storms using Hurricane Ian as a case study. The results showed that single-pile ATON structures are adversely impacted by high wind speeds and wave heights, but are not as responsive to high water levels. ATON that become discrepant are more likely to have experienced or exceeded high wind speeds and wave heights than their non-discrepant counterparts, so this information should be applied by the USCG while designing the ATON structures of the future. By making structures more resistant to these factors, the USCG can reduce the number of discrepancies following a hurricane, thus saving time, money, and resources as well as minimizing the risk exposure of responding personnel. To fully align with the Commandant's Climate Framework and goals of building resiliency into infrastructure and planning for more frequent weather emergencies, similar studies should be repeated to investigate different structure types so that the USCG can help its fixed ATON assets endure the storms of the future.

7. RECOMMENDATIONS

To advance towards the goals of storm preparedness and infrastructure resilience delineated in the Commandant's Climate Framework, the USCG should consider utilizing a methodology similar to this study to further investigate how hurricane model data can reveal vulnerabilities within ATON infrastructure. Three areas of focus have been identified that may offer beneficial insight to USCG emergency planning:

1. Historical data: This study considered a single hurricane in District 7, so the USCG should consider investigating a wide range of historical storms with varying intensities and occurring in various regions to see if results are consistent across time and space. It may also be useful to consider how ATON is differently impacted based on its side and proximity to the hurricane track.
2. ATON mode of failure: This study only grouped ATON as either discrepant or non-discrepant, a binary divide that does not adequately account for the difference in severity of damage between different discrepancy types. The USCG could investigate how environmental conditions are distributed for different discrepancy types of varying levels of damage (e.g., complete structural failure, extinguished light, damaged dayboard, etc.).
3. ATON type: This study solely focused on the impacts of storm conditions on single-pile fixed ATON. Other types of fixed ATON structures may respond differently in a given storm, so the USCG should investigate these different types and compare the results. The same methods could even be utilized to analyze discrepancies of floating aids and their distributions for varying storm conditions.

The findings of this research will benefit both the USCG's short-term preparedness and long-term planning for major hurricanes. If the service can identify consistencies in terms of the probability of different discrepancy types occurring across multiple historical storms, this information can be applied to forecasts and seasonal outlooks. In the short-term, ATON managers will be able to predict the number and type of discrepancies that will occur in a forecasted storm; this foresight will allow them to understand the potential scope of repairs that will be needed and pre-position equipment and assets to correct critical discrepancies following the storm. In the long-term, the USCG can consider seasonal forecasts such as NOAA's Hurricane Seasonal Outlook and use the modeled historical discrepancy data to develop cost estimates of emergency funds they may need to request from Congress ahead of hurricane season. In addition, this will prove useful to USCG Waterways Operations Produce Line teams, civil engineering units, and USCG construction tenders as they design and construct future ATON so that they can prioritize improvements that are robust in the areas of previous vulnerabilities.

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