New Insights on Fish Spawning Aggregation Dynamics from Autonomous Robotic Platform

Nuevas Perspectivas sobre la Dinámica de Agregación de Peces desde la Plataforma Robótica Autónoma

Nouvelles Connaissances sur la Dynamique d'Agrégation des Frayères à partir d'une Plateforme Robotique Autonome

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ABSTRACT

Fish spawning aggregations usually consist of the gathering of a large number of fishes in high concentration at a specific location. Some large fish species, such as groupers produce sounds during reproductive behaviors. Because aggregation monitoring by divers is often restricted to a limited area, our knowledge of fish spawning aggregation is most likely to be restricted to the surveyed area. In addition, Eulerian passive acoustic monitoring is also limited by the sound propagation range, hence the distance from the fish to the hydrophone. As such, this Eulerian monitoring approach implicitly creates a knowledge gap about what happens beyond the monitoring site. Fisheries independent research strives for new technology that can help remotely and unobtrusively quantify fish biomass. Fish sounds provide an innovative approach to assess fish presence and numbers during reproductive events. However, large datasets make the detection process by a human ear and eyes very tedious and lengthy. We have developed an algorithm based on machine learning and voice recognition methods to identify and classify fish sounds. This algorithm currently operates on a SV3 Liquid Robotics wave glider, an autonomous surface vehicle which has been fitted to accommodate a passive acoustic listening device. Fish sounds detection and classification results, and location along with environmental data are transmitted in real-time enabling verification of the detections with divers or other in-situ methods. Recent surveys in the US Virgin Islands with the SV3 Wave Glider are revealing for the first time the spatial and temporal distribution of fish calls surrounding a known spawning aggregation site. These findings are critical to fish population abundance and stock assessments because calling fish were detected several kilometers away from the main aggregation. These surrounding courtship associated sounds suggest that other spawning aggregations may exist in addition to the main one.

KEYWORDS: Passive acoustics, spawning aggregation, Wave Glider

INTRODUCTION

Mature adults of many fish species swim long distances and gather in high densities for mass spawning at precise locations and times (Domeier and Colin 1997). Worldwide depletion of large predatory fishes has already caused top-down changes in coral reef ecosystems and biodiversity loss (Mumby et al. 2006). Moreover, most known fish spawning aggregations (FSA) sites are shared by many species at different times (Heyman and Kjerfve 2008) and as such, represent breeding hotspots requiring some form of protection (Erisman et al. 2017). It is critical that their role in the persistence of marine populations be elucidated. FSAs share common features such as high density of large body-sized individuals, strong site fidelity, temporal predictability and geomorphological attributes, (i.e. shelf-break, capes) (Claro and Lindeman 2003, Kobara and Heyman 2010, Kobara et al 2013). Once located, they are easily over-exploited and depleted (Sadovy 1997, Sala et al. 2001, ICRS 2004). Despite numerous historical records of Caribbean-wide FSAs (Smith 1972, Eklund et al. 2000) only a few are documented to date and many remain unprotected (Sadovy et al. 2008).

The existing FSAs in the Caribbean Sea, Gulf of Mexico and the Bahamas Region (i.e the Intra-America Seas) are where a number of vocalizing grouper species such as the Nassau (*Epinephelus striatus*), yellowfin (*Mycteroperca venenosa*), red hind (*Epinephelus guttatus*) and black grouper (*Mycteroperca bonaci*), among others, aggregate to spawn (Nemeth 2005, Rowell et al. 2015). Most of these species spawn during the winter and spring months (December to May) in the northern hemisphere (Nemeth 2012). The timing of spawning is usually cued to the moon and daylight, but also to water temperatures and local current conditions (Nemeth 2009). Because remaining FSAs often occur at remote locations, are most active at dusk and are in water depths between 30 and 80 m, near the shelf break, spawning activities and fish population are challenging to observe, and thus to monitor (Kobara et al. 2013). While many of these sites are known to fishers and represent areas of intensive harvest, not all fish spawning locations have been documented. As such, there may be a significant number of unreported FSAs, which, if located, could provide a better estimate of the status of certain populations of grouper species such as Nassau, Warsaw (*Hyporthodus nigritus*), Black, Red Hind, Goliath (*Epinephelus Itajara*) and others. Data on the FSA dynamics of these species is critical to the management of these stocks, which involve the South Atlantic, Gulf of Mexico and Caribbean Fishery Management Councils (SAFMC, GMFMC, CFMC), as well as local or state entities such as the Puerto Rico Department of Natural and Environmental Resources (PR-DNER), USVI Department of Planning and Natural Resources (DPNR), Florida Fish and Wildlife Conservation Commission (FWC). Determination of the timing, duration and intensity of spawning will be of direct utility for the design and evaluation of management actions, stock assessment and effective conservation measures.

Passive acoustic monitoring (PAM) is a fisheries-independent approach that can provide *in-situ* observations of soniferous fishes, such as groupers (Mann et al. 2010, Rowell et al. 2011 and 2015, Schärer et al. 2012a&b, 2014, Wall et al. 2014, 2017). Additionally, PAMs can be relatively non-intrusive and provide data on grouper behavior and distribution, critical for understanding their biology and ecology. As particular grouper populations begin to recover from overfishing, new or previously lost aggregations may reform, also making this technology particularly relevant for surveying and evaluating the recovery of groupers. To date, fisheries monitoring efforts using PAMs have primarily used an Eulerian approach; recordings are made from fixed stations at known FSAs (Rowell et al. 2012). However, these FSAs are spatially dynamic and can shift outside the range of fixed stations in a relatively short period. As such, more mobile approaches with PAMs are required to best encapsulate FSA dynamics. For example, the use of autonomous platforms such as buoyancy-driven gliders or wave-gliders that are equipped with PAM systems can be programmed more accurately to encompass FSA spatial extents as well as scout regions of the shelf edge in the exploration of unknown FSAs. Wall et al. (2014) used Slocum gliders, buoyancy driven autonomous underwater glider (AUG) to conduct a large-scale spatial mapping across the West Florida shelf of Red Grouper (*E. Morio*) sound production. A similar survey was conducted with the same technology along the southeast U.S. (Wall et al. 2017). This survey was conducted during winter when fishery-independent survey data were lacking from traditional ship-based approaches (due to prolonged periods of inclement weather) and covered the winter-spawning dynamics of multiple species managed by the SAFMC. According to the SAFMC, the importance of increasing collection/detection and interpretation of acoustic signatures of managed species is long overdue in the South Atlantic Bight.

These surveys were conducted with low power acoustic recorders (DSG - Loggerhead Instruments (www.loggerheadinstruments.com), which are self-contained acquisition-only devices that are not integrated to their host, and do not allow for onboard processing and analysis. Therefore, AUG surveys are not capable of characterizing FSAs in real-time, nor can they provide information such as the species composition of FSA aggregates, precise location and timing, population size and the fish behavior or distance from the glider. But automated data collection means that surveys can take place at times and in places where it would be too expensive or dangerous to send human observers (Marques et al. 2013). These early attempts by NOAA to survey fish sound production from spawning aggregations as a new technique for stock assessment led us to conceive a real-time detection and classification PAM system that can be integrated on any glider. Our glider of choice was the SV3 wave glider (WG) because of its continuous real-time transmission and positioning capabilities, which are crucial to the localization of FSAs that are most of the time transient events.

The main objective of this paper is to present a new persistent robotic approach to conduct PAM surveys and its application to the study of the dynamics. Indeed, the robotic platform was deployed in the U.S. Caribbean near known FSAs and was used to explore the shelf edge up to 20 km away from them. Its findings reveal the presence of CAS of the same aggregating species both scattered and aggregated at other locations along the shelf break. In Section 2 we describe the autonomous platform and the PAM system. In Section 3 we present the characteristics of the grouper courtship associated sounds (CAS). The fish sounds detection and classification algorithms are described in Section 4. Results on FSA spatial dynamics from the field survey in the U.S. Virgin Islands are presented in Section 5. Conclusions are drawn in Section 6.

THE PERSISTENT ROBOTIC APPROACH

Marine Autonomous Systems

Marine autonomous systems, including submarine gliders and autonomous underwater vehicles (AUVs), are revolutionizing our ability to map and monitor the marine environment (Yoerger et al. 1998, Rudnick et al. 2004, Yoerger et al. 2007, Caress et al. 2008, German et al. 2008). Although truly autonomous systems are typically deployed from a research vessel, they are not tethered to the vessel and do not require direct human control while collecting data (Yoerger et al. 1998, Griffiths 2003, Yoerger et al. 2007a). Therefore, they provide opportunities for data acquisition in parts of the ocean previously inaccessible to vessel-based instruments, e.g. beneath ice sheets in polar regions (Bellingham et al. 2000, Brierley et al. 2002, Nicholls et al. 2006, Wadhams et al. 2006, Dowdeswell et al. 2008, Jenkins et al. 2010, Graham et al. 2013), and are improving the spatial and temporal resolutions of a broad spectrum of marine measurements (Niewiadomska et al. 2008, Caldeira et al. 2014). They also have the potential to transform the way fisheries scientists and oceanographers study marine population and ecosystem dynamics (Fernandes et al., 2003; Ohman et al., 2013).

Autonomous underwater gliders (AUGs), such as the Spray glider (Rudnick et al. 2004), the Slocum gliders (Teledyne Webb Research) and the Seaglider (Eriksen et al. 2001) are all capable of sampling continuously throughout the water column as deep as 6,000 m depth for the latter by gliding on wings and adjusting their buoyancy and attitude (Rudnick et al. 2004). Slocum and Spray gliders are also configured to operate in shallow shelf environments (< 200 m). Their deployments can last over 1 month and their range can expand over hundreds of kilometers, with periodic surfacing for data offload and GPS positioning. In recent years AUGs have been used in ocean soundscape mapping (Matsumoto et al. 2011, Bingham et al. 2012, Wall et al. 2012, Baumgartner et al. 2013) and more recently in fisheries independent surveys (Wall et al. 2014, 2017) on the shelf of the continental United States (U.S.). AUGs surveys are significant less contingent upon large amount of funding being available for ship and personnel time and therefore have the potential to provide long time series at a relatively lower cost. Data collected through passive acoustic surveys are used to assess the presence of soniferous fish with the ultimate goal of assessing biomass and supporting stock assessment activities, while studying the ecological importance of many important commercial species in the U.S.

Autonomous surface vehicles (AUVs) such as Wave-Gliders (WG) have the advantage of continuous GPS positioning, data access and extraction over AUGs. The SV3 wave glider is a self-propelled, unmanned persistent mobile data-gathering platform that harvests both solar and wave energy for propulsion and power (Figure 1). It can be used as station keeping or mobile data collection for up to 12 months with no fuel, emission or crew. It provides a real-time communication gateway and has the modularity and capacity to accommodate new prototype sensors and software interfaces that can eventually be integrated and operated with other systems. The SV3-WG is designed for long-term deployments to collect oceanographic and other environmental data (Manley et al. 2009, Willcox et al. 2009). It consists of a surface float tethered with an umbilical cable to a submersible glider (Figure 1). The surface float houses a command and control unit for communications, navigation, and power systems, and a modular payload unit for user-specified environmental-sensing systems. The submersible glider has a series of paired wings that generate gliding lift, a rudder to provide steering and a thruster for emergency maneuvers and adverse current. The WG harnesses wave energy for propulsion. The heave of the wave forces the submersible forward ahead of the float, which is then pulled forward over the submersible, and so on. Solar panels on the deck of the surface float recharge a lithium ion battery pack inside the WG's hold. This battery pack supplies power to systems inside the WG's command and control unit and modular payload unit. A simple, Web-based interface, called WGMS transmits control system and sensor data from the WG to shore and commands back from shore to the WG during a mission. It also provides a precise and intelligent navigation web interface. Two-way transmission via cellular network or Iridium satellite provides real-time navigational, operational, and sensor control as well as real- or near-real-time data reporting (Greene et al.

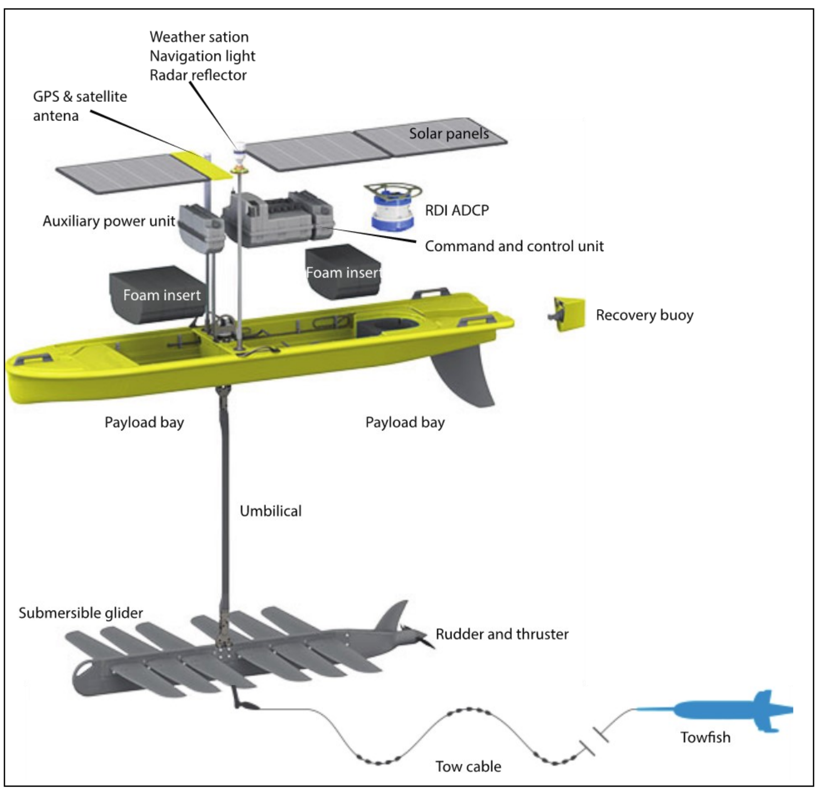

Figure 1. Components of the Liquid Robotics (a Boeing company) SV3 wave glider.

2014). Our submersible glider is connected to a custom-built two-body designed to carry a variety of off-the-shelf acoustic systems. The neutrally buoyant tow-body is deployed directly behind the submersible glider with a sinusoidal-shaped tow cable, 8 - 10 m below the ocean surface. The shape of the tow cable is the result of adding slack-tensioning elements, which greatly reduce pitch, roll, and yaw of the tow body relative to its performance with a conventional tow cable (Figure 1). Green et al. (2014) developed new technology for WGs that enable them to collect multifrequency, split-beam acoustic data sets comparable to those collected with manned survey vessels. WG equipped with PAM systems can be programmed more accurately to encompass FSA spatial extents as well as scout regions of the shelf edge in the exploration of unknown FSAs.

SV3 Wave Glider Instrumentation

SV3-WG instruments and payload — The wave glider operating system collects navigational and environmental data that are directly available to the operator in real-time. As such, a water velocity sensor informs the operator of the surface current speed and direction. The wind speed and direction are also recorded by the wave glider. In addition, our SV3-WG is equipped with a 600kHz Workhorse ADCP, which measures current profiles down to 50-m in real-time. The data is readily available through WGMS.

Passive Acoustic Monitoring System — The PAM system consists of two distinct sub systems: one located on the tow -body below the sea surface and the other, located in the surface float section of the SV3-WG. In particular, the sub-surface section of the system hosts two ultra-low frequency hydrophones (HTI-96-Min Hydrophones) and an embedded data processing module optimized in design for such application. The hydrophone frequency response is 2Hz to 30kHz with a sensitivity of -201 dB re: 1V/mPa without pre-amp. The system is connected to the host vehicle through the tow-body electrical tow cable. The hydrophone housing is a, tubular, oil-filled sealed enclosure that can accommodate up to three hydrophones (Figure 2), rated for 100 m depth. The tube is simply a fairing that mitigates unnecessary, disruptive noise caused by flow around the tow cable, eddies induced by edges on the tow-body, or any other features that would cause low frequency acoustic vibrations due to turbulent flow. The tube is made of clear polyvinyl chloride (PVC) material, making the housing acoustically transparent. It is oil-filled to couple the hydrophones to the vibrations at wall of the tube. The hydrophone housing is rigidly fixed to the tow-body using internal bolts and a machined plastic spacer. Located inside of the hydrophone housing, is a data acquisition card that contains a high-speed digital-analog converter (ADC), band-pass filter and embedded processor used to continuously collect and buffer data, which is then streamed for signal detection and classification.

The PAM electronic housing, which is located inside the tow-body holds the main processing computer that runs the detection and classification algorithm. The electronic package consists of an off-the-shelf Texas Instrument Beaglebone Black single board computer (SBC). The SBC connects to a stack of breakout daughter boards. The PAM's BeagleBone Black computer runs on Debian, an open-source variation of the Linux operating system maintained by the Debian Project. The software architecture employs the publisher-subscriber model. Seven "port" modules publish data acquired from various sources (sensors, devices, algorithms). Consumer modules subscribe to receive only the data they need and at the rate at which it becomes available. The open-source Lightweight Communication & Marshalling (LCM) middleware library uses the User Datagram Protocol (UDP) to provide the needed publish-subscribe mechanisms.

Seven port modules interact with the payload or other data sources. Five of these ports are respectively connected to:

i) A SIMRAD NSS7 Evo2 echosounder with structurescan sonar and with frequency modulation (CHIRP) sonarhub. Sonar screen movies are recorded for sound detection validation. The sonarhub is mounted on the aft of the WG.
ii) An onboard AST4000 pressure sensor.
iii) A Turner C3 Fluorometer, which measures CDOM, Chlorophyll-a, and backscattering fluorescence (Figure 2).
iv) Hydrophones, and
v) A fish sounds detection and classification algorithm.

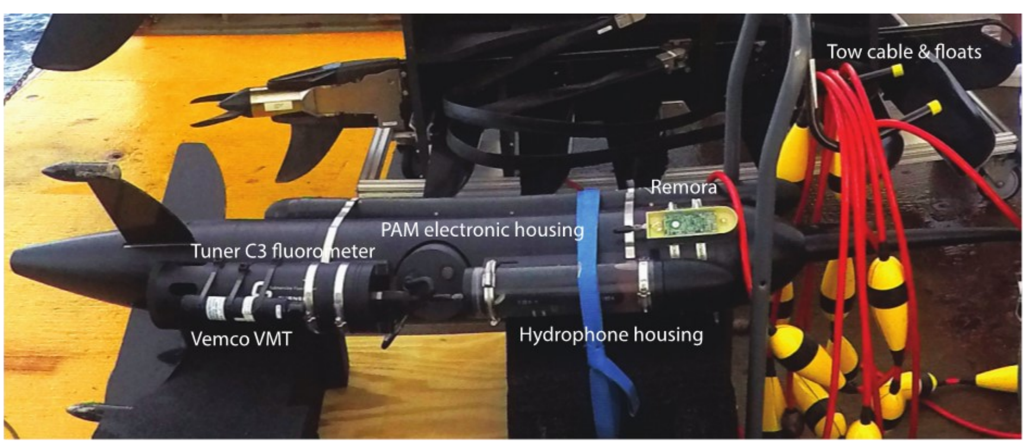

Figure 2. Components and payload of the tow-body.

The PAM records 10s audio files every 30 seconds. Each audio file is analyzed by the detection algorithm and if there is a detection, a 3 second snippet that contains the sound detected is produced by the software. However only one hydrophone channel is currently used for the detection analysis and the data is written in ASCII. The data is stored locally on the PAM on a microSD card and then copied to the vehicle payload computer for real-time access and transmission via GSM network or satellite (RUDICS). Finally, a self-powered, self-logging EXO[1] YSI multipa-rameter sonde is rigged to the tow-body and collects, pressure, pH, temperature, salinity, and dissolved oxygen (DO). Other sensors such as external Remora hydrophone from Loggerhead Instruments, or VEMCO VMT receiver/ transmitter for underwater acoustic telemetry have also been used on the tow-body (Figure 2).

FISH SOUND AND DETECTABILITY

Grouper Courtship Associated Sounds

For many species of fish, including epinephelids, sound plays a critical role in reproduction and therefore the survival and success of the species (Bass and Mckibbe, 2003). Effective communication requires both species and mate recognition for reproduction. In known sound-producing epinephelid species such as groupers, acoustic signals are used by different taxa for recognition, attracting females, defending male territories and as an alarm system against predators (Mann et al. 2010, Schärer et al. 2012a&b, Schärer et al. 2013, Schärer et al. 2014). The calls of these epinephelids consist of multiple different sounds produced in series to create a species-specific acoustic call structure. Grouper species that co-occur at spawning aggregation sites in the US Caribbe- $SNR(150) = SL - TL - NL =$ an and who produce courtship associated sound (CAS) are described in Table 1. CAS are characteristics of reproductive behaviors and can provide an estimation of relative spawning activity and relative abundance through the spawning period (Rowell et al. 2012), warranting the use of passive acoustics to locate spawning aggregations (Luczkovich et al. 1999, 2008b, Walters et al. 2009, Rowell et al. 2011) and determine tempo- ral spawning behavior and habitat use by different species (Locascio and Mann 2008, Mann et al. 2009, 2010, Nelson et al. 2011, Schärer et al. 2012).

The species-specific vocalizations are distinctive in duration, peak frequency, and tonal characteristics and are easily distinguished from each other audibly and visually in spectrograms. Figure 3 shows the spectrogram of three species targeted in this study as recorded by the WG. Nassau grouper (*Epinephelus striatus*), whose vocalizations consist of a pulse train made up of a varying number of short individual pulses and tonal sound in the 30 to 300 Hz band (Schärer et al., 2012a) (Figure 3a); Yellowfin grouper (*Mycteroterpa venenosa*), whose vocalizations consist of calls composed of two parts (one pulse train and one modulated tonal) that are usually longer in duration than the other two species, with frequency ranging between 90 to 150 Hz (Figure 3b – tonal call) (Schärer et al., 2012b); Red hind (*Epinephelus guttatus*), whose vocalizations are within the 100 to 250Hz band (Mann et al., 2010) and consist of a variable number of pulses, with one or more portion of the call being tonal, at a higher pulse rate than the rest of the pulses (Figure 3c, d). Black grouper (*Mycteroterpa bonaci*), which produce at least two variations of a low frequency, modulated tonal call, which ranges between 60-120 Hz, but generally has a longer duration than *E. striatus* (Schärer et al., 2014) was not identified in the recordings during the glider survey.

The call structures previously described and shown in Figure 3 may not reflect the full variation of acoustic features for each species as has been recently discovered in the data presented in this paper as well as in the most recent literature. For example, another agonistic call type produced by Nassau grouper was identified in Puerto Rico by Rowell et al. (2018).

Grouper Sound Detectability

The average source level (SL) of the grouper species targeted in this study is between 100 -150 dB re 1 µPa (Mann et al. 2009, Schärer et al. 2012, 2014). The potential detection range of the glider with respect to sound production by the species of interest was estimated using the spherical spreading loss model by Kinsler et al. (1999):

$$TL(f,R) = spherical\ spreading(R) + sea\ water\ absorption\ (f,z)$$

$$TL(f,R) = 20\log(R) + \alpha(f)R$$

where *TL* is the transmission loss, *R* the range, and *f* the frequency. Using a SL of 150dB re 1 µPa, the transmission loss (TL) at 100 Hz estimated for this sound level at 150 m is thus TL = 40.76 dB re 1 µPa. This spherical spreading loss model provides a conservative estimate of transmission loss given that once sound reaches the sea surface it may be spreading cylindrically. The transmission loss of the cylindrical model is about half that of the spherical model. Therefore, if the noise level (NL) was assumed to be around 85 dB at 100 Hz (Miller et al. 2008), the signal to noise ratio (SNR) at 150m would be according to the spherical spreading model:

$$SNR(150) = SL - TL - NL = 24.24\text{ dB.}$$

Table 1. Grouper sound characteristics

Type of Species	Frequency range (Hz)	Peak frequency (Hz)	Bandwidth (Hz)	Duration (s)
Red hind	50-350	213±23	38.2±18.5	1.78±1.02
Nassau Grouper	90-150	99±33.6	22.4±12.2	1.6±0.3
Yellow fin Pulse train	101.4-132.4	120.46±7.45	33.03±6.13	2.96±0.97
Yellow fin Tonal call	88.9-141.7	121.04+12.57	43.18±4	3.14+0.95
Black Grouper	60-150	108±9	31±6.3	1.7±0.85

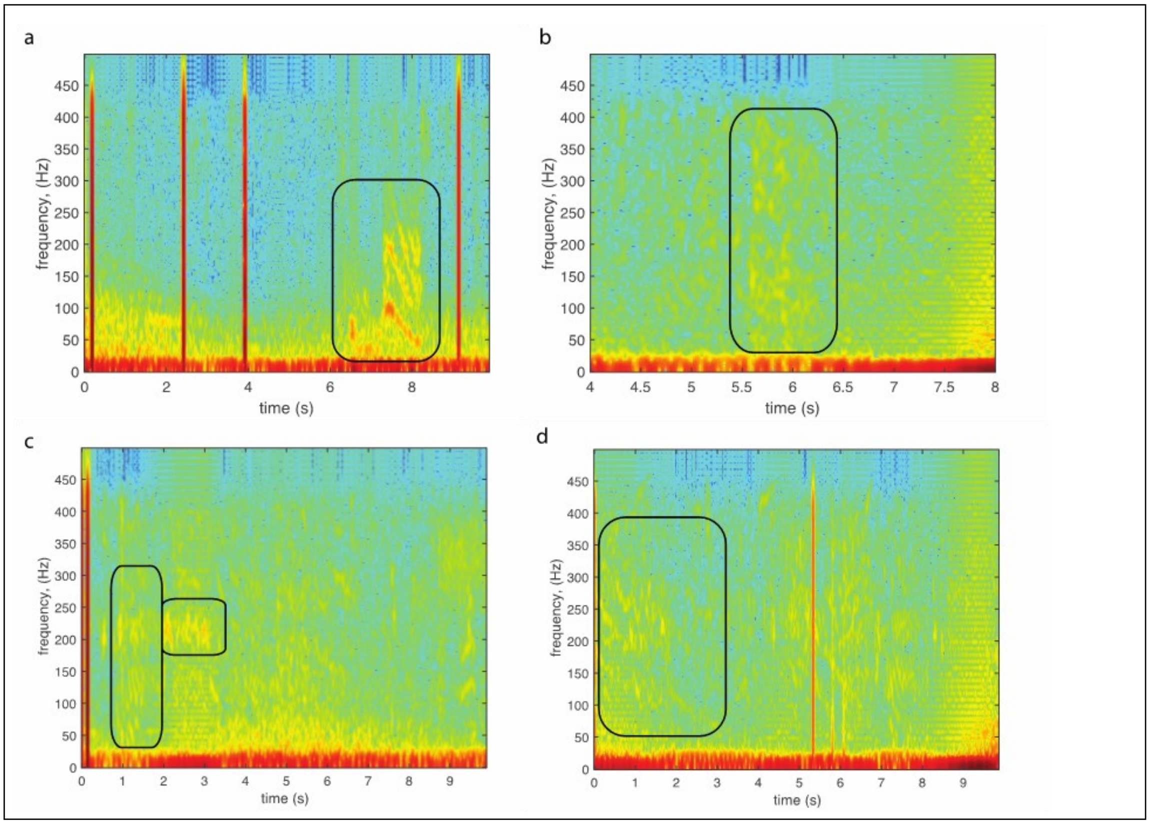

Figure 3. Fish call spectrograms recorded with the Wave Glider PAM in the Virgin Islands. (a) Nassau grouper. (b) Yellowfin grouper. (c) Red hind grouper tonal and pulse call. (d) Red hind grouper tonal call.

This result was then used to define the specification of our hydrophone system, such as peak voltage, minimum voltage with background noise and the fish sound detection threshold voltage. This simplistic transmission loss model does not account for transmission loss associated with environmental conditions, substrate and bathymetric features. However, comparison with bottom mounted hydrophones shows that fish call SNR levels similar to the SV3-WG are also recorded suggesting that distant calls can be heard by both systems (not shown).

GROUPER CALLS DETECTIONS ALGORITHMS

The PAM computer on the tow-body operates in real-time the fish acoustic detection algorithm research (FADAR) program, an automated identification scheme for fish vocalizations based on the auditory analysis for feature extraction followed by a machine-learning algorithm for classification (Ibrahim et al. 2018). FADAR was designed to detected four grouper species (Table 1). Grouper sounds were labeled initially by humans for training and testing various feature extraction and classification methods. Grouper sound data collected from bottom moored hydrophones at known FSAs were used for training. They provided the advantage of higher SNR for fish sounds than on the SV3-WG, which improves acoustic feature extraction and algorithm positive detection rate for data collected in similar conditions. However, the algorithm showed poor performance for the SV3-Wg data, which have smaller SNR. Therefore, the algorithm was specifically trained with low SNR fish calls from the WG, which improved its accuracy in the field. In the feature extraction phase, a mel frequency cepstral coefficients (MFCC) feature extraction method was used. The MFCCs are short-term spectral based features, which provide a powerful representation of sound structures. They can also be improved to include the dynamic characteristics of the sound as shown in Ibrahim et al. (2018). Experimental results showed that the overall percentage of identification using the best combination of the selected feature extractor and sparse classifier achieved 82.7 % accuracy overall, although the accuracy varied per species. *E. gutattus* and *M. venenosa* were the most successfully classified species, while *E. striatus* was slightly lower than the previous two and *M. bonaci* had the lowest accuracy rate of all. The algorithm was initially developed in MATLAB and was then converted into a C executable, which is embedded on the PAM computer of the tow-body package.

Although FADAR is an automated algorithm, this machine learning approach still relies heavily on a carefully designed preprocessing and feature extraction method whose performance may degrade in low SNR environments. In a recent study, we showed that deep learning-based detectors and classifiers do not need sophisticated preprocessing and hand-crafted feature extraction procedures. It has been demonstrated in the literature that deep learning algorithms, such as autoencoders, convolutional neural networks (CNNs), and recurrent neural networks (RNNs), can act as both feature extractors and classifiers (Zhang et al. 2017). CNNs are especially effective in identifying spatial patterns from images. On the other hand, RNNs are known to be capable of extracting discriminative patterns from time signals. However, the phenomenon of vanishing gradients prevents a standard RNN from memorizing long-term dependency of an input time sequence. Long short-term memory (LSTM) networks solve this problem by introducing parameters that selectively memorize or forget certain attributes of an input sequence (Hochreiter and Huber 1997, Gers et al. 2003, Graves 2012, Sak et al. 2014). In Ibrahim et al. (2018), we revealed the effectiveness of using CNNs and LSTM networks for classifying fish calls and we evaluated the performance of such methods against the MFCC approach. The experimental results confirmed the hypothesis that a data-driven feature extractor, like the one proposed in Ibrahim et al. (2018), can outperform with a large margin a hand-crafted one, like the one reported in Ibrahim et al. (2017). The LTSM networks achieved 93.5% accuracy, a significant improvement over the former FADAR algorithm. This latest version of FADAR will now be installed on the SV3-WG for future missions.

RED HIND SPAWNING AGGREGATION DYNAMICS

Regional abundances of red hind grouper have declined due to overfishing of their spawning aggregations, prompting permanent and seasonal fisheries closures in the US Virgin Islands (USVI). As this species produce sounds associated with reproductive behaviors (CAS), passive acoustic was used to determine temporal patterns of reproductive activity, site usage, and fish movements in order to assess the effectiveness of current management strategies at two marine protected areas (MPAs) in the USVI: the Grammanik Bank (GB) and Hind Bank Marine Conservation District (HB) (Figure 4). GB, a deep reef (30 - 40m) located on the shelf edge south of St. Thomas, USVI, is a multi-species spawning aggregation site used by several commercial1y important species of groupers and snappers. Yellowfin groupers are known to aggregate to spawn in larger numbers at GB, with peak spawning around the full moon in March and April (Nemeth et al. 2006, Rowell et al. 2015).

Eulerian Observations

Red hind in the eastern Caribbean form annual spawning aggregations during full moon periods between the months of December through February. They migrate to spawning sites several weeks before the onset of the spawning season and begin to aggregate 5 to 7 d before the full moon between December and February. Since year 2000, the area of the red hind spawning aggregation has estimated by drift-fishing, setting fish traps and diving around the aggregation area and recording GPS coordinates. Changes in population density among years were assessed using visual SCUBA surveys (no. 100/m^2) and trap catches (catch per unit effort, i.e. per trap haul, CPUE) (Nemeth et al. 2005). Most visual surveys were conducted around the full moon period and encompassed the spawning peaks which could occur up to 4 d before the full moon (Beets and Friedlander 1999, R. S. Nemeth et al. 2007). Visual surveys were used to measure both the average and peak spawning densities. Average spawning density data included counts of red hind throughout the aggregation area 4 days before and up to 2 days after the full moon in December, January, and February. Peak spawning density

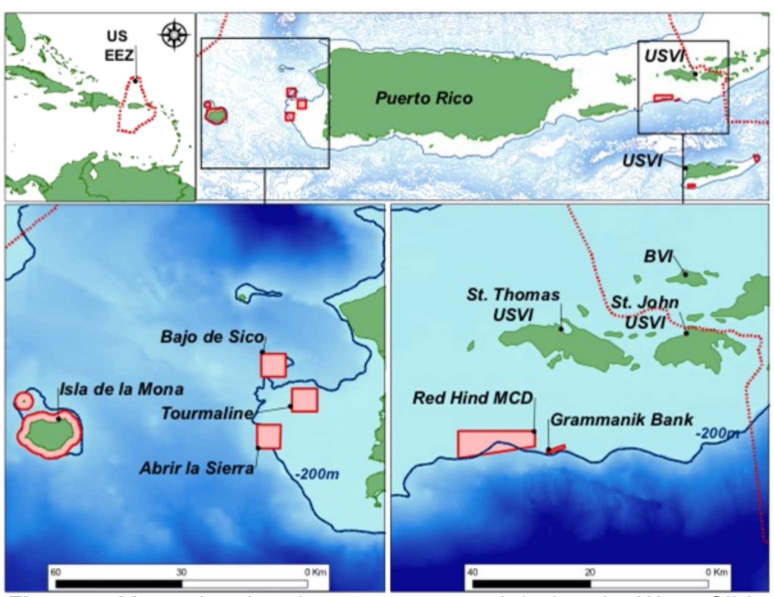

Figure 4. Maps showing the areas surveyed during the Wave Glider in February 2017. It shows the location of the Red Hind Marine Conservation District (MDC) and the Grammanik Bank on the shelf edge, south of St. Thomas in the U.S. Virgin Islands.

data included the maximum density seen on any one day during the spawning period at the approximate center of the primary spawning aggregation site. The aggregation usually peaks in January and spawning can occur from 0 to 4 days before the full moon (Shapiro et al. 1993, Beets and Friedlander 1999, Nemeth et al. 2005, 2007).

During the primary spawning week in January of 2000, 2001 and 2003, exploratory fishing with hand lines and traps was used to determine the boundary, and calculate the area of the spawning aggregation. Within this boundary occasional fish transects were conducted to verify the presence of red hind and calculate densities. Average densities of red hind throughout the aggregation area were used to estimate total number of fish within the spawning population. The area of the red hind aggregation within the MCD was calculated to be 0.24 km^2 in both 2000 and 2001 and 0.35 km^2 in 2003. This increase resulted from red hind occupying a larger area of contiguous coral reef to the west of the primary spawning aggregation.

Red hind produce a low frequency mixed tonal- pulse species-specific vocalization associated with courtship and territorial behaviors at spawning aggregations (Mann & Locascio 2008, Mann et al. 2010). Daily sound levels show trends similar to the density build-up and post-spawning departure described by Nemeth et al. (2007), with maximum levels around sunset (Mann et al. 2010) when red hind have been observed spawning (Colin et al. 1987). Using acoustic recording and visual surveys, Rowell et al. (2012) showed that there was a significant correlation between sound production and fish density. This passive acoustic approach allows for the continuous monitoring of the red hind population at both HB and GB, which started in fall 2016 at both sites.

However, it has not been shown whether peak spawning would correspond to peak calling or any temporal relationship. Nemeth et al. (2007) estimated that peak spawning typically occurred within 2 days of the full moon at HB, and peaks with fish density. Further west in the northern Caribbean Sea, on the western Puerto-Rican shelf, Rowell et al. (2012) showed that peak density occurred 8 days after the full moon (DAFM) and fish calls peaked 7 DAFM, suggesting that peak spawning also occurred around the same time. Data collected from moored digital spectrogram recorder (DSG - Ocean, Logger- head Instruments) deployed at HB and GB during 2016 - 2017 red hind spawning season show fish presence from December to March at RHB (Figure 5). The acoustic data also show that a lasting high number of calls from short after mid-December 2016 to late January 2017, with a peak after the full moon (FM) in December and peaks both before and after the FM in January. One peak before the FM and two after the FM were observed in February.

These results suggest a shift in peak spawning time at HB over the last decade that has not been observed at ALS, indicating a site-specific change, which remains unexplained. As seen in the literature cited in this study, all spawning aggregations were observed within the human possibilities to survey those aggregations. Using a mobile platform for the first time to precisely map out the distribution of fish calls along the shelf edge, provides new insights on the spatial distribution of fish along the shelf break where both HB and GB are located.

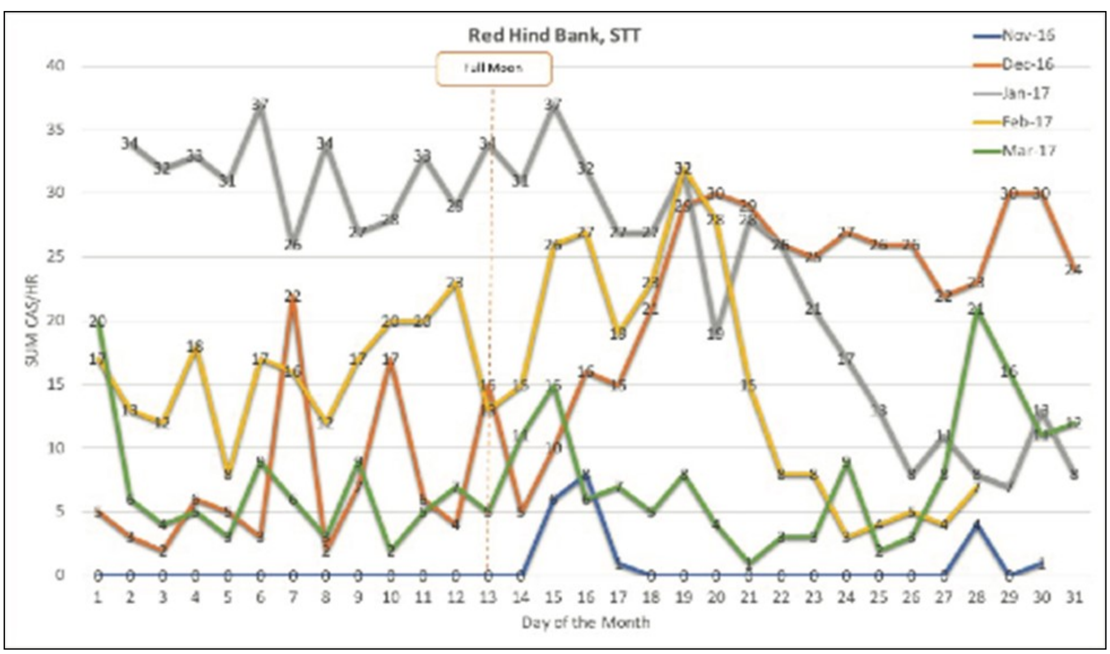

Figure 5. Monthly time series of the hourly call rate at Red Hind Bank fish spawning aggregation. Numbers on each line indicate the call rate. Each color corresponds to a month as indicated by the legend. The dashed vertical line indicates the day of full moon.

Lagrangian Robotic Observations

Glider path and glider detections — As part of a study on the effects of management of red hind spawning aggregation in the U.S. Caribbean Islands, the wave glider survey took place between 07 and 15 February 2017 along the southern shelf of the Island of St. Thomas, in the U.S. Virgin Islands (Figure 6). West of GB and HB, the southern shelf is known for other historical spawning aggregation southeast of Puerto-Rico and south of Vieques. One of them called "El Seco" is shown on Figure 6. Others, not as clearly identified, were reported by fishers east of GB. Therefore, the WG survey was designed to encompass all these sites during the spawning week, which was the week of the full moon on 11 February 2017. Figure 6 shows the full survey and each of the 24 h transects along the shelf. On 12 February, the WG measurements were paused at 9 am in order to fully charge the batteries during the day and the measurements resumed at 11 am on 13 February. On 15 February the glider made his way back to the island. Figure 6 also shows that fish call detections occurred all along the glider path during the week of spawning, with areas of higher densities than others. These results suggest the wide spread distribution of fish calling beyond the main aggregation site at RH Bank, and maybe the presence of other spawning aggregation sites.

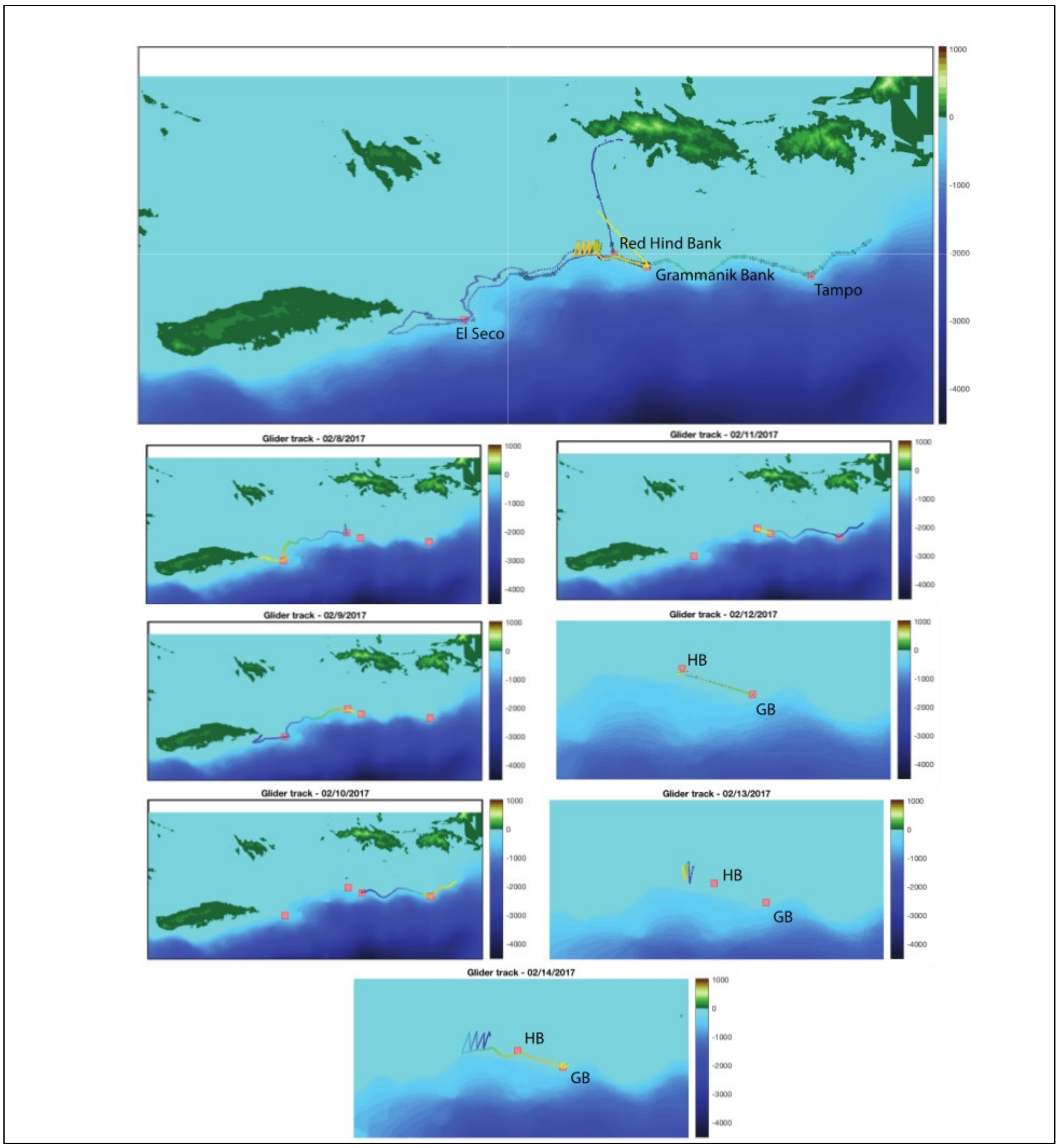

Figure 6. Global (top) and daily maps of the glider path along the northern Caribbean islands shelf edge from 8 to 14 February 2017. Colors of the map's background indicates altitude (shades of green and brown) and depths (shades of blue). Colored lines indicate the glider track and color change from blue to yellow the time forward. Red squares indicate known fish spawning aggregations. Crosses on the top graph indicate fish sound detections.

Daily detection and call patterns — Red Hind sound production recorded in 2007 west of Puerto-Rico exhibited diel variations that were similar at two distinct sites (Mann et al. 2010). Red hind sounds were recorded at all times of the day and night, but sound production peaked near dusk and decreased after 7 pm, local time. In 2017 at the RHB and the GB south of St. Thomas, USVI, the diel variations differs from the 2007 observations (Figure 7). Although sounds were recorded all time of day and night, sound production did not peak near dusk during the spawning week, which was on 8 - 14 February 2017. Instead, at RHB, peak calling is observed in the morning, 2 to 3 hours after sunrise, in the early to mid-afternoon and then mostly in the late evening with a peak at 23:00 most days following the FM including on the day of the FM. The further from the FM, the more peak calling times are shifted to the hours after 23:00 as can be seen from day 12 to day 14. The call rate diel variations at GB exhibit the same trends as observed at RHB although the call rate is much lower at GB. However, the trend associated with an increased call rate toward the 23:00 and later day further from the FM is also observed.

Sounds recorded by the wave glider suggest that calling patterns may differ from one location to another. On Day 8, the glider moved south toward RHB spawning site and a peak in call rate around 6:00 can be seen (Figure 8). The glider moved east during the day and the next peak of the call rate was around 21:00 near El Seco (not shown). Calls were recorded along the way at relatively low call rate. The following day, on 9 February the glider returned east along the same track. This time significant call rates were recorded at midday and mid-afternoon in an area where very few calls were recorded the day before. No calls were recorded at RHB around sunset (also relatively low at RHB mooring – Figure 7) but the call rate suddenly increased at GB around 23:00. On 10 February, the glider continued westward to the British Virgin Island (BVI) border along the shelf break. Although call rates were relatively low most of the way they increased around 18:00, which is close to sunset and when the glider reached a specific area. Close to the BVI border, the call rate peaked around 23:00. Call rate remained relatively high near the BVI border and decreased through the night on 11 February as the glider made its way west again to increase again as the glider got close to GB near 9:30. On its way to RHB from GB on 11 February, between 9:30 and 15:00 the call rate slightly increased. However, the call rate peak as the glider moved closer to GB around sunset an ultimately peaked at 23:00 in the same area. The glider continued through the night moving back and forth between RHB and GB until its recording was stopped around 9:00 on 12 February. A significant call rate (> 30/hour) was recorded around 4:00 in the same area as the call rate peaked at sunset and at 23:00 just west of GB. It decreased again as the glider moved closer to RHB. Call recoding resumed on Day 13 around 10:00, this time west of RHB, within the MCD (Figure 5). Call rates were relatively high around noon decreased through the afternoon but peak right after sunset and in the following hours further west in the MCD. A very low call rate was recorded around 23:00. On the following day, 14 February, the glider moved further west into the MCD. Call rates were relatively high but concentrated in certain areas of the MCD that were reached around 01:00, 07:00, 10:00, and 11:00. As the glider moved closer to RHB, call rate peaked even higher around 16:00 just west of RHB but not in the close vicinity of RHB where calls were recorded the early hours of 12 February. Further, no peak in call rate were observed just west of GB around sunset, but instead they were concentrated around and just north of GB at the highest rate recorded by the glider from 21:00 to 23:00.

CONCLUSIONS

Although the glider diel call rate variations and the fixed recording at RHB and GB FSAs can't be directly compared, the glider survey confirms the tendency for the 23:00 call rate peak seen in the Eulerian data. It also supports the morning peak call rate tendency seen in the Eulerian data and also the possibility of a RH spawning aggregation near GB. If we assume that in certain areas the call rate is proportional to the fish abundance; the fact that certain areas along the glider track had relatively higher sound concentration (not shown) than most areas surveyed including RHB and GB, indicated the potential for other FSAs, which remains to be verified in-situ.

All call types were included but it seems that if calls could be segregated they could tell us what the fish are doing and provide a more accurate picture of the role of the different areas where sounds were heard. It is not clear what the peak in call rates at hours other than sunset mean. It could be explained by the call types to understand how the fish use this extensive habitat. If not for decrease in detectability, there seem to be some significant movement of the fish unless silence is driven by biotic or abiotic factors that remain to be determined. It seems that the fish had moved much closer to RHB FSA on 14 February, were further away from the glider path and could not be heard. One could argue that ocean noise could explain why the fish could not be heard. One of the significant sources of noise during the survey was the wave crashing noise at the surface that would mask most other sounds. One would assume that this wave noise would lower our detection rate and a clear drop in recording would be seen along with large wave height. Figure 8 shows that detection rate increased regardless of the increased wave height, thus noise, in the evening of 11 February. On 14 February, wave noise was relatively low when the glider passed by RHB, although it could have been further than in previous days.

This survey extended between 64.67°W and 65.3°W, which is about 67 km long. It revealed for the first time the extent of the distribution of the fish population that may participate in more than one FSA. It also suggests the possibility of significant fish movement between areas, that may be associated with unknown fish behaviors during spawning time. This wave glider technology has offered fisheries scientists a new insight into the world of grouper spawning aggregations in the Caribbean Sea, yielding more question than answers. Based on these findings one could extrapolate that the fish presence could extend further east and west than where the survey stopped. Such question however can now be answered thanks to our persistent monitoring platform that we anticipate will contribute to new discoveries about the extent and status of the population of endangered grouper species such as the Nassau Grouper.

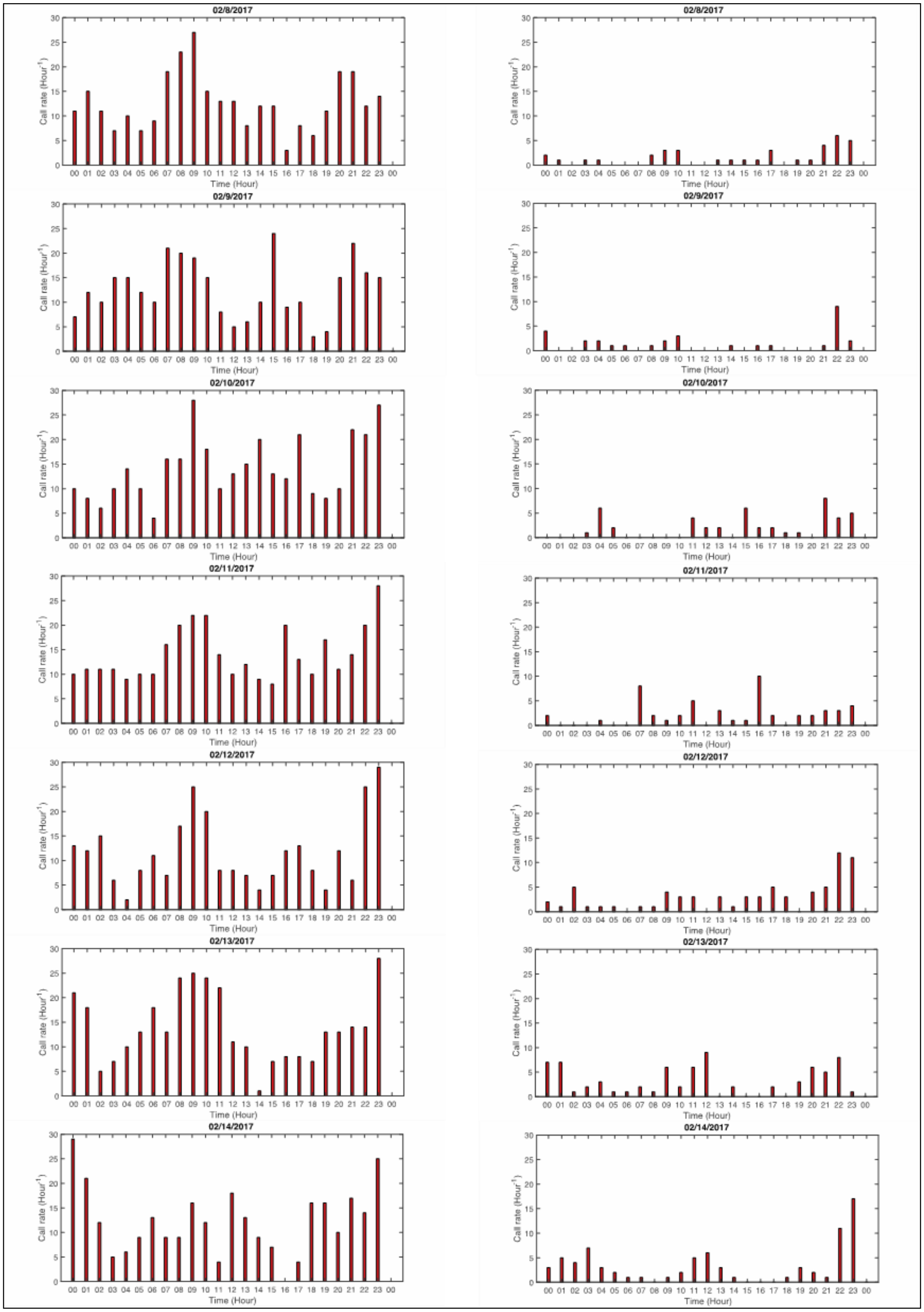

Figure 7. Daily time series of hourly red hind call rates from 8 to 14 February 2017 from Eulerian measurements at Red Hind Bank (right column) and at Grammanik Bank fish spawning aggregations (left column).

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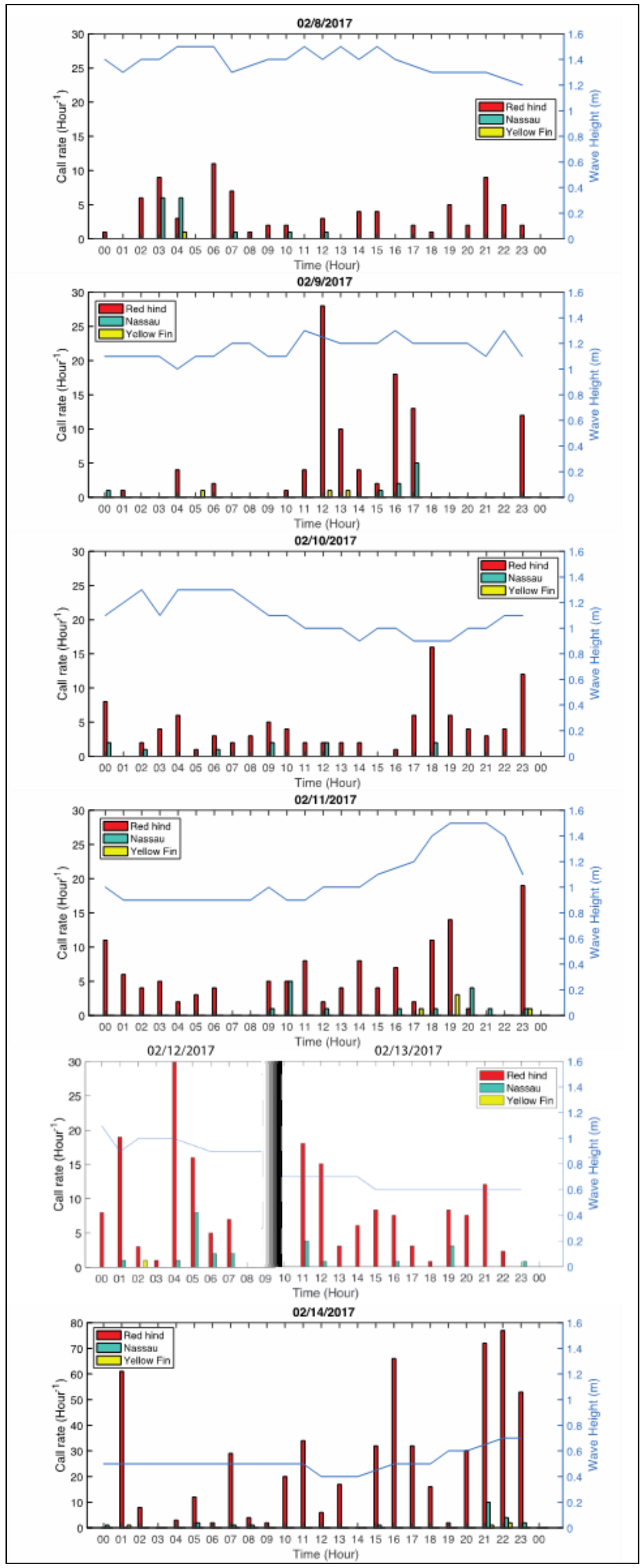

Figure 8. Same as Figure 7 for the wave glider. The blue line shows the wave height during the glider surveys as measurement by the CARICOOS Rincon Buoy (https://www.caricoos.org).

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