Aerial deployment of Spotter wave buoys during Hurricane Ian

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***Abstract*—In this paper, we will discuss the ongoing progress by Sofar in contributing to state-of-the-art hurricane prediction efforts as part of the National Oceanographic Partnership Program (NOPP) Hurricane Coastal Impacts (NHCI) project, a joint collaboration between government, academic and industry partners. Through a massive collaborative effort across remote sensing, in situ observations, and numerical modeling, this project is working to improve our capacity to predict hurricane impacts to coastlines — from coastal erosion to infrastructure damage.**

As part of the project, Sofar provides in situ observations from Spotter buoys deployed, alongside other wave buoys, via airplane in a rapid-response fashion. The Spotter is a basketball-sized metocean buoy which collects a range of observations including directional wave spectra, sea surface temperature and barometric pressure. Observational data from Spotters can in turn be used to improve the initialization of wave forecasts (i.e. data assimilation), as well as validate and improve modeling frameworks in a hindcast manner for extreme weather events. We will review the progress of the NHCI project, the hardware developments made to collect in situ observations at the air-sea interface in extreme events with Spotters (i.e., ruggedizing the buoy platform for air deployment), and the successful collaborative rapid-response deployment and data collected during Hurricane Ian in 2022.

***Index Terms*—Hurricanes, oceanographic instrumentation, sensors**

I. Introduction

A. Hurricanes and their impact on coastal environments

Extreme weather events, such as hurricanes, yield major social and economic impacts to the United States, particularly in the Gulf of Mexico. An understanding of the complex air-sea interactions during hurricanes is of ongoing and ever-increasing importance due to the expansion of infrastructure along vulnerable coastlines and projected increases in the destructive capacity of land-falling hurricanes. The combination of waves and storm surge from hurricanes is both difficult to fully resolve and crucial to accurately predicting coastal impacts. Previous work in resolving wave, tide, and storm surge interactions indicates accurate predictions of storm surge are particularly sensitive to model implementation [1], especially in the nearshore, shallow water environments of the Gulf of Mexico [2]. The presence of GPS-enabled surface buoys can be used to validate and improve these models and extend our understanding of the ocean's response to hurricane wind fields [3].

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B. Objectives of NOPP and the NHCI project

The National Oceanographic Partnership Program (NOPP) is a federal program established to facilitate collaboration between private industry, academia, and federal agencies to tackle large, cross-functional challenges related to advancing ocean research. The NOPP Hurricane Coastal Impacts (NHCI) project is a multi-year (2021 to 2024) project targeted at improving our ability to predict coastal impacts from landfalling hurricanes by creating and improving forecast models of impacted coastlines. Specifically, this project focuses beyond accurately predicting the hurricane itself, but rather the impacts to the coastlines resulting from storm surge and waves.

Within the NHCI project, there are several sub-components divided by team specialization: (0) provide hindcasts, reanalyses, and forecasts (depending on the project year) of hurricane tracks and intensities, (1) create and update a digital elevation model (DEM) of relevant spatial regions, (2) create and improve methods of collecting elevation measurements to inform DEMs and provide a point of comparison for model forecasts, (3) collect in situ observations of waves and water levels for validation and assimilation, and (4) generate forecasts of impacts with a particular emphasis on coastal infrastructure interactions [4]. Sofar's contributions to the NHCI project lie solely within task (3); the collection of in situ measurements for which there is an offshore and a nearshore component. These components are more formally named "Air-deployed wave buoys for hurricane forecast improvements" (task 3A) [5] and "Real-time and observed measurements of hurricane-induced hydrodynamics and flooding" (task 3B) [6], respectively.

As part of the nearshore component, moored configurations of the Spotter equipped with a bottom-mounted pressure

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sensor provide both surface wave and water level to the modeling teams on the project. Deployment sites for these moored units were initially selected in conjunction with other monitoring instruments developed and installed near important coastal infrastructure by other collaborators on task 3B (United States Geological Survey (USGS)).

As part of the offshore component, Sofar is responsible for providing free drifting observations of wave conditions in the open ocean, prior to hurricane landfall. In the first year of the project, about 50 free-drifting Spotters were preemptively deployed in the Gulf of Mexico by our deployment partners in the region in the months leading up to the peak of the 2022 hurricane season, in addition to the pre-existing global network in the open Atlantic [10]. An additional 25 Spotters were allocated for aerial deployment in a rapid-response fashion for the 2022 hurricane season along with instruments developed by other collaborators on task 3A (Applied Physics Laboratory at the University of Washington, Scripps Institute of Oceanography). A similar number of Spotters are expected to be deployed aerially during the 2023 hurricane season. The following sections detail the aerial deployments of wave buoys and resultant data.

II. The Spotter platform

The Spotter buoy is an approximately spherical drifter with a mass of 5.5 kg, and a diameter of 38 cm (Fig. 1). An array of solar panels provides sufficient power for the Spotter buoy to remain charged indefinitely following deployment. Each free-drifting Spotter is equipped with a sea surface temperature (SST) and a barometer, in addition to the GPS capabilities that allow Spotter to calculate and report information about local wave and inferred wind conditions. These measurements are transmitted hourly through the Iridium satellite network.

Fig. 1. Free-drifting Spotter configuration. Handles along the hull edge and light, compact structure maximize the device's ease of deployment.

The moored, subsurface-sensor-equipped configuration of Spotter is referred to as "Smart Mooring". In this configuration, a cable containing kevlar-sheathed power and electronics wires extends from the foot of the Spotter's hull through the water column to a given anchor configuration. Along the length of the cable, a number of in-line sensors can be installed to collect ocean measurements at depth. Smart Moorings deployed as part of the NHCI project were equipped with a pressure sensor as close to the ocean bottom as possible. Measurements from the pressure sensor, in combination with real-time, surface atmospheric pressure measurements, can be used to accurately calculate water levels at the deployment location.

The robustness and versatility of Sofar Ocean's devices have allowed us to contribute to observations spanning the open ocean to the nearshore for the NHCI project.

III. Accessing Spotter data

Spotters, as part of the NHCI project, are configured to transmit messages hourly, from the time they are first turned on. Smart Moorings transmit most of their data at hourly intervals, except for pressure measurements, which are made available every 30 minutes.

Data from Spotters can be viewed and accessed as a downloadable CSV file from a Sofar Ocean-hosted dashboard [7].

Spotter data can also be accessed via an Application Programming Interface (API) [8]. The Sofar API allows our NHCI partners to access our buoy data easily and reliably. Sofar also supports a python package called "pysofar" [9] which provides tooling to efficiently work with the API data.

IV. Process of ruggedizing Spotter

In its off-the-shelf form, Spotter can be deployed via large shipping and research vessels – the typical deployment method for Sofar Ocean's global network of buoys which provide observations to our weather models. Operational constraints on plane deployment (minimum altitude and speeds), however, introduced the risk of instrument damage from impact forces if no additional deployment aides are used. Ensuring the success of aerial deployments ahead of hurricanes consequently required additional testing and modifications to the Spotter platform.

While attachment of a parachute is a traditional solution for aerial deployment, we sought a solution that minimized the logistical complexity of rigging and static line deployment necessitated by parachutes.

During spring 2022, a seaplane, in coordination with an on-the-water crew, enabled the first comprehensive test of aerial deployment of off-the-shelf Spotters from a variety of altitudes and speeds (> 100 mph, 500-3000 ft). Without instrument reinforcement, the primary cause of failure for a subset of buoys was attributed to tumbling during descent and thus instability of the orientation Spotters impacted the ocean surface; Spotters hypothesized to land upright had a higher survival rate than those that landed on their side. Failed Spotters exhibited internal cables separated from their ports, batteries breaching the bottom of their housing, and cracked hulls. The descent and impact behavior during the tests were captured by video from the perspective of the plane (Fig. 2), from the crew on the support vessels, and in some cases from the perspective of the unit itself (Fig. 3). Observations of the device tumbling behavior motivated development of a structure to stabilize the Spotter's descent and control the landing orientation.

Fig. 2. Crew members prepare to drop a Spotter out of the window of a deployment partner's plane over Monterey Bay, California February 7th, 2022.

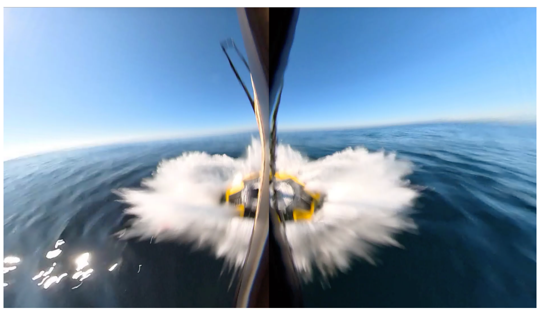

Fig. 3. 360 GoPro screen capture of one of the airdropped Spotters impacting the ocean surface. The GoPro mounting appeared to stabilize the fall, causing this particular unit to land upright and subsequently suffer minimal damage. Units that landed with other orientations experienced higher failure rates.

By mid-June 2022, a final form factor for fall stabilization was realized: a stabilizer composed of cardboard and packing tape (Fig. 4). Additional modifications to the buoy itself included reinforcement of cable connections with epoxy and the removal of unnecessary objects within the hull (desiccant packs, SD card).

Following initial iterations (such as test drops from a skydiving airplane by University of Washington Applied Physics Laboratory (UW APL) collaborators), a final airdrop test was conducted in mid-August 2022 (Fig. 5), using several test Spotter devices with reinforced internal cables and cardboard stabilizers. Survival of all units indicated readiness for operational deployment during hurricane season 2022.

Fig. 4. Cardboard stabilizers to be attached to the air-deployable Spotters.

Fig. 5. Spotters lined up in the cabin of the plane used for the final deployment.

V. Performance during Hurricane Ian

The first operational airdrop as part of the NHCI project occurred on September 26th, 2022, just ahead of Hurricane Ian's landfall on the Florida Gulf Coast on September 28th, 2022. A total of 10 Spotters were deployed alongside A-sized Directional Wave Spectra Drifters (A-DWSD) and micro Surface Wave Instrument Float with Tracking (microSWIFT) [12] devices developed by the Lagrangian Drifter Lab at Scripps Institution of Oceanography and UW APL, respectively. The locations of the devices which successfully reported after the drop can be seen in Fig. 7 relative to the hurricane's path in Fig. 8. All Spotters were deployed at an altitude of 1000 ft and an airplane speed of 130 knots by the Naval Research Laboratory (NRL) VXS-1 crew (Fig. 6). These drop locations were selected to focus an array of devices in quadrant 1 ("right front") of the developing hurricane, where weather conditions are typically the most intense. The most recently available forecast at the time of deployment provided supporting evidence of this behavior in the context of Hurricane Ian.

Among the deployed buoys, on September 27th, 2022, the eyewall of Hurricane Ian passed directly over one of the Spotters prior to its landfall (Fig. 9, left). As the eye traversed overhead, the device recorded wave heights exceeding 11 meters, a drop in sea surface temperature of 1.5 degrees Celsius in the hurricane's wake, and a surface atmospheric pressure drop of 70 millibars offshore of Naples, Florida.

Fig. 6. A Spotter buoy to be deployed by NRL VXS-1 partners in advance of Hurricane Ian.

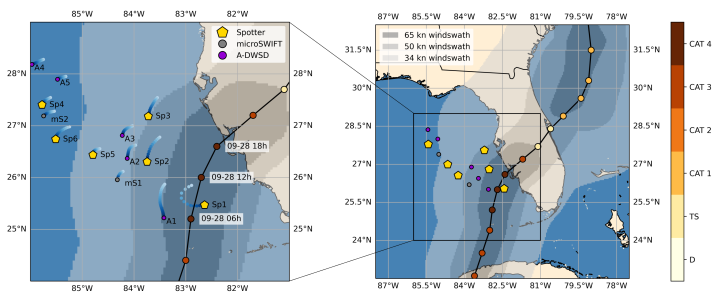

Fig. 7. Locations of all devices aerially deployed on September 26th, 2022 (left). Regions of increasing hurricane intensity appear as varying shades of gray surrounding the hurricane path (black line). Hurricane Ian's intensity at different locations can be seen in warm colored circles overlying the hurricane's path (right).

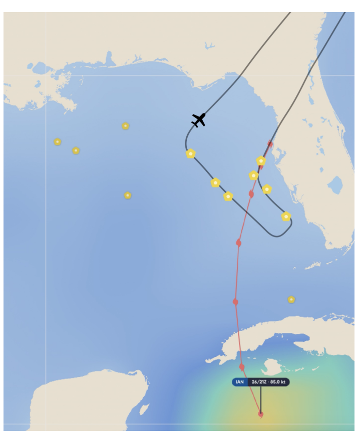

Fig. 8. The locations of air-dropped Spotters are indicated by the larger, yellow pentagons along the black line, which represents the flight path of the aerial deployment platform. The light red line indicates the predicted path of Hurricane Ian's eye close to the time of the deployment - 12:00Z on September 26th, 2022. Smaller yellow pentagons indicate Spotters that had been preemptively deployed by vessels earlier in 2022.

The Spotter that captured the conditions within the eye of Hurricane Ian continued its deployment (along with the other deployed Spotters) within the Gulf of Mexico for several months after Hurricane Ian had passed.

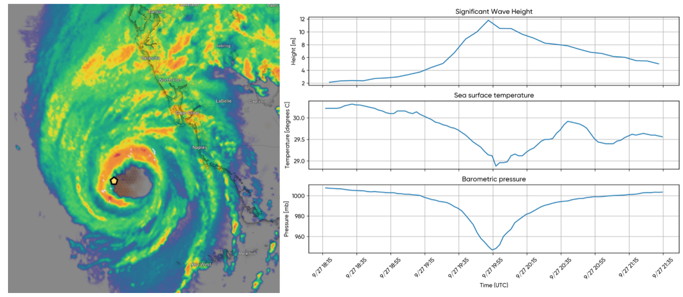

Fig. 9. One of the air deployed Spotters encountered the western side of Hurricane Ian's eyewall prior to landfall on September 27, 2022 (left). Measurements of significant wave height (right, top) and barometric pressure (right, bottom) captured by the same Spotter reveal the magnitude of the intensity of the storm's conditions at the device's location. Fluctuations in the recorded sea surface temperature (right, middle) are indicative of the ocean mixing induced by the hurricane.

Observations collected during and after Hurricane Ian were then distributed to collaborators for validation of the forecasts run in a variety of modeling frameworks (A Coupled-Ocean-Atmosphere-Wave-Sediment Transport Model, ADvanced CIRCulation Model, XBeach). These observations, in addition to observations in Hurricane Fiona by the pre-deployed Atlantic Spotters, were also utilized for analysis of wind-wave growth under tropical cyclones, specifically toward understanding saturation of wave steepness [11]. Further, the publicly available dataset is valuable toward a variety of research questions at the air-sea interface during extreme events, as well as toward Sofar's broader data assimilation efforts.

VI. Conclusions

Spotters are viable wave measurement devices that can be reliably deployed from aerial platforms when supplied with the proper modifications. The developments required to ensure the survivability of Spotters in time for the 2022 hurricane season proved to be a challenging, but successful endeavor. A series of test air deployments facilitated by our NHCI team members and local partners were interspersed with swiftly executed modification iterations. These modifications included reinforcement of internal cables, removal of non-essential internal components, and the creation of easily reproducible, attachable, and biodegradable stabilizers, which maximized the survivability of the Spotter devices. The support of the NOPP program, the close collaboration between other NHCI teams, and the hardware development expertise at Sofar enabled the successful collection of observations by the Spotter devices during Hurricane Ian. The observations made during 2022 have been, and are continuing to be, used to validate and improve the models for coastal impact forecasting.

Logistical efforts for the 2023 hurricane season are already underway. Twenty-five Spotters (along with additional microSWIFTs and A-DWSDs) are prepared for the repeated, rapid response method of capturing observations in and around landfalling hurricanes. These devices will retain many modification characteristics of the last batch of Spotters deployed at the end of the 2022 hurricane season, and their observations will continue to be used to iterate on the work already accomplished by the NHCI modeling teams. These in situ observations are essential to improving the skill of models designed to accurately predict the impact hurricanes will have on coastal communities.

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REFERENCES

[1] P. C. Kerr, R. C. Martyr, A. S. Donahue, M. E. Hope, J. J. Westerink, R. A. Luettich, A. B. Kennedy, J. C. Dietrich, C. Dawson, and H. J. Westerink, "U.S. IOOS coastal and ocean modeling testbed: Evaluation of tide, wave, and hurricane surge response sensitivities to mesh resolution and friction in the Gulf of Mexico," J. Geophys. Res. Oceans, vol. 118, pp. 4633–4661, September 2013.

[2] A. B. Kennedy, U. Gravois, B. C. Zachry, J. J. Westerink, M. E. Hope, J. C. Dietrich, M. D. Powell, A. T. Cox, R. A. Luettich, and R. G. Dean, "Origin of the Hurricane Ike forerunner surge," Geophys. Res. Lett., vol. 38, April 2011.

[3] M. Curcic, S. S. Chen, and T. M. Özgökmen, "Hurricane-induced ocean waves and stokes drift and their impacts on surface transport and dispersion in the Gulf of Mexico," Geophys. Res. Lett., vol. 43, pp. 2773-2781, March 2016.

[4] R. A. Beach (2023) National Oceanographic Partnership Program (NOPP) Hurricane Coastal Impacts (NHCI) [Powerpoint slides]. Available: https://www.weather.gov/media/nws/IHC2023/Presentations/Beach_NHCI-NOPP.pdf

[5] Sofar Ocean. "Air-deployed wave buoys for hurricane forecast improvements." https://nopphurricane.sofarocean.com/team/thomson (accessed July 26, 2023).

[6] Sofar Ocean. "Real-time and Observed Measurements of Hurricane-Induced Hydrodynamics and Flooding." https://nopphurricane.sofarocean.com/team/brown (accessed July 26, 2023).

[7] Sofar Ocean. "Sofar Spotter Dashboard." https://spotter.sofarocean.com/ (accessed July 26, 2023).

[8] Sofar Ocean. "Sofar API." https://docs.sofarocean.com/ (accessed July 26, 2023).

[9] Sofar Ocean. "pysofar: Python client for interfacing with the Sofar Wavefleet API to access Spotter data." pypi.org. https://pypi.org/project/pysofar/ (accessed July 26, 2023).

[10] Sofar Ocean. "Sofar Weather Dashboard." https://weather.sofarocean.com/ (accessed July 26, 2023).

[11] J. Davis, J. Thomson, I. A. Houghton, J. D. Doyle, W. A. Komaromi, C. W. Fairall, E. J. Thompson, and J. R. Moskaitis, "Saturation of ocean surface wave slopes observed during hurricanes," Geophys. Res. Lett., 2023, accepted.

[12] J. Thomson et al., "Development and testing of microSWIFT expendable wave buoy," Coastal Eng. J., 2023, submitted.