Implementation of a Passive Acoustic Monitoring System on a SV3 Wave Glider and Applications

Implementación de un Sistema de Vigilancia Acústica Pasiva en un Wave Glider SV3 y Aplicaciones

Mise en Oeuvre d'un Système de Surveillance Acoustique Passive sur un Wave Glider SV3 et Applications

LAURENT M. CHÉRUBIN[1*], FRASER DALGLEISH[1], ALI IBRAHIM[2], MICHELLE SCHÄRER-UMPIERRE[3], RICHARD NEMETH[4], RICHARD APPELDOORN[3], BING OUYANG[1], and ANNI DALGLEISH[1]

[1]*Florida Atlantic University — Harbor Branch Oceanographic Institute, 5600 US Highway 1, Fort Pierce, Florida 34946 USA. *lcherubin@fau.edu.*

[2]*Department Computer & Electrical Engineering and Computer Science — Florida Atlantic University, 777 Glades Road, Boca Raton, Florida 33431 USA.*

[3]*HJR Reefscaping, P.O. Box 1442, Boquerón, Puerto Rico 00622 USA.*

[4]*Center for Marine and Environmental Studies — University of the Virgin Islands, #2 John Brewers Bay. St. Thomas, 00802 US Virgin Islands.*

ABSTRACT

Fisheries independent research strives for new technology that can help remotely and unobtrusively quantify fish biomass. Some large fish species, such as groupers vocalize during reproductive behaviors. 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 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, which has been fitted to accommodate a passive 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. Results from deployments in the US Virgin Islands and Puerto-Rico confirmed the location of known aggregations and their specific species and revealed the presence of potential new ones.

KEYWORDS: Passive acoustic, fish vocalization, wave glider, monitoring, machine learning

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 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. 2012 and 2014, Wall et al.

2014 and 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.loggerheadintruments.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, these devices are not capable of characterizing a FSA 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 ephemeral events. The main objective of this paper is to present the development of an operational autonomous system for identifying and monitoring FSAs by tracking fish sound production during spawning aggregation. The following *Method* section provides the rationale for this approach by describing fish acoustics and the SV3-WG. The second section presents the instrumentation, the integration of our PAM system onto the SV3-WG, and the fish sounds detection and classification algorithm. Results from field surveys in, the U.S. Virgin Islands and Puerto-Rico, and the Florida Keys are presented, as well as a summary of results.

METHODS

Grouper Vocalizations

Fish sound production, including that of groupers, has long been known. Some fish sounds are species-specific in frequency and pulse rate, which allows their presence to be detected from acoustic recordings. Grouper species that co-occur at spawning aggregation sites in the US Caribbean 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). 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 1 shows the spectrogram of four species targeted in this study. Red hind (*E. guttatus*), whose vocalizations are within the 100 to 200Hz 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 1a); Nassau grouper (*E. 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) (Figure1b); Black grouper (*M. 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). Yellowfin grouper (*M. venenosa*), whose vocalizations consist of calls composed of two parts (one pulse train and one modulated tonal) that are usually longer in duration, with frequency ranging between 90 to 150 Hz (Figure 1c – pulses & d – tonal call) (Schärer et al. 2012b).

Table 1. Groupers 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

The average source level (SL) of the grouper species targeted in this study is between 100 -150 dB (Mann et al., 2009; Schärer et al. 2012 and 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):

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

$$TL(f,R) = 10\log(R) + \ \alpha(f)R$$

The sound pressure level (SPL) used for this calculation was 150dB referenced to (re) 1 µPa root mean square (RMS). The transmission loss (TL) at 100 Hz estimated for this sound level at 150 m was thus TL=21.76 dB. The spherical spreading loss model provided a conservative estimate of transmission loss given it did not account any for environmental factors that were known to affect sound transmission, such as depth, bottom type, currents, and temperature profile, $SNR(150) = SL - TL - NL =$

and it assumed that humans can detect the presence of a signal in a spectrogram at a 0 dB signal to noise ratio

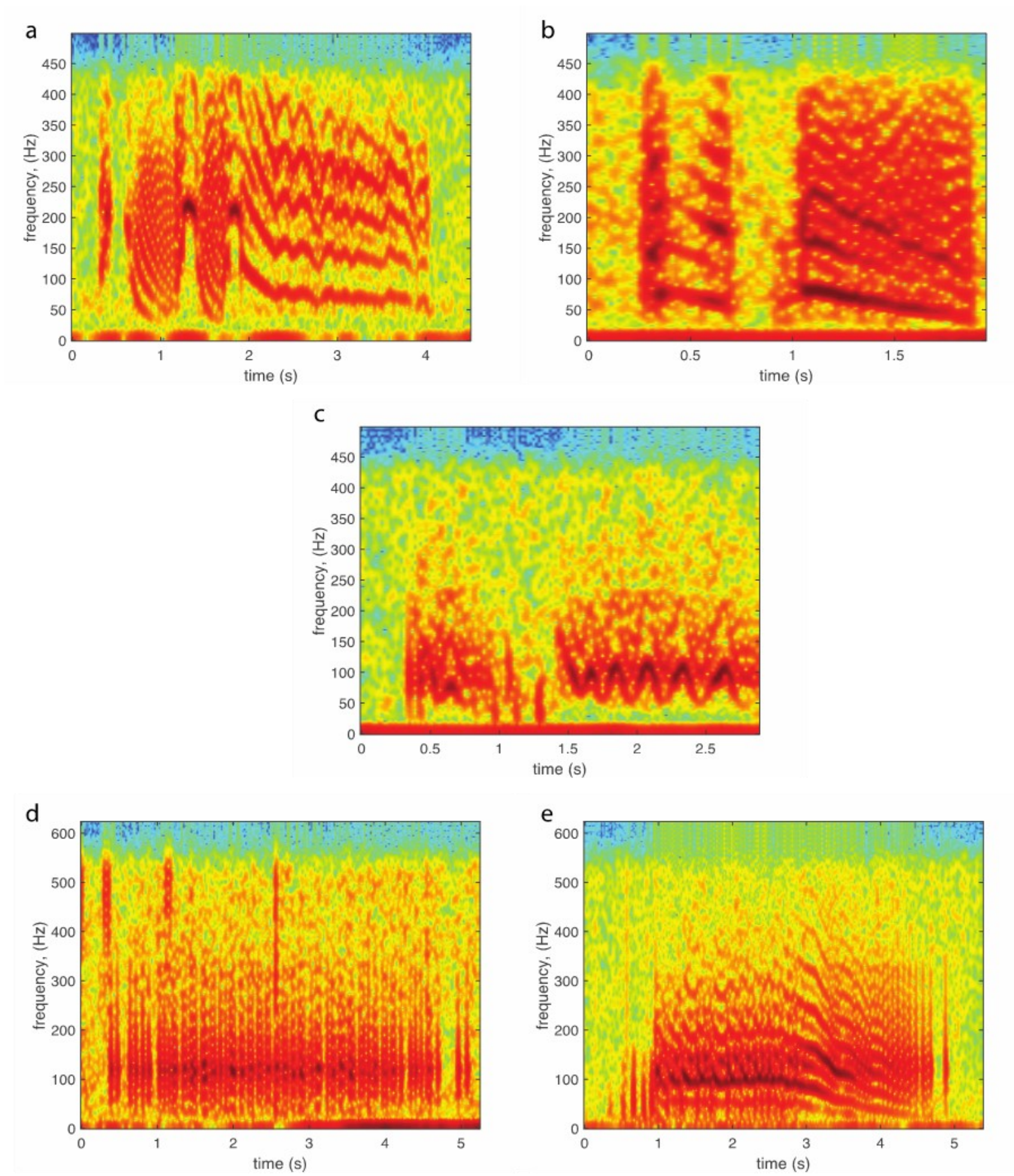

Figure 1. Grouper courtship associated sound spectrograms. (a) Red Hind tonal call (*E. guttatus*). (b) Nassau grouper tonal call (*E. striatus*). (c) Black grouper tonal call (*M. bonaci*). (d) Yellowfin grouper pulse calls (*M. Venenosa*). (e) Yellowfin grouper tonal call (*M. venenosa*).

(SNR). Therefore, if the noise level (NL) was assumed to be around 85 dB at 100 Hz (Miller et al., 2008), 43.24 dB at 150m.

This result was then used to define the specification of our hydrophone system and to set-up the detection threshold at 20dB re 1 µPa.

SV3 Liquid Robotic Wave Glider

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 2). 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 2). 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. 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 2). Further information can be found in Greene et al. (2014).

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

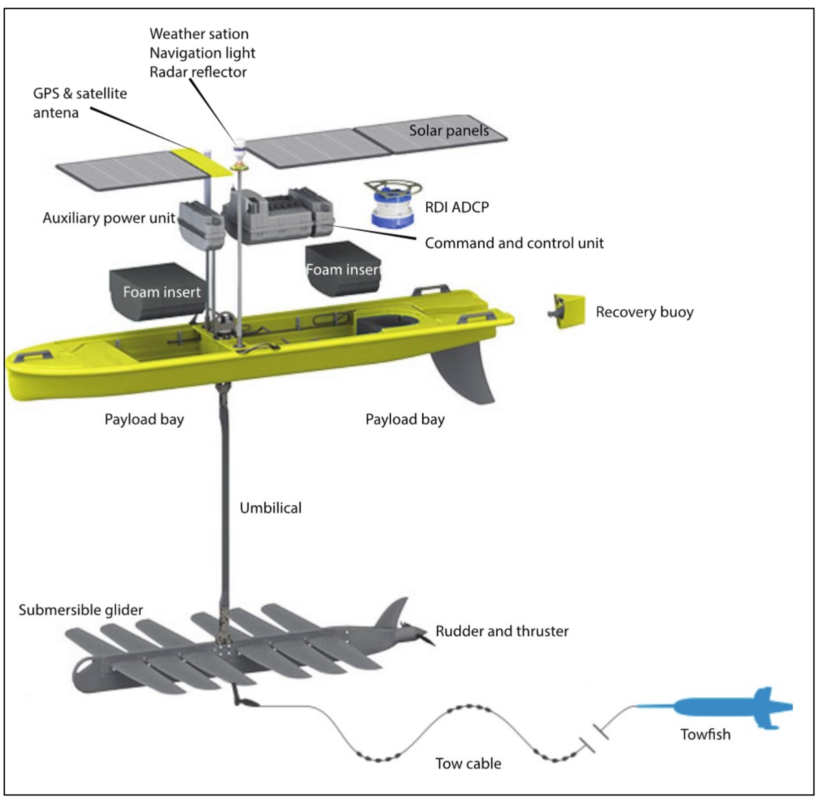

Figure 2. Components of the SV3 wave glider.

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 3), 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 3).,
iv) Hydrophones, and
v) A fish sounds detection and classification algorithm.

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 multiparameter 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 3).

Fish acoustic detection algorithm research (FADAR) —
The PAM computer on the tow-body operates in real-time fish acoustic detection algorithm research (FADAR) program, an automated identification scheme for fish

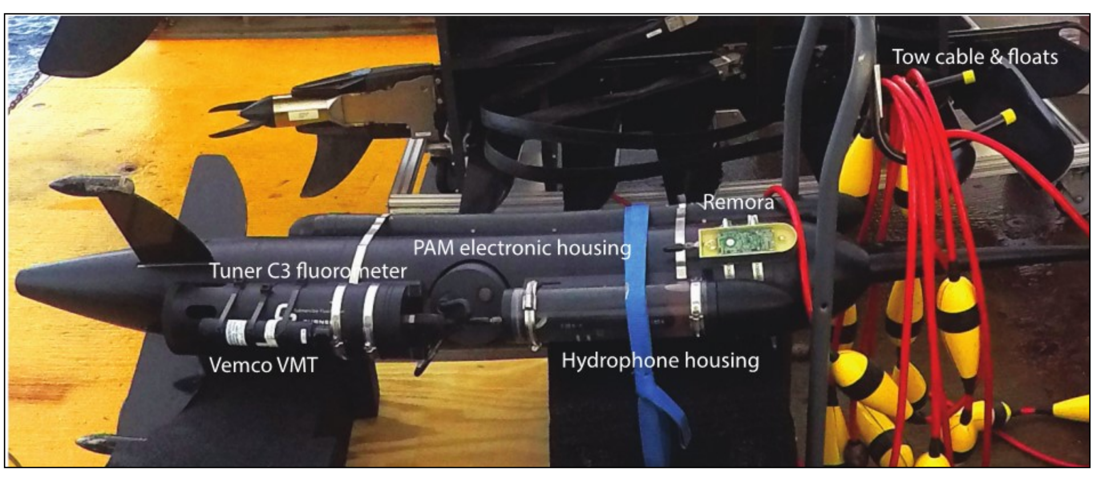

Figure 3. Components of the tow-body.

vocalizations based on the auditory analysis for feature extraction followed by a machine-learning algorithm for classification (Ibrahim et al. 2018). This approach has been tested for 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. In the feature extraction phase, four types of features were used to extract features of sounds produced by groupers. Experimental results showed that the overall percentage of identification using the best combination of the selected feature extractor Weighted Mel Frequency Cepstral Coefficients and sparse classifier achieved 82.7 % accuracy overall, although the accuracy varies 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.

FIELD SURVEYS

Acoustic Data

Recent surveys, in marine conservation districts (MCD) in Puerto-Rico and the US Virgin Islands, and in the Florida Keys National Marine Sanctuary (FKNMS) at known FSAs have shown that, the WG-PAM system was able to record and classify all four grouper species courtship associated sound (CAS) in real-time. A survey along the shelf edge of the US Virgin Island in April 2016 (Figure 4a) detected the sounds associated with reproduction of yellowfin grouper at the known FSA site, the Grammanik Bank, but also reported CAS along other sites further to the east supporting the findings of the migrations to FSA sites documented by Rowell et al. (2015). Grammanik Bank, 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 Grammanik Bank, with peak spawning around the full moon in March and April (Nemeth et al. 2006, Rowell et al. 2015).

We repeated the same U.S. Virgin Islands survey in February 2017. Our target species was red hind which aggregate to spawn around the full moon from December to February at the Red Hind Bank, on the southern shelf of St. Thomas and just west of Grammanik Bank (Figure 4). The aggregation usually peaks in January and spawning can occur from 0 to 4 days before the full moon (Nemeth 2005). Result from the survey showed a scattered distribution of red hind grouper CAS and most of them were localized inside the Red Hind Bank MCD and a few near the Grammanik Bank (Figure 4b). Nassau and yellowfin grouper were also recorded, in particular at Grammanik Bank where Nassau groupers are known to aggregate for spawning (Fig. 4b). This pattern was previously documented with PAM from fixed sites combined with acoustic telemetry of tagged Nassau grouper (Rowell et al. 2015).

Following the U.S. Virgin Island survey, the wave glider was shipped to Puerto-Rico's west coast to survey the known FSA sites within the MCDs at Abrir la Sierra (ALS) and Bajo de Sico (BDS), located along the shelf edge in the Mona Passage. ALS has FSA sites of red hind grouper at a depth of 30 m, which occur from December to March and peaked 7 - 9 days after the full moon (Rowell et al. 2012). BDS is a submerged seamount approximately 27 km west of Puerto Rico, surrounded by depths of over 250 m to the southeast near the Puerto-Rican insular shelf and over 1000 m to the north. This site, where Nassau groupers aggregate to spawn was documented in 2012 and intensively studied with PAM by Schärer et al. (2012b). BDS is also a spawning site for black grouper (Schärer et al. 2014, Sanchez et al. 2017). Results from the glider survey confirmed the presence of CAS for red hind and Nassau grouper with species segregation between ALS and BSD. Red hind sounds were detected only near ALS, though at two distinct locations (Figure 5), whereas Nassau grouper sounds were detected only at BDS, although at two separate locations, which provides new information for this site (Figure 5b).

In August 2016, the wave glider was deployed from aboard the NOAA ship Nancy Foster, near Riley's Hump (RH) in the FKNMS, which is a FSA site for at least two species of snappers (e.g. Cubera snapper (*Lutjanus cyanopterus*) and mutton snapper (*Lutjanus analis*) in summer months and one species of grouper (black grouper) in winter months (Locascio et al. 2016, Sanchez et al. 2017). Although no grouper CAS were identified during the summer survey in the Dry Tortugas, numerous red grouper (*Epinephelus morio*), squirrel fish (*Holocentrus* spp), and grouper alarm calls were identified in addition to other unidentified marine sounds, near the documented FSA site (Figure 6).

Environmental Data

Environmental conditions, such as current and temperature can have significant impact on spawning activity and egg initial dispersal. Current can also change fish spawning behavior and was shown to be a potential cue for spawning in red hind (Chérubin et al. 2011). Fish can change their reproductive behaviors, spawning location, timing and depth of gamete release in response to environmental changes. Therefore, synchronized vocalization and environmental parameters recordings can provide meaningful insights on the ecological constraint of the spawning habitat (Ciannelli et al. 2014). During each survey the glider collected temperature, salinity, depth of the PAM, Chl-a, CDOM, pH, DO, and turbidity at the depth of the tow body. In the U.S. Virgin Islands, turbidity, Chl-a and DO (not shown) showed significant changes between the shelf and the shelf break (Figure 5a), while not as significant along the Puerto-Rican western shelf (Figure 5b-right panel). Other quantities, such as temperature and salinity did not show much change during the survey (Fig 5b-left panel). In the FKNMS, the wave glider environmental data show the tidally driven influence of both the Loop Current (warm and salty) on the western side of RH and the West Florida shelf waters (warm and less salty) on the eastern side of RH (Figure 5c). The highest salinity recorded along the glider path was associated with a strong northwestward flow (not shown). Interestingly, the mutton snapper spawning site is on the eastern side and the cubera snapper aggregation on the western side of RH, suggesting that each species may be cuing to a different spawning habitat. Moreover, the flow interaction with RH, a coral seamount, could results in a wake regime that would yield enhanced retention and concentration of fish eggs, while increasing their survivorship due to increased food supply from nutrient upwelling and transport away from reef predators (Karnauskas et al. 2011, Chérubin and Garavelli 2016).

SUMMARY

Quantification of deepwater reef fish abundance has historically presented challenges to fisheries researchers due to the logistical constraints of sampling their naturally complex habitats (reefs, ledges, banks, etc.). These habitats are often too sensitive for fixed-area gears such as trawls, which can damage or remove rugosity of these

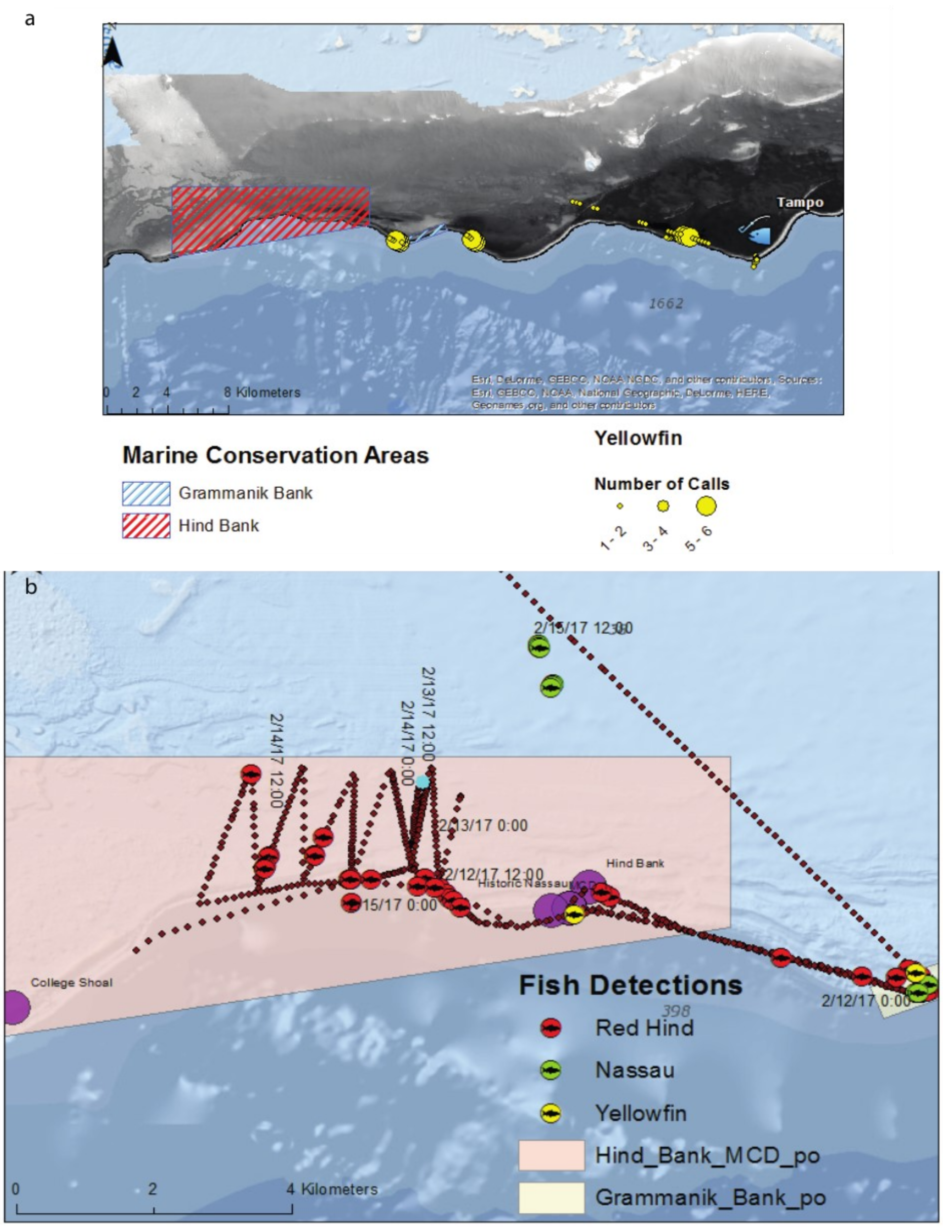

Figure 4. Glider surveys fish detection in St. Thomas, U.S. Virgin Islands. (a) In 2016. Line filled polygons show marine conservation areas. Yellow dots show yellowfin grouper calls. (b) In 2017. Shaded areas show marine conservation areas. Brown dots show the glider path. Purple circles are specific monitoring or known FSA sites that were targeted with the wave glider. Red (red hind), green (Nassau grouper) and yellow (yellowfin grouper) dots show fish detections. Dates and times along the glider track are also indicated.

benthic substrata (Thrush et al. 2002, Kaiser et al., 2003). Thus, deepwater reef fish surveys have relied on gears that provide indices of abundance from fishing, video cameras, or active acoustics. More recently, passive acoustic methods have been used to assess the presence of soniferous species at FSAs using bottom mounted hydrophones. However, the placement of such hydrophones requires the knowledge of the exact location of the FSA *a-priori*, which precludes exploration and discovery of undocumented aggregations. Therefore, with the advent of AUGs, the range of exploration of underwater sounds has naturally increased, providing information on not only the presence but also the distribution of the soniferous fish species (Wall et al. 2014 and 2017). Notwithstanding the potential for locating undocumented FSAs, AUGs rely on internal dead-reckoned position estimates based on velocities from a hydrodynamic vehicle model and from GPS position only available at the ocean surface. Consequently, the internal

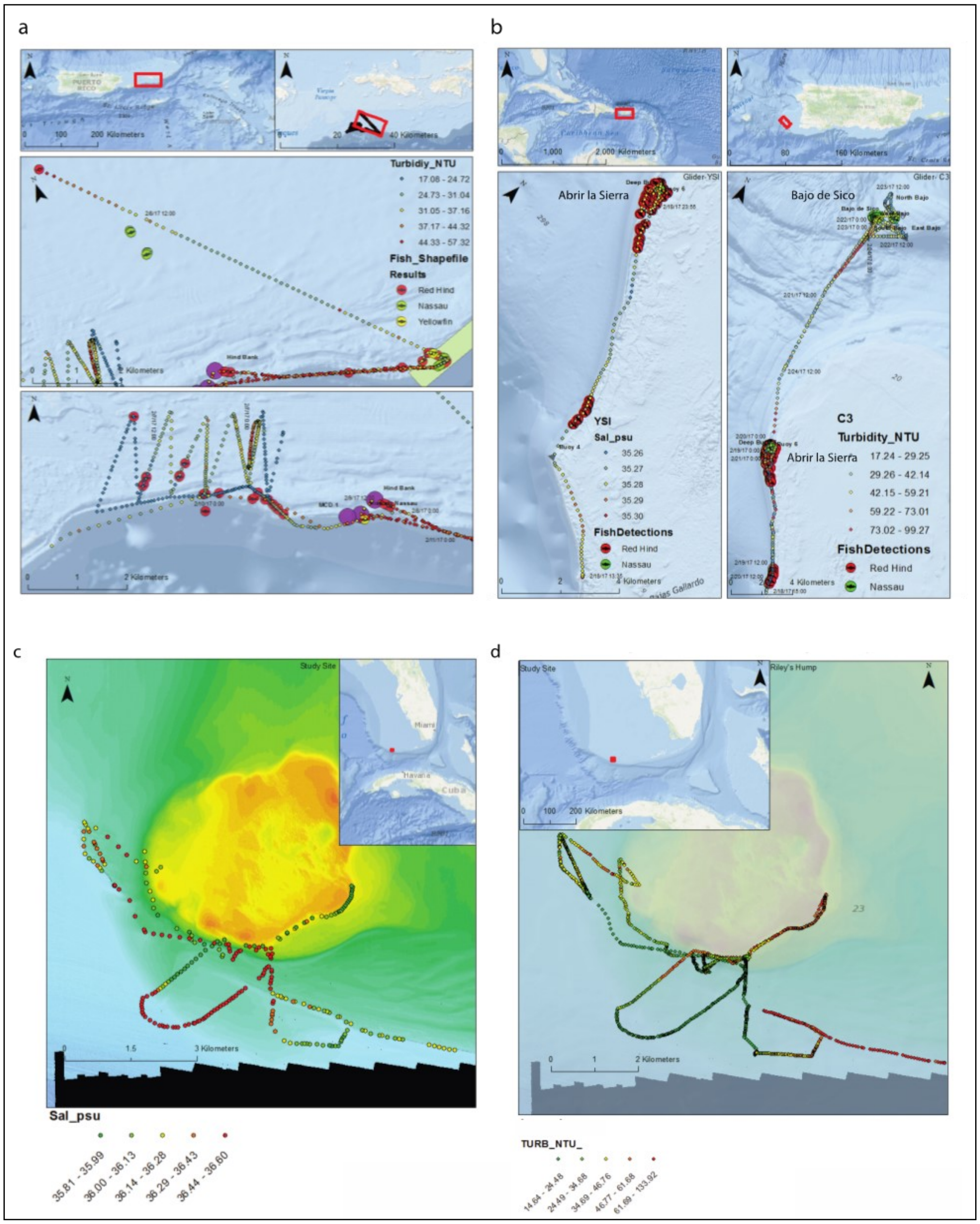

Figure 5. Glider tracks, fish detection and environmental parameters. (a) St. Thomas U.S. Virgin Islands. Colored dots show turbidity measurements (NTU). (b) Puerto-Rico western shelf. Colored dots show salinity (psu) on the left plot and turbidity (NTU) on the right plot. Left plot shows the lower part the right plot, south of Abrir la Sierra only. Purple circles are specific sites. Red (red hind), green (Nassau grouper) and yellow (yellowfin grouper) dots show fish detections. Dates and times along the glider track are also indicated. (c) Salinity (psu) along the glider track around Riley's Hump in the Florida Keys National Marine sanctuary. (d) Same as (c) for turbidity (NTU).

navigation error of AUGs is high if no underwater navigational aids are available (Smith et al. 2010), which precludes users from obtaining accurate positioning of FSAs or fish distribution.

In this project we demonstrated that an ASV powered by the sun can be equipped with a larger payload than would an AUG, conduct longer range surveys, collect more data, transmit its data in real-time, and achieve higher positioning accuracy, while surveying similar shelf and shelf edge environment. In addition, current hydrophone payloads are only able to record sounds, not classify them. This PAM system is able to detect and classify sounds in real-time, which increases the positioning accuracy of the sounds detected, which is essential to discern the extent and the precise location of FSAs. Notwithstanding these advantages, sounds recorded by upper water hydrophones can be very dissimilar from sounds recorded close to their sources by bottom mounted hydrophones. There is a strong attenuation of the fish vocalization toward the surface which consists of a reduction of the frequency bands, distortion and energy loss in the time frequency space as shown in Figure 7. These distorted CAS are accounted for in the detection and classification algorithm, which has been originally trained with fixed hydrophone data. Consequently, the acoustic data collected at each survey has to be manually analyzed to identify to the species level when distorted CAS are detected by the algorithm and are then added to the acoustic features library. This process, which is poised to increase the performance and accuracy of FADAR, would also benefit from data collected at additional documented FSA sites.

We believe that this new monitoring approach will improve our ability to discover new FSA sites in the wider Caribbean and in the Gulf of Mexico and to provide a regional assessment tool of some of the fisheries resources and potentially the regional status of FSAs for commercial-

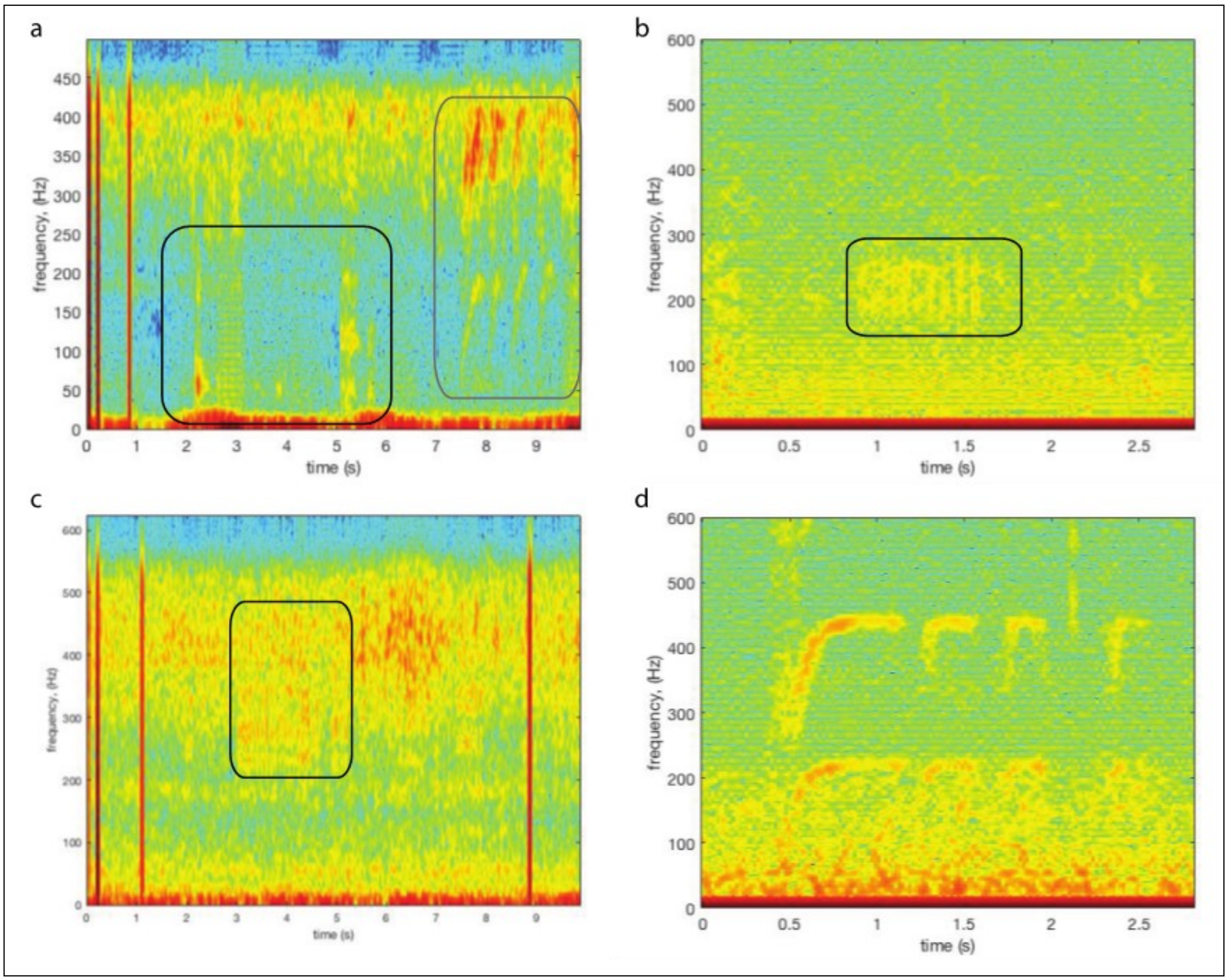

Figure 6. Fish call spectrograms recorded with the PAM at Riley's Hump. (a) Red grouper (lower left rectangles) and unknown calls. (b) Grouper alarms calls. (c) Squirrel fish. (d) Unknown calls.

ly and ecologically important species. This type of acoustic survey can be used for FSAs localization and in addition the technique can be adapted for relative abundance estimation when repeated at regular intervals (Rowell et al. 2012).

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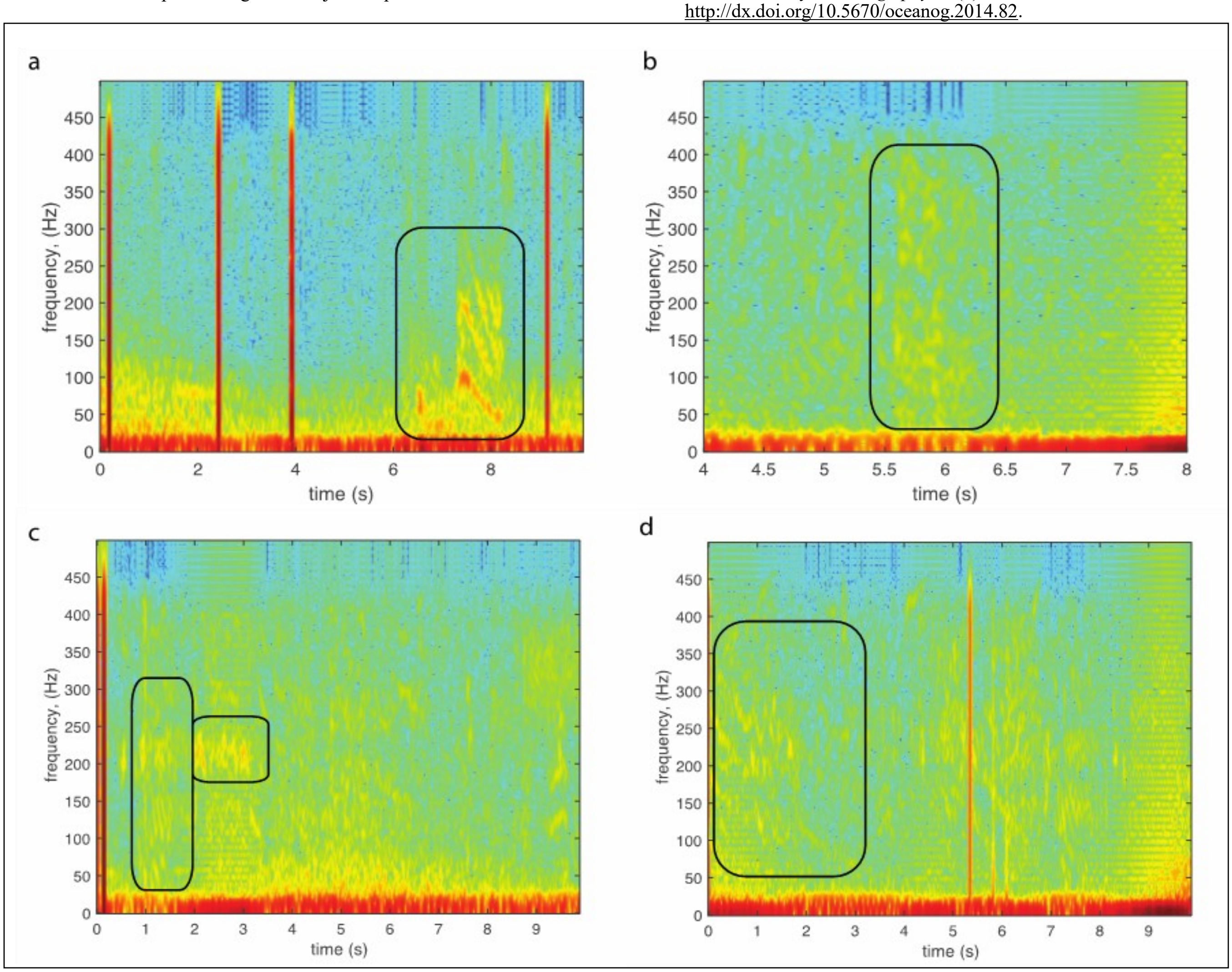

Figure 7. Same as Figure 6 in the Virgin Islands and Puerto-Rico. (a) Nassau grouper. (b) Yellowfin grouper. (c) Red hind grouper tonal and pulse call. (d) Red hind grouper tonal call.

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