Marine Physical Laboratory of the Scripps Institution of Oceanography University of California, San Diego

Gulf of Mexico Deepwater Seismic Airgun Recordings 2010-2024



Credit: PXGEO

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Executive Summary

The Gulf of Mexico (GOM) underwater soundscape is known to have high sound levels at low frequencies as a result of the oil and gas (O&G) industry's use of seismic airgun surveys for exploration and monitoring of sub-seafloor petroleum reserves.

At frequencies below 100 Hz, airgun pulses from seismic surveys dominate the GOM soundscape with long-term, basin-wide average sound spectrum levels up to 30 decibels (dBs) higher than other regions without airguns or major shipping.

In this report, we evaluate underwater sounds recorded at various locations around the GOM over a 14-year period (2010-2024), and spatio-temporally correlate these recordings with seismic airgun survey vessel activity using Global Positioning System (GPS) locations from the Automated Information System (AIS) and Protected Species Observation (PSO) reports recorded aboard seismic vessels. The correlations provide detailed insights on where, when, and how seismic surveys operate and how their sounds propagate in the GOM including temporal, spatial, and spectral patterns in received sound levels during seismic operations.

Seismic vessel activity decreased over the recording period with fewer vessels and fewer surveys in later years, while the sound levels from seismic surveys increased, likely due to technological advances and efficiencies. Further, received sound levels were affected by sound propagation differences, due to seismic source locations and the GOM's bathymetry along the propagation paths, and the directional characteristics of survey array spectra relative to vessel heading.

This overview provides a first look at the acoustic effect of seismic surveys on the Gulf-wide deepwater soundscape as a basis and direction for more detailed research on seismic airgun activity, sources, sound propagation, and influence on soundscapes using the current 14-year and future underwater recordings in the GOM.

Background

The first marine oil well beyond sight from land was drilled in the Gulf of Mexico (GOM) in 1947 at a water depth of 19 ft (~6 m), marking the start of the oil and gas (O&G) offshore industry. For the next 30 years, exploration and production of oil fields were concentrated on the continental shelf, with efforts to expand to deeper water sites farther offshore. In 1975, the first deepwater [DW > 1,000 ft (305 m)] well was drilled in the Mississippi Canyon (MC) protraction area, which resulted in the Cognac oil field discovery and the first DW production in 1979 in the Cognac field. The O&G industry continued advancing DW technologies to explore and produce in deeper waters, including the first subsalt discovery at the Mica Field in MC protraction area in 4,356 ft (1,328 m) of water in 1990, and the first well to encounter Lower Tertiary sediment at the BAHA prospect in the Alaminos Canyon protracted area in 7,620 feet (2323 m) of water - considered ultra-deepwater [UDW > 5,000 ft (1,524 m)]. By 1999, DW oil production overtook shallow water oil production, which continues today along with ongoing technological developments required for DW exploration, reservoir monitoring, and production (BOEM 2016-057).

The O&G industry uses a number of sound sources for activities related to discovery and extraction of marine energy reserves, but seismic airgun sources have the highest source levels at low frequencies, especially when used in multiple airgun array configurations. Individual airguns are ~1 m long metal cylinders and are pressurized with air up to ~2,000 psi (13.8 MPa) that is released at set intervals, typically around 5 to 10 s (Figure 1). They are towed behind survey source vessels at a depth of a few meters and are connected to the ship by electro-mechanical cables and pneumatic hoses (cover page). When the high-pressure air volume is released from an airgun, it expands and contracts creating an impulsive sound pressure wave with high acoustic intensity that travels through the water column and into the seafloor, reflecting off of subsurface geological features to provide imaging of oil reserves.

Single airguns are typically used for shallow, sub-seafloor (< 1 km) imaging using a single ship and single hydrophone streamer for recording reflected sound waves to create two-dimension (2D) profiles of the subseafloor. These types of surveys occur in a relatively small area, such as a single Outer Continental Shelf (OCS) lease block, and last for only a few days. In addition to the O&G industry, academic research occasionally uses single airguns (or small arrays) for high-resolution imaging over small areas spanning a few days to about one month.

Larger seismic airgun surveys use arrays of multiple airguns distributed in a rectangular configuration towed aft of the source vessel (cover page; Figure 1). Arrays can consist of single or multiple strings with each string containing multiple airguns, and surveys can consist of single or multiple source vessels. For example, in a recent 2024 seismic survey with two vessels (permit L23-025), each vessel towed two source arrays with each array consisting of three strings of 10-12 airguns per string for a total of 32 airguns per array and 64 airguns per vessel. The spacing and the timing of firing each of the airguns in the array are designed to focus the pulsed acoustic energy downward toward the seafloor and to minimize the bubble pulse, producing a cleaner source signature that improves the interpretability of seismic reflections. The airgun spatial-temporal tuning sets the individual airgun signals to be in-phase (coherent) in the vertical direction and out-of-phase horizontally. This results in higher source Sound Pressure Levels (SPL, rms) than a single airgun, with levels up to ~260 dB re 1 µPa-m allowing for deeper penetration into the seafloor (BOEM 2023-016). Seismic surveys using airgun arrays often cover large regions (1,000's of km^2) and last long durations (many months) in the GOM.



Figure 1. Seismic airgun functional illustration, and single and array configurations.
From upper left clockwise: airgun cut-away illustration with modeled air pressure release upon camber opening (Teledyne Bolt); Bolt 1900LLX-T airgun (Teledyne Bolt); airgun array with 10 airgun elements in five groups of two, prior to deployment (Sercel).

Computer modeling is used to design airgun array configurations that optimize the source signature and sound penetration into the seafloor (e.g., Landrø 1992, Li et al 2011, Shen et al 2020). Results from the modeling provide estimated source signal details useful for analyzing and interpreting acoustic recordings for sub-seafloor imaging (Long et al 2006, Schuster 2010). Gundalf is a physics-based airgun array modeling program which, given an array geometry and airgun specifications, calculates the source pulse waveform, spectrum, and array frequency directivity (https://www.gundalf.com/).

For example, an array geometry can be specified as a 22-gun (5,370 cu-in) array configured as 2 lines, 12 m deep and 8 m apart, with 11 airgun elements per line spaced 3 m apart, with a combination of 1500LL and 1900LLX Bolt airguns. For this array, Gundalf predicts directional (dipole) root-mean-square source levels (SL_{rms}) of 232 dB re 1 µPa-m and peak-to-peak source levels (SL_{pp}) of 262 re 1 µPa-m. The modeled waveform, spectrum, and frequency-angle directivity show the expected bubble-pulse and surface-ghost features (Figure 2).

The simulated signal is omni-directional below ~50 Hz and becomes complicated with angle-dependent nulls and side (grating) lobes above ~70 Hz. Further, frequency directivity shows higher sound pressure levels and fewer side lobes for crossline directions compared with inline.

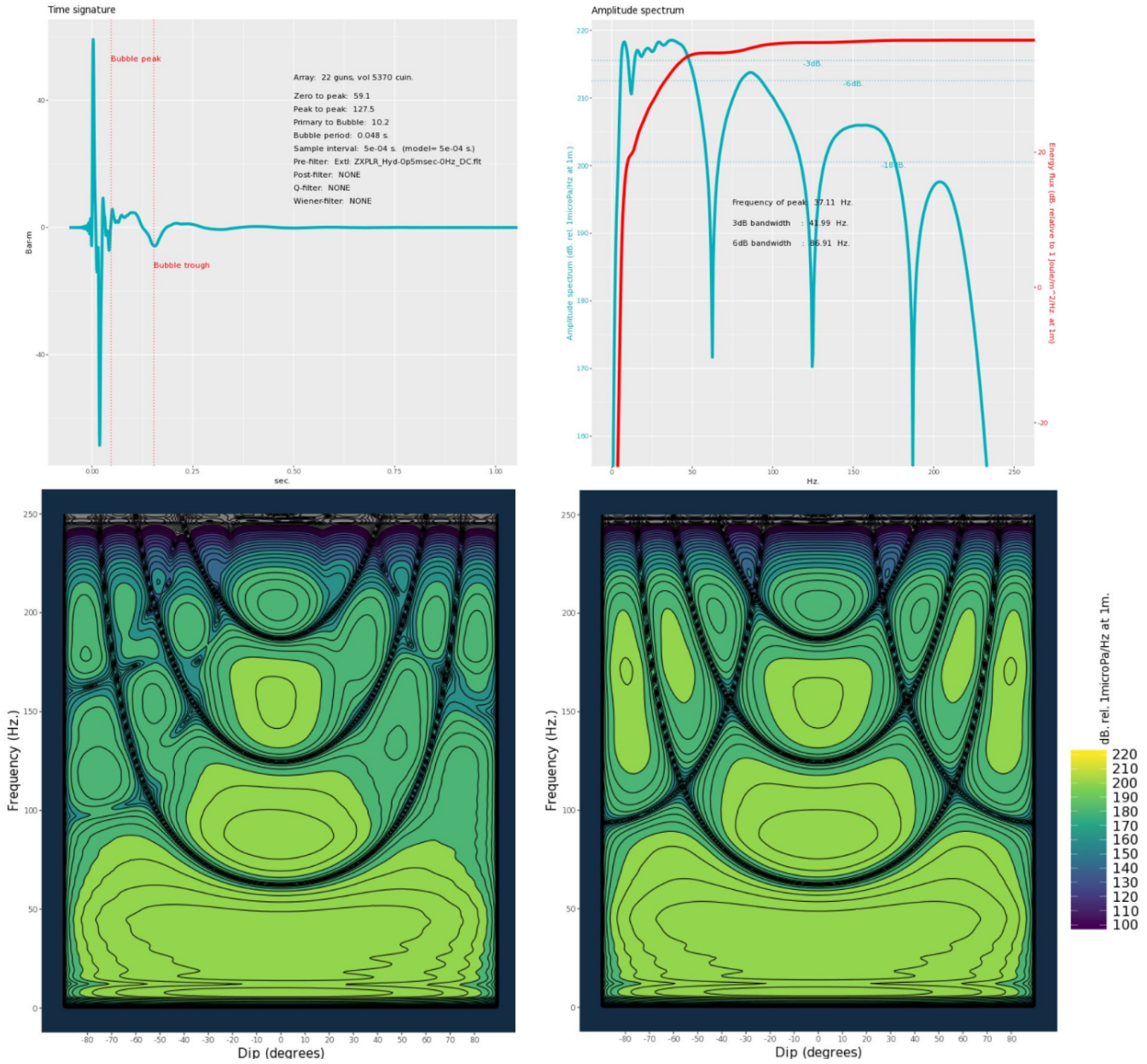

Figure 2. Airgun array modeled pulse, spectrum, and spectral directivity.
GUNDALF modeled 22-airgun array source sound pressure pulse waveform (upper left), sound source frequency spectrum (upper right), and spectral directivity shown as source sound spectrum levels from 0 to 250 Hz and -90 to 90 degree dip angles for inline (lower left) and crossline (lower right) receiver directions relative to vessel heading (WesternGeco Letter of Authorization Application, BOEM permit L22-004 – copyright Oakwood Computing Associates Ltd. 2002).

The drivers of oil exploration activity in the GOM are likely economic-based. For example, from 2006 to ~2016, GOM seismic vessel effort has followed oil prices, with numbers of seismic vessels active in the GOM lagging oil prices by ~1.5 y (Fig. 3; BOEM 2021-005), suggesting profits from higher oil prices allow for more seismic vessel activity. In more recent times, it appears this correlation may no longer hold true (Fig. 3).

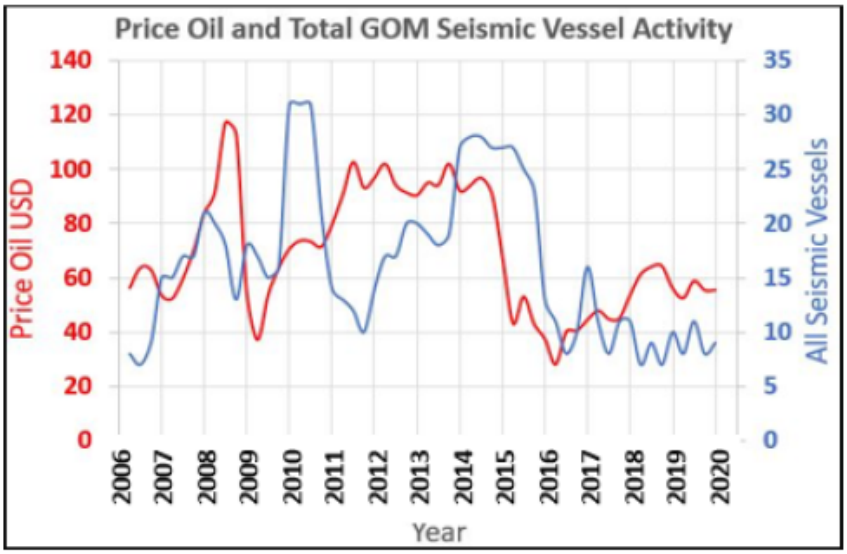

Figure 3. GOM oil price and seismic vessel activity.
GOM oil price and seismic vessel activity averaged by quarter from 2006 to 2019 correlate well with an approximately 1 – 1.5 year time lag (BOEM 2021-005, Fig. 54).

At frequencies below 100 Hz, airgun pulses from seismic surveys dominate the GOM soundscape (Wiggins et al., 2016, Snyder 2007, Newcomb 2002, Sidorovskaia and Li, 2017) with long-term, basin-wide average sound spectrum levels up to 30 decibels (dBs) higher than other regions without airguns or major shipping (e.g., McDonald et al., 2008; Jones et al., 2023). The aim of this report is to highlight insights gained from multi-year effort to improve our understanding of seismic survey activities in the GOM, by linking information from publicly available sources with observational passive acoustic data collected by LISTEN GoMex - a large international research program.

Methods

A. Seismic Airgun Surveys

For purposes of this report, a seismic airgun survey (shortened to *seismic survey* hereafter) is defined as an area during a specified time period in which one or more source vessels were engaged in seismic surveying activities. These activities typically involve transiting along parallel tracks ("mowing the lawn") over long periods and large areas while towing and firing seismic airguns nearly continuously. Seismic surveys are numbered YYNN, where YY is year from 2000 and NN is the survey number for that year in chronological order per the survey start date. For example, seismic survey 2205 is the fifth survey of 2022. Survey start date sets the survey numbered year, even if the survey extends into the next year, as

for the preceding example into 2023. At the time of writing reporting information for 2024 was not fully available, therefore the analyses described in this section are limited to 2023 and earlier data.

At a minimum, each seismic survey is described using (1) Automated Identification System (AIS) records. AIS data provide the main extent of the area and time period of a defined seismic survey via survey tracks. Additional information is gained from (2) Protected Species Observer (PSO) at-sea logs and (3) PSO survey final reports and Letter of Authorization (LOA) permit applications which can provide details about source characteristics including seismic array configuration, full power array source levels, and shot line[1] timing, as wells as supplemental details about seismic source vessel GPS locations and time. Survey start dates are determined using PSO reports and AIS, where available, in combination with acoustic detections.

(1) AIS records 2010-2023

The Automated Identification System (AIS) is a maritime navigation tool that provides information about vessels via automatic Very High Frequency (VHF) radio transmissions. In real-time, vessels transmit standardized coded timestamped signals with a wide range of information about the vessel such as vessel name, type, status, identification numbers, dimensions, location, speed, heading, and other details. This information is used to avoid collisions, enhance traffic management, and improve emergency operations, in addition to other vessel-tracking objectives. These VHF transmissions can only be received ~10-50 nm at sea, which typically limits coverage to near-coastal waters where receivers are placed. However, in the GOM, oil platforms often are equipped with AIS receivers and are located in areas where seismic surveys occur, allowing survey vessel tracks to be recorded at distances farther offshore. VHF transmission ranges are influenced by antenna height (both ship and receiver), line of site, and atmospheric conditions. Variation in effective transmission distances leads to spottiness in the AIS records.

Marine Cadastre (NOAA & BOEM) archives AIS records and provides compressed (zipped) comma-separated value (CSV) files of the corrected and filtered recordings with one-minute resolution for either Universal Transverse Mercator (UTM) zones 1-20 for 2009-2014 in monthly files or for U.S. coastal waters for 2015 onward in daily files (see https://hub.marinecadastre.gov/pages/vesseltraffic). At the time of writing, AIS data was not available for 2024. Embedded in each AIS one-minute data string is the vessel's Maritime Mobile Service Identity (MMSI), which can be used with other tools to identify details about the vessel. For example, a Marine Traffic (https://www.marinetraffic.com/) search on a specific MMSI provides details on the vessel such as name, current location, size, vessel type, and photos of the vessel that can be used to distinguish whether or not the vessel is a typical seismic survey vessel. Seismic vessels are typically large (> 70 m long / 15 m wide), have a helipad, and include a large boxy stern with openings to accommodate large air compressors for the airguns and spools of long (3-12 km) seismic hydrophone streamers (see cover page figure).

After Marine-Cadastre-archived AIS records were downloaded to a local computer, an analyst (LH) filtered and reorganized the AIS records into multi-month workbooks with individual months spreadsheets organized as tabs. Each record (i.e., row) includes up to 20 parameters (i.e., column). The filters were based on area (Lat: 18°-32° N; Lon: 98°-80° W), time (by month-year), and ship MMSI for ~130 known seismic-related vessels including seismic vessels and drilling ships (MSS/LH ship filter). All duplicate records were removed.

The workbooks (xlsx) monthly tabs were converted into monthly mat-files (GOMAIS_yymm.mat; yy=year from 2000 and mm=month 01-12), to allow for easier and more efficient processing and analysis in MATLAB. GOMAIS files contain all the original AIS record parameters and can be used directly for

[1] A shot line is the specific, pre-determined path that a survey vessel travels while towing a tuned array of airguns.

analysis, but we chose to reorganize the AIS records into yearly mat-files (GOMVessels_YYYY.mat) and retain 7 of the primary parameters: T, MMSI, LAT, LON, SOG (speed over ground), COG (course over ground), and HED (heading) for analysis perspective and ease, especially since many surveys span multiple calendar-months.

Using the GOMVessels yearly files, maps were generated iteratively of seismic vessel tracks over a reference bathymetric basemap by adjusting spatial (LAT/LON), temporal (T), vessel (MMSI), and vessel speed over ground (SOG) filter settings. First, AIS pings from the GOMVessel yearly files were plotted to identify regions with potential seismic survey activity. Next, a temporal filter was applied to isolate surveys occurring within the same region but at different times, thereby distinguishing them as separate survey events. Vessel positions that formed geographically dense sequential patterns transiting at less than 5.5 kts were considered tracks. The SOG filter cutoff speed was selected based on a histogram analysis of SOGs during survey activities. Vessel tracks from different individual vessels that occurred in close locations over the same time period were considered participants in the same survey. The final iteration AIS parameter filter settings were saved into a script for each defined seismic survey. Surveys that occurred over a short duration (less than a day, numbering approximately 5-10 per year) were excluded from the filter to focus solely on large-scale, long-duration survey events, i.e. those more likely to be detected in acoustic recordings and contribute to long-term trends. The script was used to generate a master filter settings mat-file, and individual mat-files for each seismic survey (GOM_AGSurvey_SFYYNN.mat; YYNN = seismic airgun survey number) from which additional analysis was performed on individual and groups of surveys.

(2) Survey PSO Bi-weekly Effort and Operations Logs: 2009-2020

Protected Species Observer (PSO) bi-weekly logs from aboard seismic vessels were downloaded from the U.S. Department of the Interior (DOI) Bureau of Safety and Environmental Enforcement (BSEE) Scanned GG Permits Query (https://www.data.bsee.gov/Other/FileRequestSystem/ScanGGPermits.aspx) and evaluated for seismic survey details. There are typically three logs provided every two weeks: Effort, Operations, and Detections, which provide at-sea details aboard a seismic vessel such as permit number, vessel name, date/time of observer effort, date/time of shot line start/end, source ramp up periods[2], source tests, and animals observed. The bi-weekly logs were provided as pdf files. These were converted to spreadsheets so that quantitative details could be extracted and used to analyze and better characterize seismic surveys.

Effort Logs provided vessel positions and water depths at the start and end of an observer watch cycle. These positions can be used to check or add to poor coverage from the AIS records.

Operations Logs provided times of source ramp-up, tests, and full-power shot lines. Shot line times can be used to investigate patterns associated with temporal, spatial, and vessel use of airguns, which can be correlated with the acoustic recordings. In our analysis, these details were useful for matching acoustically detected seismic airgun signals with specific surveys.

A spreadsheet (PSO_Surveys_250304.xlsx) with metadata from the bi-weekly logs was generated and organized by PSO seismic survey number (this is different from the AIS seismic survey numbers used throughout the analyses in this report). For each PSO survey number, this document provides information on permit number, survey type, survey vessel names and MMSIs, biweekly log filenames, first and last shot times, survey type, and other metadata associated with the survey. The PSO bi-weekly logs span

[2] During a seismic survey ramp-up period, seismic airgun array sound levels are gradually increased to full power.

2009 through mid-2020, some logs appear to be missing, particularly before 2014, and logs occasionally have errors likely associated with observer input.

(3) Survey PSO Final Reports: 2021-2023

Survey PSO final reports were downloaded from the NOAA Fisheries Letters of Authorization webpage (https://www.fisheries.noaa.gov/marine-mammal-protection/issued-letters-authorization-oil-and-gas-industry-geophysical-survey). These detailed documents, often spanning hundreds of pages, contained the main sections: executive summary, project overview, monitoring and mitigation program, data records and analysis methods, results, and PSO results. The executive summary and project overview provided information that was used to confirm and add to specific seismic survey metadata such as vessel(s) used, survey type, survey area, permit number, for what entity the survey the was conducted, what entity conducted the survey, over what period the source vessel(s) conducted operations, how long the seismic source(s) were active and how long they were at full power, and details about what source(s) and configurations were used. Details on the PSO methods and results were not used in this analysis but could be extracted to include a protected species component in a future study.

B. Passive Acoustic Recordings

High-frequency Acoustic Recording Packages (HARPs - Wiggins and Hildebrand, 2007) were used to record marine mammal, ambient, and anthropogenic sounds in the GOM. HARPs are autonomous, battery-operated instruments capable of recording underwater sounds from 10 Hz to 100 kHz continuously over long periods (up to ~1 year) to provide a comprehensive time series of the marine soundscape. HARPs are configurable into standard large oceanographic-style moorings, medium or small moorings, and seafloor mounted instrument frames, all of which use a releasable ballast-weight anchor to secure the instrument to the sea floor until planned recovery. A combination of these configurations was used in the GOM, and were chosen depending on deployment and site requirements.

To capture underwater sounds, HARPs use hydrophones tethered and buoyed above the seafloor approximately 10 – 30 m at depths < ~1,500 m; at greater seafloor depths the hydrophone is typically placed ~1000 m below the sea surface. The hydrophones were initially constructed with two channels, one for low-frequency sounds (<2 kHz) and the other for mid- and high-frequency signals (>2 kHz) with different lead-zirconium-titanate (PZT) ceramic elements and different preamplifier, filter, and signal conditioning electronics for each channel. More recent hydrophones, introduced gradually between 2016 and 2018, use one PZT spherical element for the whole band 10 Hz – 100 kHz. Each hydrophone's electronic circuit board was calibrated in the laboratory at Scripps Institution of Oceanography and representative data loggers with complete hydrophones were end-to-end full-system calibrated at the U.S. Navy's Transducer Evaluation Center in San Diego, CA to provide the full-band frequency response of the system so that accurate sound pressure levels can be measured from the recordings.

Time-varying sound pressures were recorded to an array of standard laptop computer style 2.5" hard disk drives or micro-SD cards in a compressed format. Upon instrument recovery, used batteries and disk drives were removed and replaced with new batteries and empty disk drives along with a new ballast-weight anchor to ready the HARP for the next deployment.

Starting in 2010, five HARPs were deployed in the GOM (Fig. 4), three (GC, MC, and DT) at deepwater sites (~1000 m) and two (MP and DC) in shallow water (~100-250 m). These sites are part of a long-term array, with recordings spanning 14 years. Starting in 2020 and continuing to the present, HARPs have

been deployed at an additional four (MR, AC, LC, and CE) multi-year deepwater sites, two (GA and SL – MP was removed) multi-year shallow water sites, and four (Y#A, Y#B, Y#C, and Y#D) yearly-moving deepwater sites providing a large aperture array with a total of 14 one-year HARP deepwater sites covering the greater GOM area between mid-2020 and mid-2024.

In total from mid-2010 to mid-2024, about 1 petabyte (1 PB = 1,000 TB) of underwater recordings have been collected in the GOM, resulting in a combined 89 instrument-years (32,427 d) of high-fidelity sound pressure measurements. The recordings from the long-term array of three deepwater sites totaled almost 34 instrument-years (12,388 d). The four multi-year sites and 14 yearly deepwater sites from the large-aperture array recorded a total of 40 instrument-years (14,745 d).

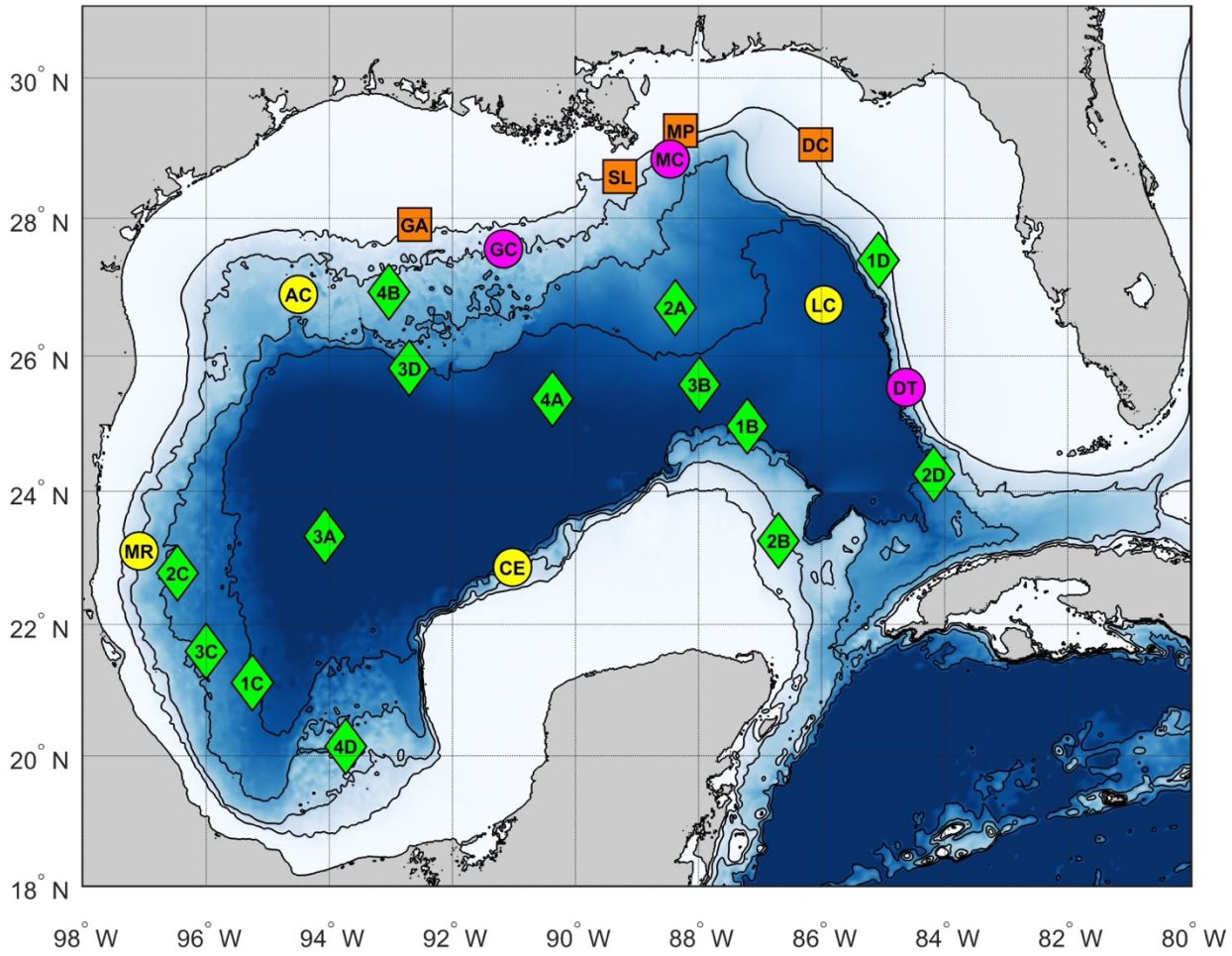

Figure 4. Bathymetric map of GOM with HARP sites.
Bathymetric contours are at 300, 1,000, 2,000, and 3,000 m depths with the continental shelf white, the continental slope changing from light blue to dark, and the deep-water basin dark blue. Recording sites are shape- and color-coded: orange squares = shallow; circles = deepwater multi-year array sites and magenta = 15 year, yellow = 5 year; green diamond = deepwater 1-year sites.

Airgun Survey Acoustic Metrics

The hydrophone sound pressure was sampled once every 5 μs (200 kSample/s) over the deployment periods of each site. A subset of recorders sampled once every 50 μs (20 kSample/s). These levels of resolution are not needed for evaluating low-frequency, far-field airgun signals, so the sound pressure time series were decimated by factors of 100 and 10 respectively to reduce the effective signal bandwidth to 1 kHz for more efficient data processing and analysis. Decimation was performed using MATLAB's built-in function decimate(), which applies a low-pass filter to the original recordings and then resamples the sound pressure samples at a lower rate. Standard sound pressure time series XWAV and corresponding Long-term spectral averages (LTSA) files were generated from the decimated recordings for use with Triton and other custom software for evaluating airgun sounds.

LTSAs are essentially spectrograms or a time series of sound pressure power spectral densities. For the decimated 2 kSample/s XWAV files, a 5 s time window and 1 Hz spectral resolution were used to construct LTSAs for each deployment at each site. Because of the large number of long-duration recordings for our study, and to provide an overview of seismic survey acoustic activity throughout the GOM over many years, additional temporal averaging of 1 d was applied to the LTSA to produce daily averages. However, airgun sound spectral character is a function of propagation environment and survey direction; to reduce this complexity, we chose the spectrum level at one specific frequency to investigate how seismic survey sounds impact the GOM soundscape. The daily averaged sound pressure spectrum level at 40 Hz (DASPL@40Hz) is used as a measure of seismic survey acoustic signals in the recordings because airgun array sounds are at or near their peak levels and are omni-directional at this frequency (Figs. 2 & 5).

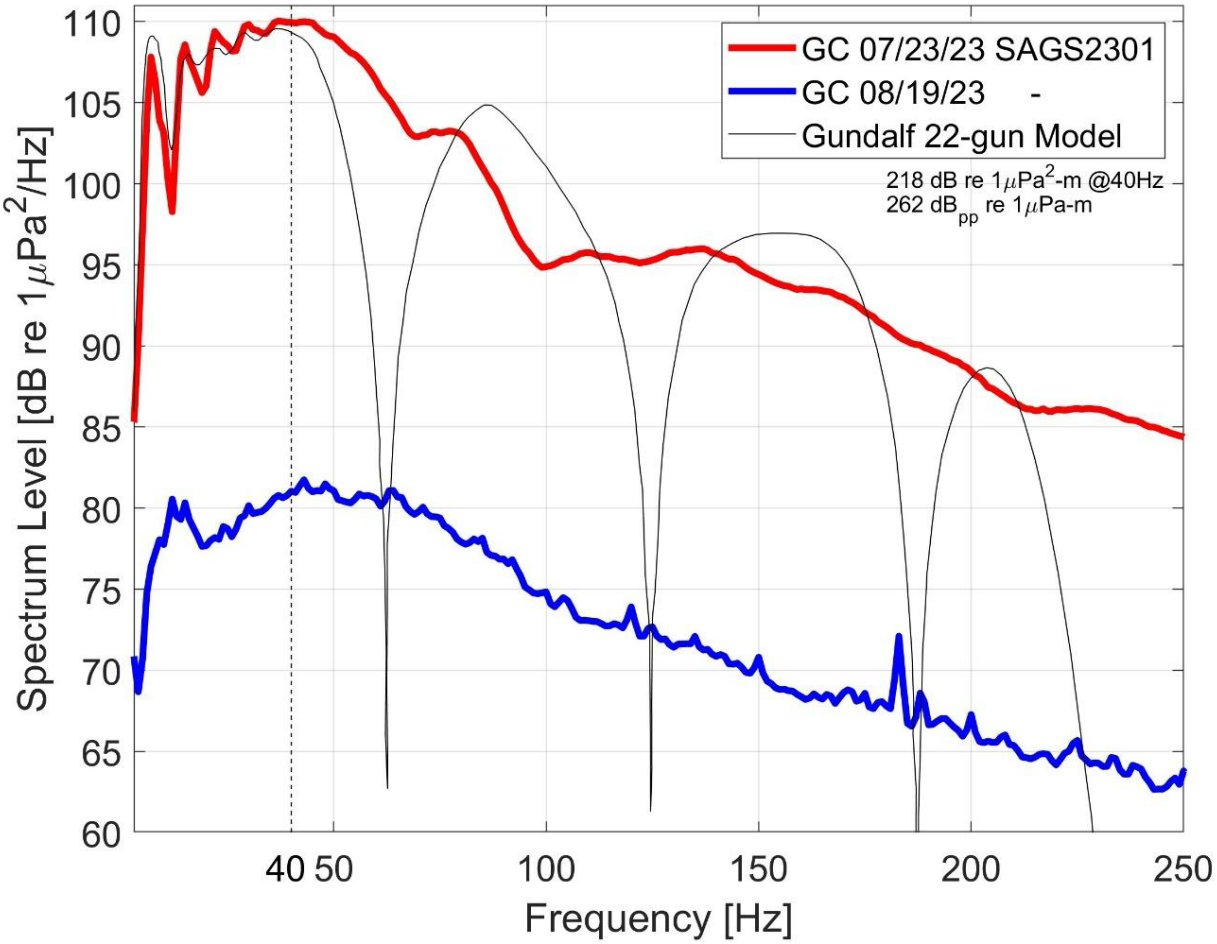

Figure 5. Sound pressure spectrum levels with airguns present and absent at site GC.
Daily averaged sound pressure spectrum recorded at site GC during a nearby (35 – 100 km) seismic survey (red: 7/23/2023), during a period without a nearby survey (blue= 8/19/2023), and overlaying Gundalf modeled airgun pulse signature sound pressure spectrum. The modeled source estimate has been reduced by 108 dB for comparison with the recorded spectrum (thin black line from Fig. 2). Vertical dotted line at 40 Hz shows the spectrum level used as a measure of seismic survey acoustic levels at recordings sites.

Airgun pulse detection can also provide detailed quantitative measures of airgun use. The signal-to-noise ratio (SNR) for airgun pulses in the GOM is typically good, especially for nearby seismic surveys, but waveform dispersion with increasing range can spread out the signal from 10's of milliseconds near the source (e.g. Fig. 2) to 1 s or more at long ranges. This dispersion can make airgun pulse detection and the evaluation of how much sound energy is being injected into the marine environment more challenging.

An airgun detector was developed to identify individual airgun pulse signals and provide measures of each signal, including signal: timestamp, peak-peak sound pressure levels (SPL_{pp}), duration, root-mean-square sound pressure levels (RMS), and sound exposure level (SEL), where the latter three are SNR sensitive but also provide a sound energy quantification of received dispersed pulses. Airguns were detected automatically using a matched filter detector on the low-frequency band data. The acoustic recording timeseries were filtered with a 10th order Butterworth low pass filter to exclude frequencies above 150 Hz. Thresholds were determined based on a manual review of a subset of data, including a

minimum cross-correlation score, minimum start time difference between consecutive detections (1 seconds), minimum amplitude (120 dBpp), minimum and maximum detection duration (0.6 to 5 sec), and minimum differences between RMS and peak-to-peak amplitude measurements of noise before and after each detection (1 dB).

To better understand the interplay among airgun metrics, DASPL@40Hz, daily cumulative SEL (cSEL), and daily number of detections were compared for two years (Aug 2020 to Nov 2022) of recording at site GC, for which all three metrics show distinct periods of increased acoustic activities (Fig. 6). However, because airgun pulses occur at most once every ~5 s to allow for signal penetration into the seafloor, reflection, and return to either seismic streamers or Ocean Bottom seismometer Nodes (OBNs), the maximum number of pulses per day per survey is ~17,000, which is shown as a nearly flat maximum during survey periods and does not provide insight on how much sound energy is being recorded. Detector saturation may also occur in cases where when multiple surveys are active simultaneously. On the other hand, cSEL shows varying levels based on the amount of sound energy being recorded. Since SEL is calculated for each airgun detection, both cSEL and the number of detections is sensitive to the detector threshold and resulting false positive detections, which appears to be around 100+ per day in this example when no significant seismic surveys are present and DASPL@40Hz is ~80 dB re 1 μPa^2. The DASPL@40Hz metric provides the best description of how received sound levels change due to seismic survey events for our recordings in the GOM.

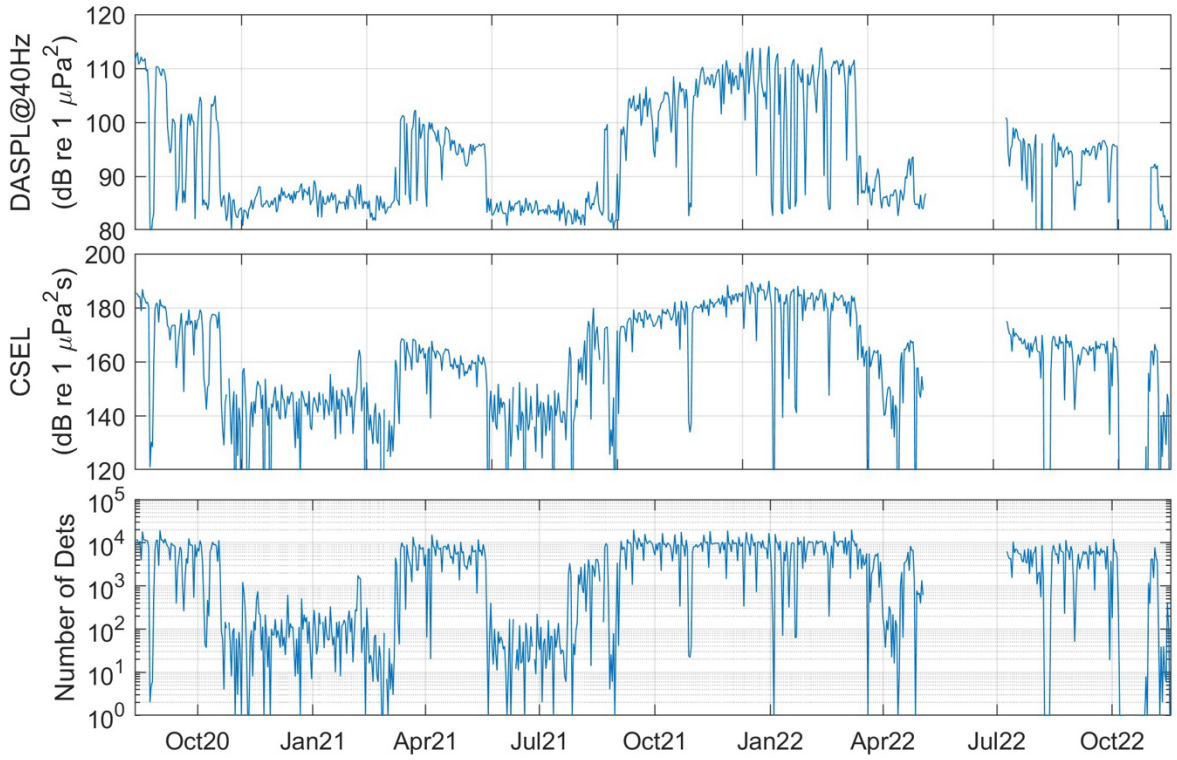

Figure 6. Sound metrics for identifying seismic surveys.
Daily averaged sound pressure spectrum level at 40 Hz (DASPL@40Hz) (top), daily cSEL (middle), and daily number of detections (bottom) recorded over two years at site GC show distinct periods of increased acoustic activity due to seismic surveys along with periods of lower sound levels when no significant surveys are present, resulting in potentially false positive or distant airgun pulse detections around 100 per day.

C. Sound propagation modeling

Transmission loss (TL) is the reduction in sound pressure levels as sound travels (propagates) between two locations. It is a summation of losses from geometric spreading, absorption, scattering, and reflections, and is dependent on the varying water and seafloor properties along the sound propagation path. In simplified models, the dominant component of TL is geometric spreading, which is commonly approximated as either spherical spreading (TL ≈ 20·log10R, expected near the source where sound radiates outward in all directions) or cylindrical spreading (TL ≈ 10·log10R, often used when sound becomes trapped and guided between the seafloor and sea surface, or within a subsurface duct such as the deep sound channel). These simple spreading laws provide useful first-order estimates, but do not account for environmental effects such as bottom interaction, refraction, and scattering that strongly influence propagation in real ocean settings. More complex models, such as parabolic-equation solvers, incorporate these environmental parameters explicitly but require more detailed inputs and far greater computational effort.

Seismic airgun arrays have high source levels often greater than 260 dB_{pp} re 1 µPa-m which travel long distances (100s – 1,000 km) in the GOM in either “shallow water” waveguides with multiple reflections with the seafloor and sea surface, or in “deep water” waveguides in which the ray paths refract in the

water column sound channel, or in a mix of both types (e.g., Carey 1986, Tashmukhambetov et al 2008, Heaney & Campbell 2019, Lin 2021). Typically, TLs are lower for water column paths than for paths that interact with the seafloor due to the latter's scattering and sound energy transmission and absorption into the seafloor. Furthermore, waveguides distort sound signatures such that an original short duration (milliseconds) airgun pulse becomes longer (seconds) and frequency dispersion occurs along with amplitude reduction.

Because all of the recordings in the GOM were made with calibrated hydrophones, absolute sound pressure levels can be derived from these recordings. Also, because low-drift, high-precision clocks were used to timestamp the recordings, the same concurrent individual or groups of airgun pulse sound pressure levels can be compared across the array site recordings to help build a better understanding of how seismic airgun sounds propagation and TL vary around the GOM. For example, recordings can be compared with propagation model outputs to iteratively improve model parameters, which could be used to provide better predictive estimates of sound levels around the GOM, including those from future surveys and even with different source configurations.

A range-dependent parabolic equation (PE) model (Collins 1995) was used to model propagation of airgun sound sources within the GOM. The model included range-dependent environmental parameters including data for bathymetry, sediment type, and water column properties. Bathymetric data were obtained from ETOPO Global Relief Model (ETOPO 2022), which has a spatial resolution of 15 arcseconds (~465 m). Sediment data from Gulf Data Atlas (NCEI 2011) provided sediment type and % gravel, % sand, and % mud. Sediment type percentages were used to map compressional wave speed (m/s), attenuation (dB/m), and density (g/cm^3) based on theoretical values from Hamilton & Bachman (1982). Daily water column data, including temperature, salinity, and depth were collected from HYCOM (HYCOM-TSIS GOMb0.04) in ~4 km resolution. The Makenzie (1981) nine-term equation for sound speed in the ocean was used to derive daily sound speed profiles.

For the purpose of this report – an overview of the GOM seismic surveys - acoustic-based source localization was not needed because AIS records and PSO reports provided ample detail on timing and location of seismic vessels; however, higher resolution source locations can be estimated from the acoustic recordings as needed (e.g., Hildebrand et al., 2025). For future acoustic-based source location, the use of group velocity is recommended as sounds are traveling in a waveguide. Over long distances, travel times can span several minutes, and the source signature may become distorted, which needs to be accounted for during analysis.

D. Directivity

Above ~50 Hz, the Gundalf airgun array model for a 22-gun array shows directivity differences in spectrum level such that along the direction of travel for the seismic survey vessel (inline – forward and aft) the side lobes are lower level, have more peaks, more complexity, and are asymmetric (forward to aft) compared to crossline (port and starboard) directional spectrum which has higher level but fewer and wider side lobes (Fig. 2). The influence of these peaks on sound pressure level measurements received across the wide-aperture HARP array was preliminarily investigated by identifying vessel directionality from AIS data, identifying the surveys withing the passive acoustic recordings, and incorporating any available information on the airgun array types and configurations used.

Results

Most seismic airgun surveys over the past couple of decades occurred in the northern Gulf of Mexico (NGOM), on the continental shelf < 200 m and on the continental slope ~300 m – 2,000 to 3,000 m. While the Bureau of Ocean Energy Management (BOEM) considers "deepwater" to include the continental slope (>300 m) and the abyssal plain, BOEM refers to this area from 300 m to the US EEZ as the outer continental shelf (OCS). In this report, we focus on the seismic surveys occurring mainly on the continental slope because airgun sounds in this region often travel long distances across the GOM resulting in large areas (footprints) of chronic noise impact, and because petroleum exploration and monitoring is focused on the slope based on large oil and gas reserves and greater production than on the continental shelf (Barkaszi & Kelly, 2019).

A. AIS-derived Survey Characterization

AIS-derived seismic surveys varied between large area, long duration surveys and small area, short duration surveys, and took place on the outer continental shelf, the continental slope, and farther offshore. We focused on large area, long duration deepwater surveys as they produce the largest impact across the GOM.

In this study, 95 large-area deepwater seismic surveys were identified between mid-2010 and mid-2023 (Figs. 7 & 8, Supplementary Figures). Some survey areas were revisited year after year (i.e., many overlapping surveys), mostly in northern GOM on the slope from 300 to 3,000 m deep. For example, in the Mississippi Canyon area at approximately 28.1°N and 89.5°W, directly south of the most southern tip of Louisiana and site SL, 12 surveys were recorded over the 14-year period, typically using only one vessel and covering an average area of 1,200 km^2 over 53 survey days.

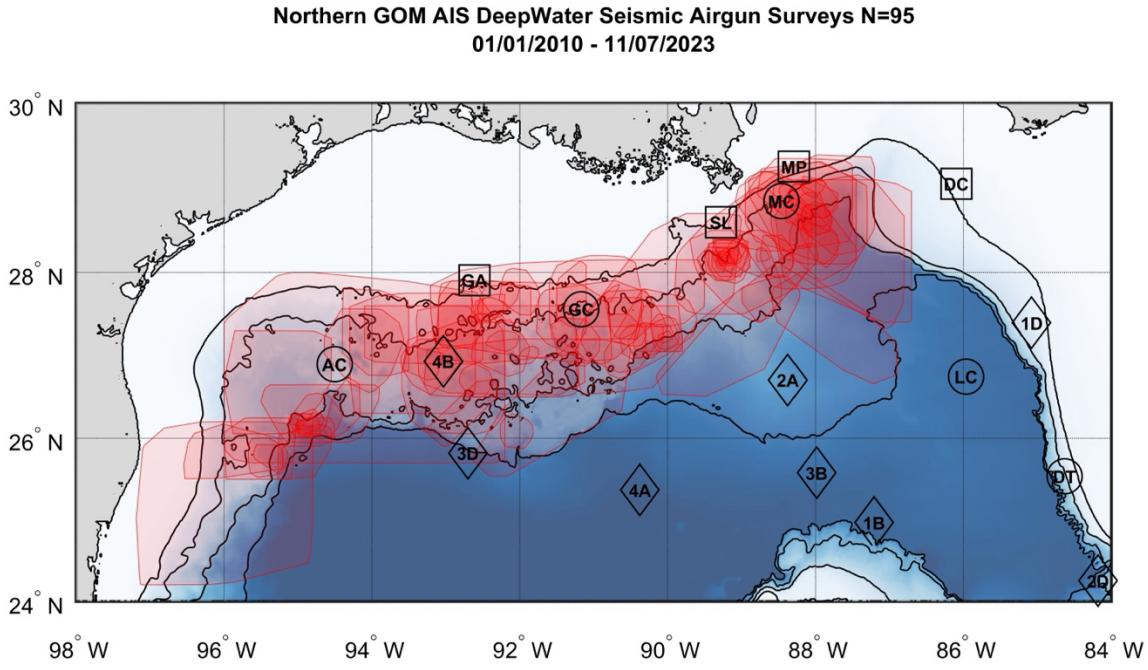

Figure 7. Map of seismic airgun surveys 2010-2023.

Northern GOM bathymetric map of 95 seismic surveys from 2010-2023 shown as transparent red convex hulls surrounding survey AIS locations provide a slightly over-estimated extent of each survey. Bathymetric contours are at 300, 1,000, 2,000, and 3,000 m depth. Acoustic recorder site name and location are as per Fig. 4. See Supplementary Figures for detailed yearly survey tracks.

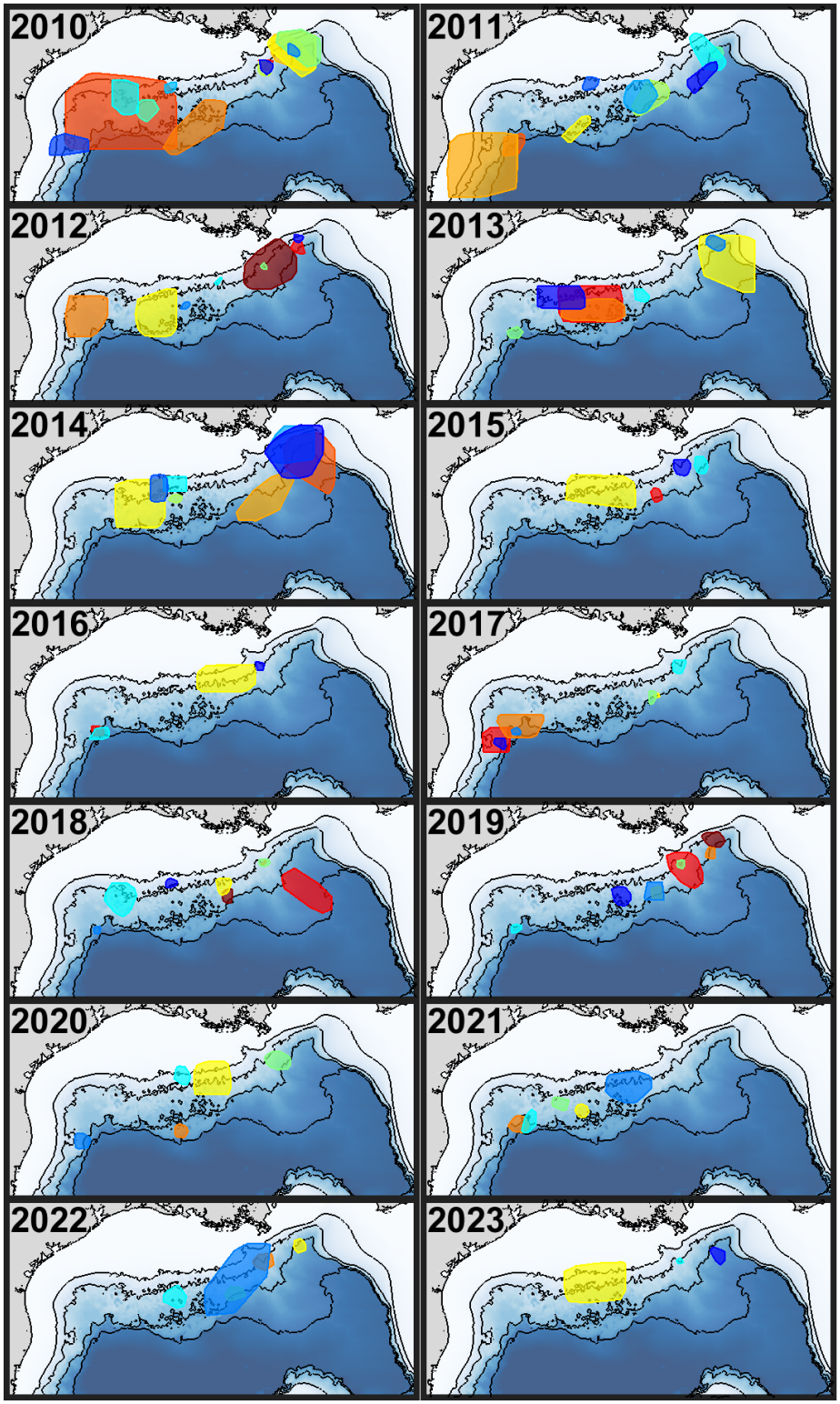

Figure 8. Map of seismic airgun surveys by year, 2010-2023.
Northern GOM bathymetric map of 95 seismic survey areas by year from 2010-2023 shown as colored polygons. Color indicates survey number within each year, from red (first) to blue (last). Surveys are assigned to the year they started. Bathymetric contours are at 300, 1,000, 2,000, and 3,000 m depth.

Grouping of annual seismic survey activity provides temporal comparisons in the Northern Deepwater GOM from 2010-2023 as the number of surveys, number of individual ship-surveys, cumulative survey duration, and total area surveyed each year. For all of these measures, the amount of seismic survey activity generally decreased over the 14 years evaluated, although some increases occurred in 2013 and 2014, including a strong peak in the number of ships used in 2014 (Fig. 9).

Distributions of the three metrics by survey (ships per survey, survey duration, and survey area) were long-tailed (Fig. 10). The number of vessels per survey ranged from one to 15 (median = 2), the survey durations spanned from approximately one week to about one year (median = 63.8 days), and survey area covered ranged from ~150 to ~89,000 km^2, although the upper extremes were not common (median = 2,553 km^2).

By year, survey metric median and mean values were often similar and near the lower end of the distributions (Fig. 11) The median and mean number of ships per survey were usually around two to three, with the 2014 calendar year anomalously high around five ships per survey. Yearly median and mean survey duration was typically around two to three months except for 2015, which was five months. Survey area yearly medians and means were more variable than the other two metrics during 2010 – 2014, ranging from ~1,000 to ~15,000 km^2. From 2015 to 2023 yearly median survey areas were more consistent at approximately 1,000 – 2,500 km^2 with higher means suggesting one or a few very large area survey(s) during those years.

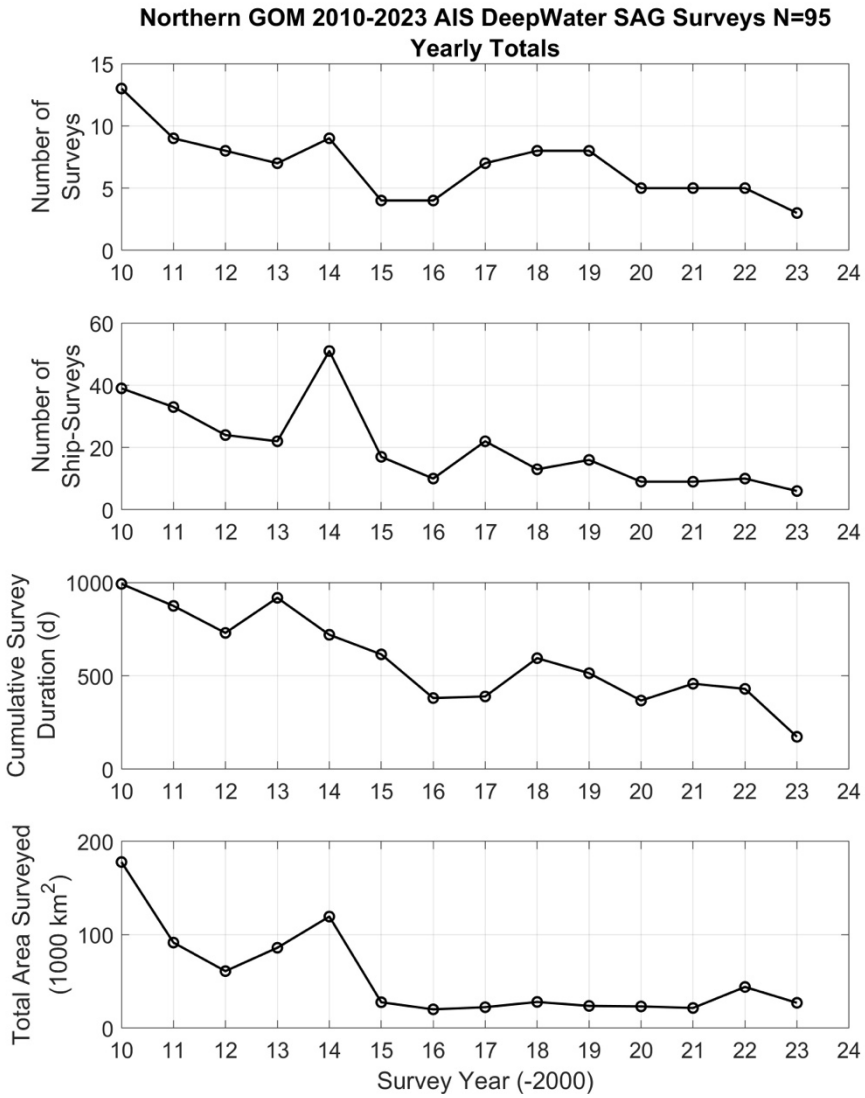

Figure 9. Time series of Northern GOM Yearly seismic survey activity 2010-2023.
Top to bottom: Number of surveys, number of ship-surveys, total survey duration, total survey area (area of the associated survey polygon from Figure 7). Note: Ship-surveys is computed as the total number of surveys completed by all survey ships involved in the 95 largest surveys. If a ship participated in two surveys in one year, then that is counted as two "ship-surveys" for that year.

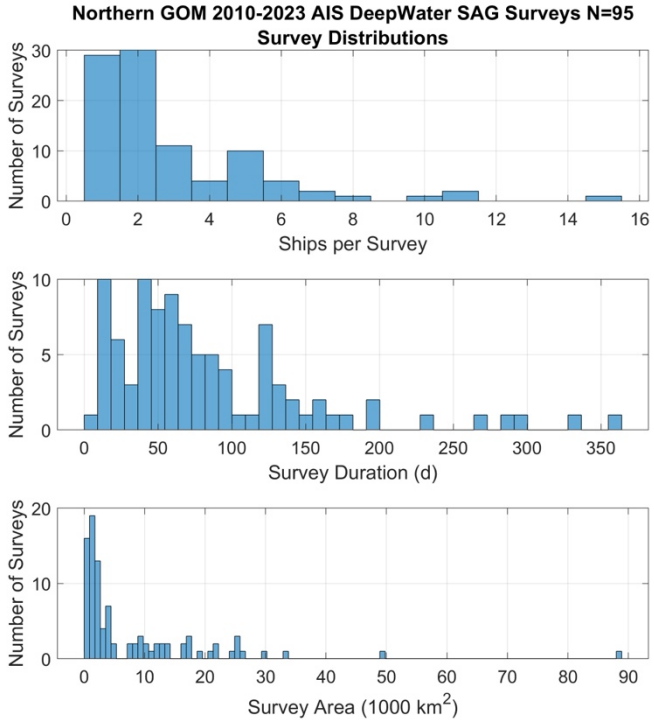

Figure 10. Northern GOM seismic survey activity metric distributions combined 2010 - 2023.
Top: Number of ships per survey. Middle: Survey duration. Bottom: Survey area.

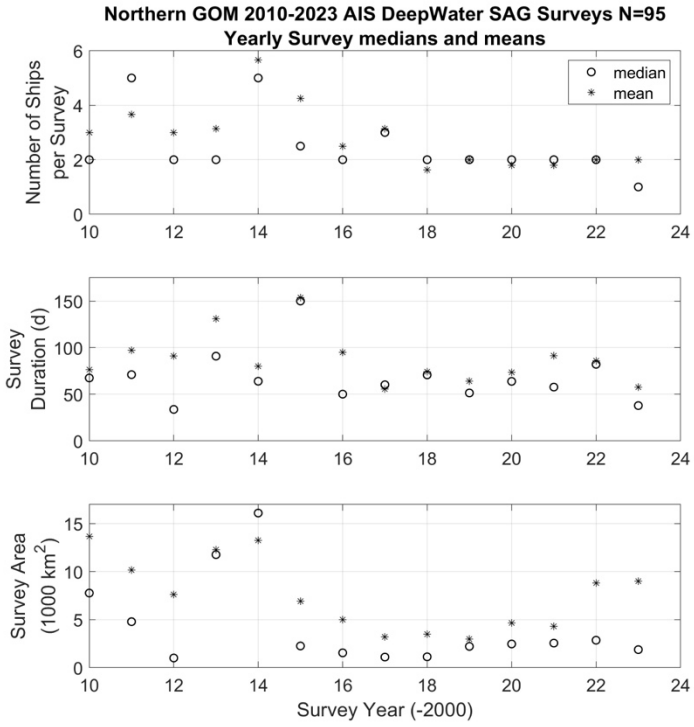

Figure 11. Time series of Northern GOM seismic survey metrics, medians and means by year 2010 – 2023.
Top: Number of ships per survey. Middle: Survey duration. Bottom: Survey area.

B. Passive Acoustic Survey Characterization

(1) 2010-2024 Long-term HARP array

The long-term deepwater HARP array consisted of three sites, two in the northcentral GOM (GC, MC) and one to the southeast: (DT; Fig. 4, magenta circles). Recordings started in June 2010 and continue to beyond when this report was finalized, but we only report from 2010 to mid - 2024 (14 years).

Across the 14 years at the three sites, the yearly average DASPL@40Hz per site showed variability of a few dBs with a slight increase in recent years (GC mean ± std: X ± Y; MC: X ± Y; DT: X ± Y). Day to day variability in DASPL@40Hz was greater, ranging from 80-110 dB re 1µPa^2/Hz at site GC, from 80 to 106 dB re 1µPa^2/Hz at MC, and from 82 to 98 dB re 1µPa^2/Hz at DT, reflecting seismic survey activity and locations over time.

Based on the locations of the 95 AIS-defined seismic survey areas, the two northern sites GC and MC were waters with deepwater seismic survey activity along the continental slope, whereas, site DT to the southeast is outside of waters with seismic survey activity (Fig 7). Site DT is located along a clear unobstructed deepwater path from the survey source area with its south-southeastward down-sloped seafloor to the recorder along the Florida Escarpment. This makes it an excellent location for monitoring seismic airgun activity along the northern slope over the 14 years of this study, and beyond. Conversely, the sites on the slope are better positioned for monitoring surveys near each recording site GC or MC, but not for surveys near the other site. For example, seismic surveys nearby and recorded at GC often were not recorded at high enough levels to be noticeable at MC, and vice versa, but each significant high sound level survey near and recorded by either GC or MC can be observed in the DT recordings (Fig. 12, also see Fig. 8 for survey locations). For instance, surveys 1901 and 1903 were near MC, but were not clearly recorded at GC, and survey 1904 was nearer GC with higher levels than MC, but all three surveys were clearly received at DT. On the other hand, there are surveys that are near neither GC nor MC recorders, but were still received at DT, such as survey 2005 (Fig. 12; bottom panel).

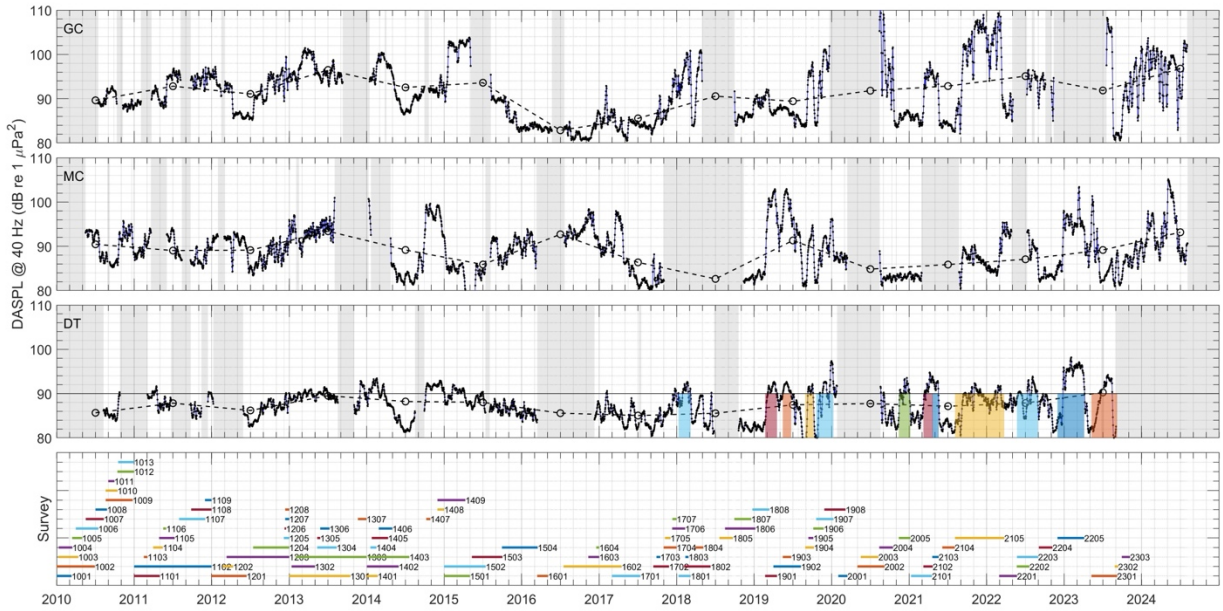

Figure 12. Long-term HARP array DASPL@40Hz and seismic airgun surveys 2010 - 2024. Seven day running average of DASPL@40Hz (2010 – 2024) for three long-term deepwater sites (top-down: GC, MC, DT) show variable sound levels temporally correlated with seismic surveys (bottom panel). Twelve surveys are color-coded as high sound level surveys that rise above 90 dB re 1 μPa^2 at site DT. Five of the surveys occurred before 2020 and seven after 2019 and were investigated further below. Yearly average levels are shown as circles for the three sites.

While DASPL@40Hz trends show variability year-to-year, the overall levels have not decreased over the study period even though the yearly number of seismic vessels has decreased, and recent sound pressure levels appear to have increased.

Twelve seismic surveys from the most recent recordings have DASPL@40Hz levels above 90 dB re 1 μPa^2 recorded at site DT (Fig. 12 – color-coded). From 2016 to 2019, five of these seismic surveys were recorded and found to cluster in two main locations between 1,000 and 2,000 m depth, with two of the seismic surveys just east and south of site MC, and the other three seismic surveys southeast of GC (Fig. 12; top panel).

The remaining 7 recent high sound level seismic surveys occurred from 2020 to 2023 and are detailed in the next section below, including a four-month, 96$^+$ dB re 1 μPa^2 DASPL@40 Hz survey (2205) which was the highest daily average level yet for a seismic survey recorded at site DT (Fig. 12). The seismic surveys in this period were spread over a larger region on the continental slope (Fig. 13) and included longer duration surveys that covered more area than surveys from the previous four years (Figs. 12 & 14; bottom panel).

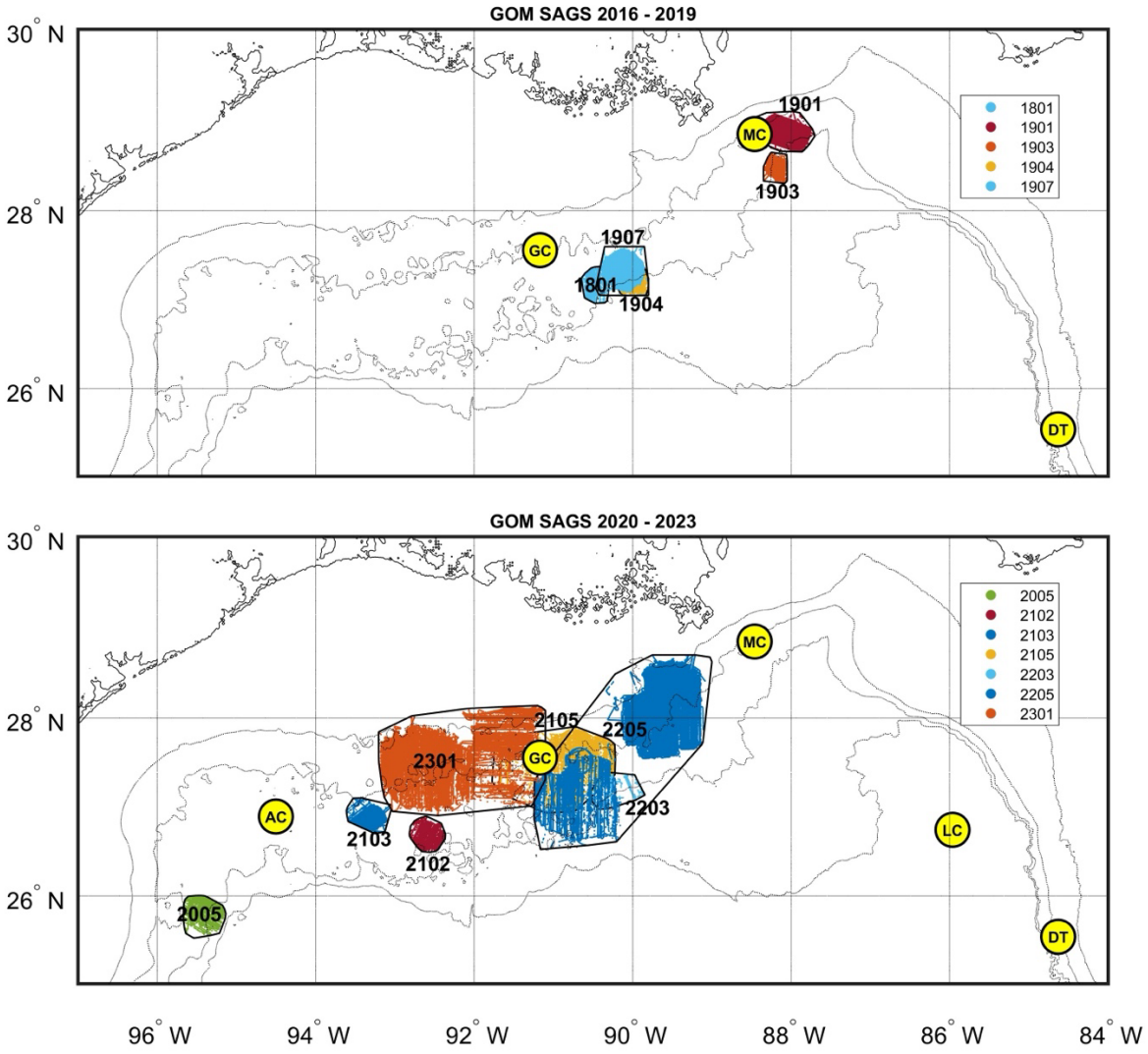

Figure 13. Maps of high sound level seismic surveys 2016-2019 & 2020-2023.
Twelve seismic surveys with high (>90 dB re 1 µPa^2) sound level DASPL@40 at DT. Top panel covers 2016 – 2019. Bottom panel covers 2020 – 2023. AIS survey positions are color-coded and surrounded by thin black line convex hull perimeters. Bathymetric contours are at 300, 1,000, 2,000, and 3,000 m depth.

(2) 2020-2024 Large-aperture deepwater HARP array

The large-aperture, basin-wide array was composed of 11 or 12 deepwater sites per year including the 7 stationary and 14 one-year sites over the period from mid-2020 and mid-2024 (Fig. 4). This array includes the three long-term sites reported in B(1) for the 2010-2024 period as part of the 8 total long term sites. In the 3-site long-term array, site DT's location provided the best reception of all seismic survey sounds from the northern GOM slope, and site DT was included in the large-aperture array; however, site CE's location was even better positioned with higher sound levels recorded for the same surveys as DT (Figs. 4 & 14).

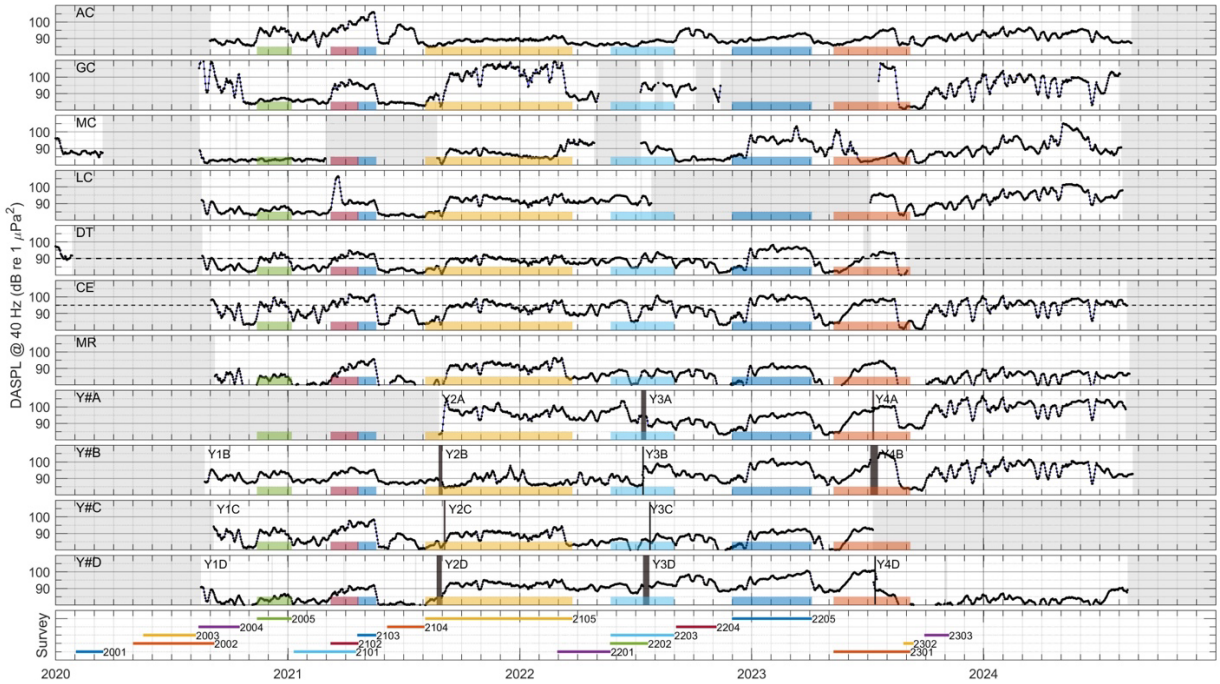

Figure 14. Large-aperture HARP array DASPL@40Hz and seismic surveys 2020 - 2024.
Seven day running average of DASPL@40Hz (2020 – 2024) for 11 yearly deepwater sites (top-down: 7 stationary sites (AC, GC, MC, LC, DT, CE, MR) and 14 one-year sites (Y#A, Y#B, Y#C, and Y#D) show variable sound levels temporally correlated with seismic surveys (bottom panel). Seven surveys are color-coded (per Fig. 11) as high sound level surveys that rise above 90 dB re 1 µPa^2 at site DT and above 95 dB re 1 µPa^2 at site CE. Note, some of the Y# recordings appear discontinuous along time with sound level offsets because the one-year sites may have been positioned at much different sound environment sites.

High sound level surveys

The following section summarizes the 7 surveys with high DASPL@40Hz levels recorded with the large-aperture array between 2020-2024 (highlighted in Fig. 14). PSO final reports provided detailed information on the most recent high sound level surveys: 2301, 2205, 2203, and 2105; reports for earlier seismic surveys currently are not available on the NOAA Fisheries Letters of Authorization webpage. Final report details typically included survey vessel names, permit number, survey type, sources used, and survey regions and periods. All of this information was obtained from publicly available sources.

Seismic Survey 2301

Survey 2301 (identified acoustically based on elevated DASPL@40Hz across the array) consisted of two distinct surveys in adjacent survey areas (A=east; B=west). Each area was about 12,000 km^2, within a single larger region – Green Canyon and Garden Banks protracted area[3] (Figs. 13 & 15) – in which vessels operated simultaneously for approximately four months from May through September 2023. Two seismic survey ships operated in each area for a total of four source vessels. PSO final reports indicate two separate permits were issued and executed; 2301A= L23-002, 2301B= L21-041 (RPS 2023a; RPS 2023b):

- Survey 2301A, Western Geco Engagement IV, was a 3D ocean bottom node (OBN) survey using the source vessels Shearwater (SW) *Mikkelsen* and SW *Gallien*. Each vessel towed three airgun arrays with each array consisting of two strings with 14 airgun elements (Bolt 1900 LLXT) on each string. Each array was activated in succession ("flip flop flap" pattern) with a shot every 6 seconds. Each 28 airgun-array had a total volume of 5240 cu. in. and SL_{pp} of ~220 - 266 dB re 1 µPa-m (RPS 2023a).

- Survey 2301B, Shell Momentum, was also a 3D OBN survey with two source vessels Fulmar Explorer and Sanco Sword; however, each towed dual Tuned Pulsed Source™ (TPS, Sercel) sources which operate at lower frequency and lower source sound levels (0-100Hz, ~244 dB re 1 µPa @ 10 m, RPS 2023b) than the standard airgun arrays, such as those used concurrently in survey 2301A which potentially masked the survey 2301B TPS pulses in the far-field acoustic recordings. During post-acquisition testing in early September 2023, both TPS sources and conventional airgun arrays were utilized. This likely accounts for the elevated DASPLs observed at some sites at the end of the survey period.

AIS records how survey 2301A vessels traveled in parallel east-west lines starting in the north and going south just to the east of site GC, with closest point of approach to GC in mid-June. Survey 2301B vessels traveled north-south starting to the east (at the west side of survey 2301A) and continuing westward away from GC, with both surveys centered ~1,000 m seafloor depths (Figs. 13 & 15). Sound levels at sites across the basin from the survey location progressively increase as the survey moves into deeper water, consistent with more efficient propagation. Survey 2301B had much better AIS coverage than survey 2301A. This is potentially due to poor AIS transmission equipment on the SW *Mikkelsen* and SW *Gallien*, as a similar effect was also observed with survey 2205B AIS coverage of the same two ships in a nearby area.

[3] A protracted area refers to a geographically extensive region in which a survey vessel operates for a sustained duration while acquiring seismic lines.

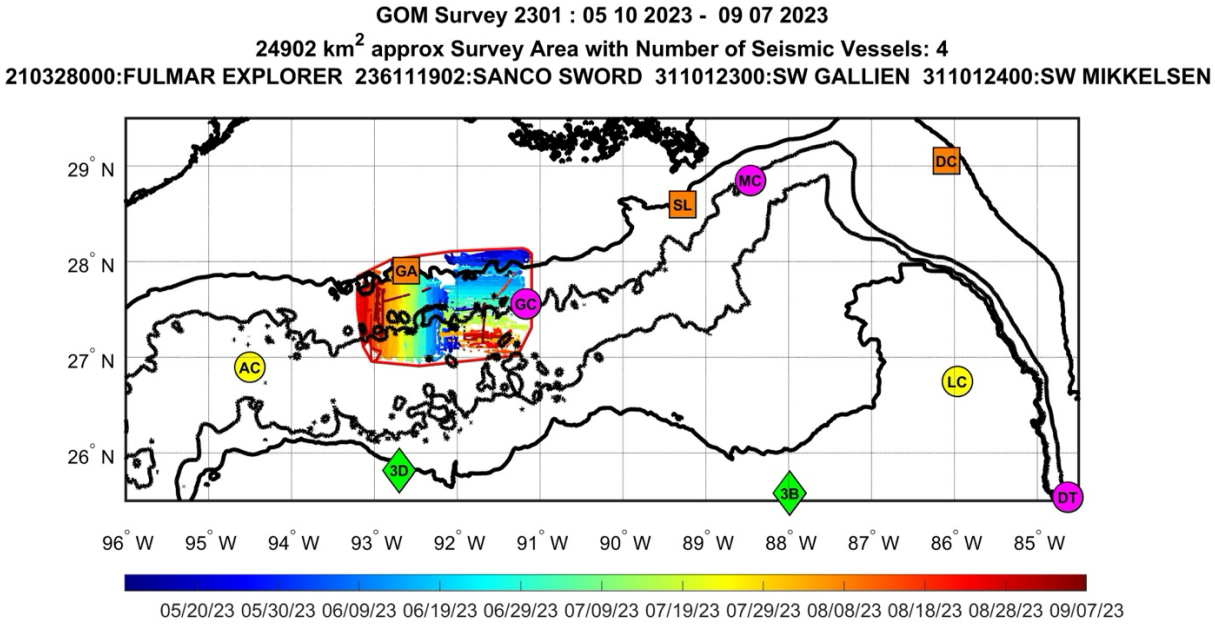

Figure 15. Map of seismic survey 2301 vessel AIS tracks.
Survey 2301 vessel AIS tracks mapped west of site GC in two distinct areas (each ~12,000 km^2): right 2301A= permit L23-002; left 2301B= permit L21-041. Track color indicates date/time spanning ~4 months. Bathymetric contours are at 300, 1,000, 2,000, and 3,000 m depth.

Survey 2205

Survey 2205 also occurred in two distinct areas (A=southwest; B=northeast), each about 12,000 km^2, within one larger general region in the Garden Banks, Green Canyon, Keathley Canyon, and Walker Ridge protraction area (Figs. 13 & 16) – and simultaneously for approximately four months from December 2022 to April 2023 with two seismic survey ships in each area for a total of four source vessels. The PSO final report (RPS 2023c) for permit L22-004 aligns with survey 2205A; whereas survey 2205B aligns with permit L22-007 area and period (for alignment, see Gulf of Mexico Incidental Take Regulation Annual Report April 2023 – April 2024: Data Reporting and Analysis – Feb 2025 Energeo), but the PSO final report for L22-007 is not currently available, therefore survey details and dates could not be confirmed.

Survey 2205A, Western Geco Engagement III, was a 3D OBN survey using the source vessels SW *Mikkelsen* and SW *Gallien*. PSO final reports indicate that each vessel towed two airgun arrays with each array consisting of three strings and 10-12 airgun elements (Bolt 1900 LLXT) per string (RPS 2023c, total airguns not reported). Each array had a total volume of 5240 cu. in. and peak-to-peak source level of ~262 dB re 1 µPa-m at full volume. Note, the Letter of Authorization Application indicated that the arrays would consist of 22 airgun elements per the included GUNDALF modeling (Fig. 2). Uncertainty with respect to actual array configurations may impact future detailed interpretations.

Survey 2205B was a 3D OBN survey (Energeo) with two source vessels Fulmar Explorer and Sanco Sword. Without the PSO final report, there is little information on the sources used. Based on the similarities between surveys 2301 and 2205 with two nearly identical offset track areas and the same

vessel pairs, it is possible that survey 2205B towed the same TPS sources as 2301B, calling for additional analysis of acoustic recordings from the survey 2205 and 2301 periods for confirmation.

AIS records show survey vessels traveled in parallel north-south lines starting in the east and progressing westward to the southeast of site GC; whereas, survey 2205B transited in the same pattern but to the northeast of GC near and within Mississippi Canyon. DASPL@40Hz increases gradually at western sites throughout the survey period as the survey lines move westward. Even though the quality of the AIS is poor for survey 2205A compared to 2205B, the overall area coverage and temporal patterns are quite similar but offset spatially. AIS records for surveys 2205A and 2205B suggest coordinated but not coincident vessel tracks (Fig. 17).

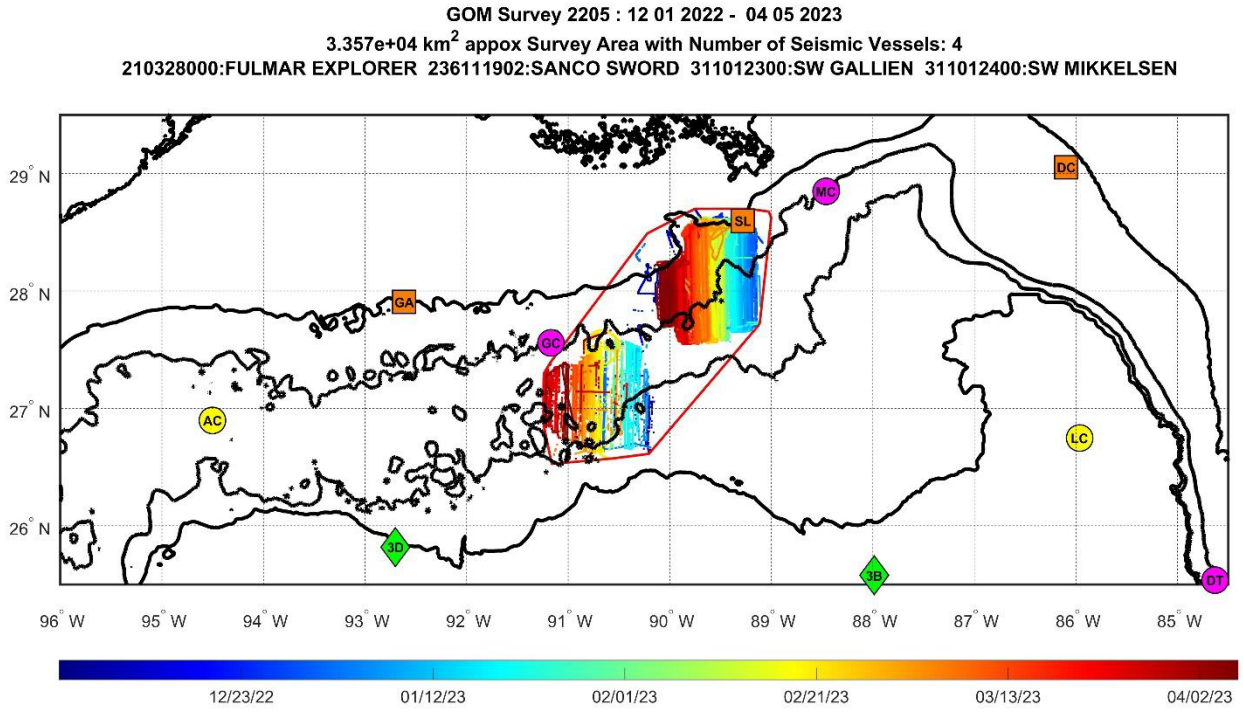

Figure 16. Map of survey 2205 vessel AIS tracks.
Survey 2205 vessel AIS tracks map in two distinct areas (each ~11,000 km^2): left 2205A= permit L22-004; right 2205B = permit L22-007*. Track color indicates date/time spanning ~4 months. Bathymetric contours are at 300, 1,000, 2,000, and 3,000 m depth.

*Assumed based on an annual summary document, no PSO report found.

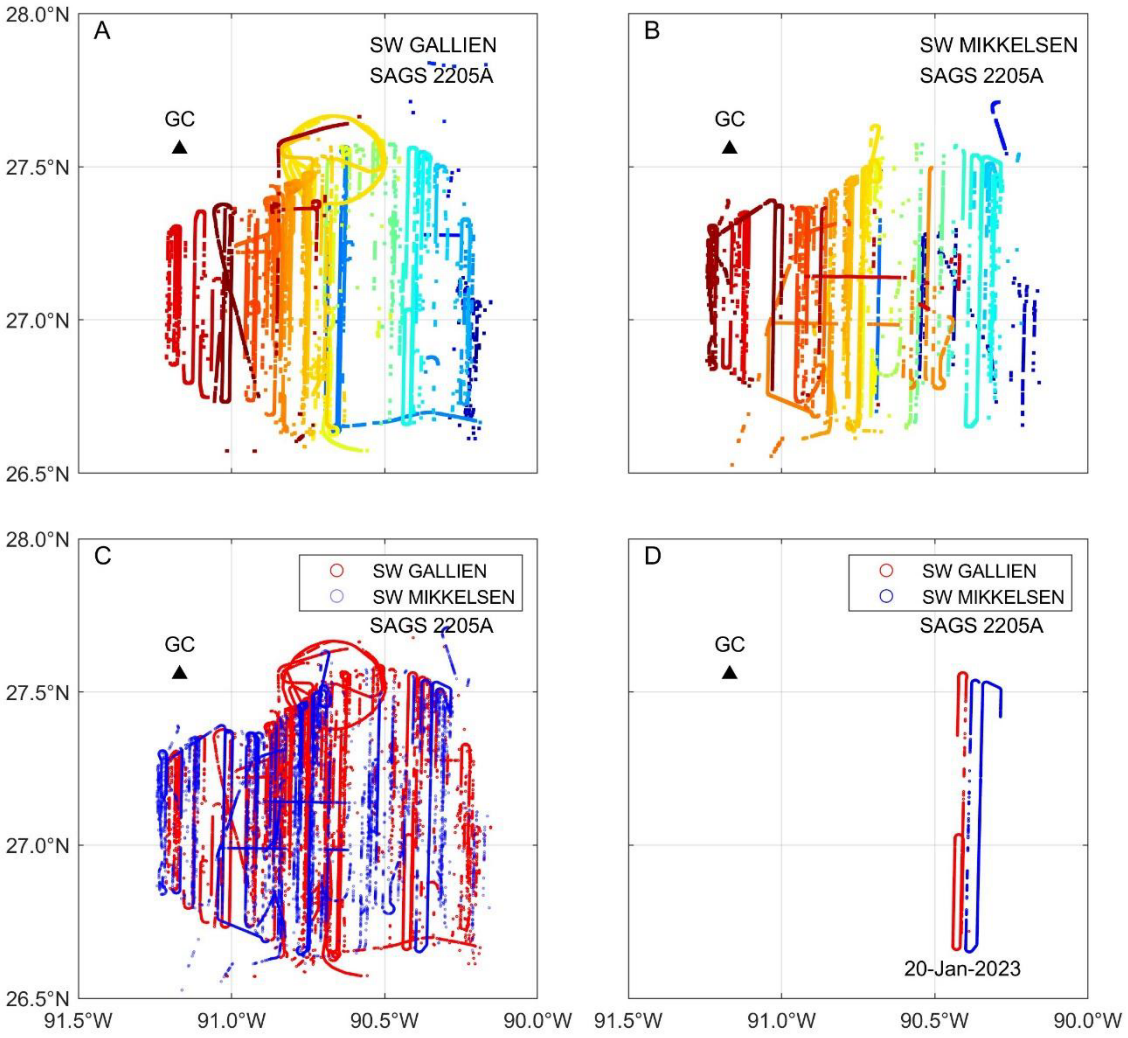

Figure 17. Comparison of survey 2205A vessel AIS tracks showing the coordination between the two vessels involved in time.
Survey 2205A vessel individual (A & B), combined (C), and one day (D) tracks 73 – 127 km range from GC (see section D. Directionality below).

Survey 2203

Survey 2203, BP Exploration & Production Inc. Mad Dog 4D Survey[4] L21-039, used two source vessels, Sanco Spirit and Artemis Arctic which towed airgun arrays and conducted operations under permit L21-039, for over 3 months from 23 May to 1 September 2022 southeast of site GC (Fig. 18; RPS 2022). The vessels each towed two source arrays with three strings per array with 10-12 airgun (Bolt 1900 LLX-T) elements per string for a total of 32 airgun elements in each array. Each airgun had a total volume of 5110 cu in. The Artemis Arctic reported a peak-to-peak source level of ~262 dB re 1 µPa / 0-120 Hz, while the

[4] A 4D seismic survey is a repeat 3D survey of a region that has previously been surveyed with a prior 3D survey. The new survey provides information on the movement of reserves over time.

Sanco Spirit reported 175 dB at 183 Hz. These differences in reported amplitude and frequency ranges are not well understood and merit further investigation.

In this survey, a 'flip flop' pattern (alternating between arrays) is used for dual source array with shot point interval spacing 26.6 m per vessel at survey speed no greater than 6.4 kts (1 shot every ~7.9 s), which is faster than the average vessel speeds during airgun pulse firing described in other reports (typically no greater than 5 kts). This survey covered a relatively smaller area of 2200 km^2, with AIS tracks running cross-bathymetry, approximately north-south, starting more centrally then heading east, returning westward for a closest point of approach to GC in mid-July, and returning eastward again to end near where it started. AIS points are sparse for this survey as well. Survey 2203, a summer survey, covers a deep slope region also covered by 2205A in winter months. DASPL measurements are elevated for both surveys at cross-basin sites CE and Y3B, but differ at site DT where 2203 DASPL measurements are lower than 2205A. A more detailed comparison investigating the influence of summer and winter sound speed profiles on these long-range propagation paths could be informative.

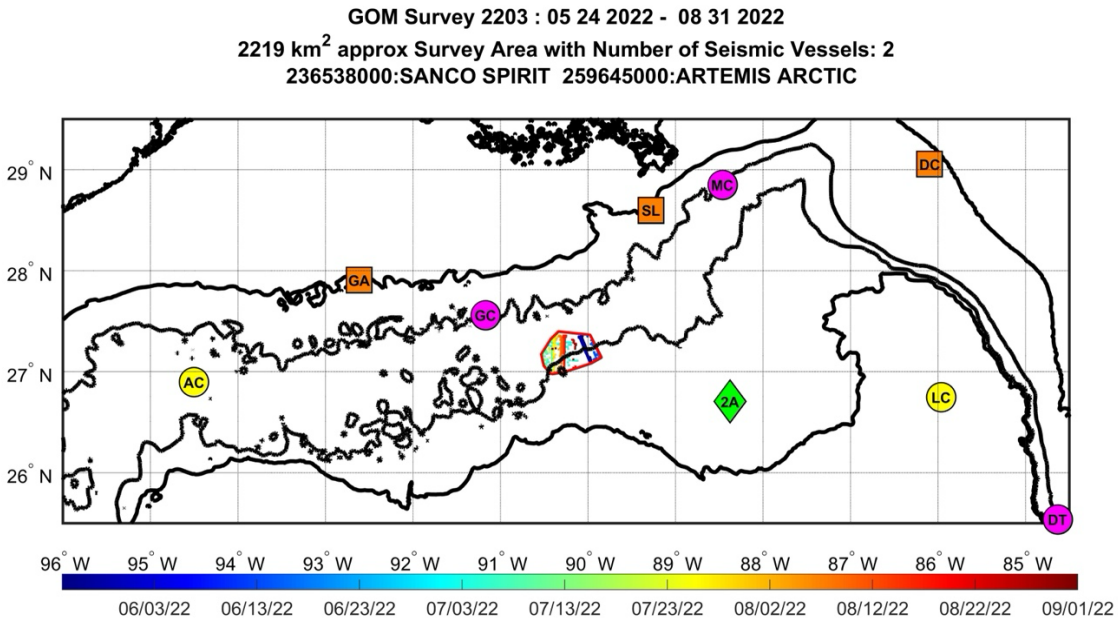

Figure 18. Map of survey 2203 vessel AIS tracks.
Survey area coverage was ~2,200 km^2. Track color indicates date/time spanning ~3 months. Bathymetric contours are at 300, 1,000, 2,000, and 3,000 m depth.

Survey 2105

Survey 2105A

The PSO final report for survey 2105A was unavailable at the time this report was finalized, but *Artemis Odyssey* and *Artemis Arctic* AIS positions were reported in the area over an 8-month period from Aug 5, 2021 to Mar 24, 2022 (Figure 19). Perhaps 2105A ended Dec 31, 2021 and 2105B started the next day. Also, it appears from Gulf of Mexico Incidental Take Regulation Annual Report April 2023 – April 2024 that 2105A may be associated with permit L21-014 and a TPS or Gemini source (Udengaard et al., 2024). Speculation regarding survey 2105A can be resolved upon release of the appropriate PSO final report(s).

Survey 2105B

Survey 2105, Schlumberger Engagement II Ocean Bottom Node (OBN) Survey, was conducted by Magseis Fairfield. Two vessels towed seismic source arrays and conducted operations under the permits L20-027 and L21-024. Survey activity appears to begin on 5 August 2021, but data on L20-027 activities in 2021 was unavailable at the time of writing (permit related activities are mentioned in BOEM L21-024). The L21-024 report includes *Artemis Arctic* effort from 1 January 2022 to 11 March 2022, the *Sanco Spirit* from 1 January 2022 to 16 March 2022. The vessels primarily traveled along north-south lines starting in the east and progressing west (Fig. 19), with surveys crossing over top of site GC in late December/early January.

Both vessels each towed three source arrays with two strings per array with 14 airgun elements per string for a total of 28 airgun elements in each array. Airgun elements were Bolt 1900 LLX-T and 1500 LLX-T airgun elements, full volume 5200 cu in. *Artemis Arctic* had a peak-to-peak source level of ~266 dB re 1 µPa / 128 Hz with only Bolt 1900 LLX-T elements, while *Sanco Spirit* reported ~240 dB re 1 µPa / 128 Hz with a mix of both airgun types.

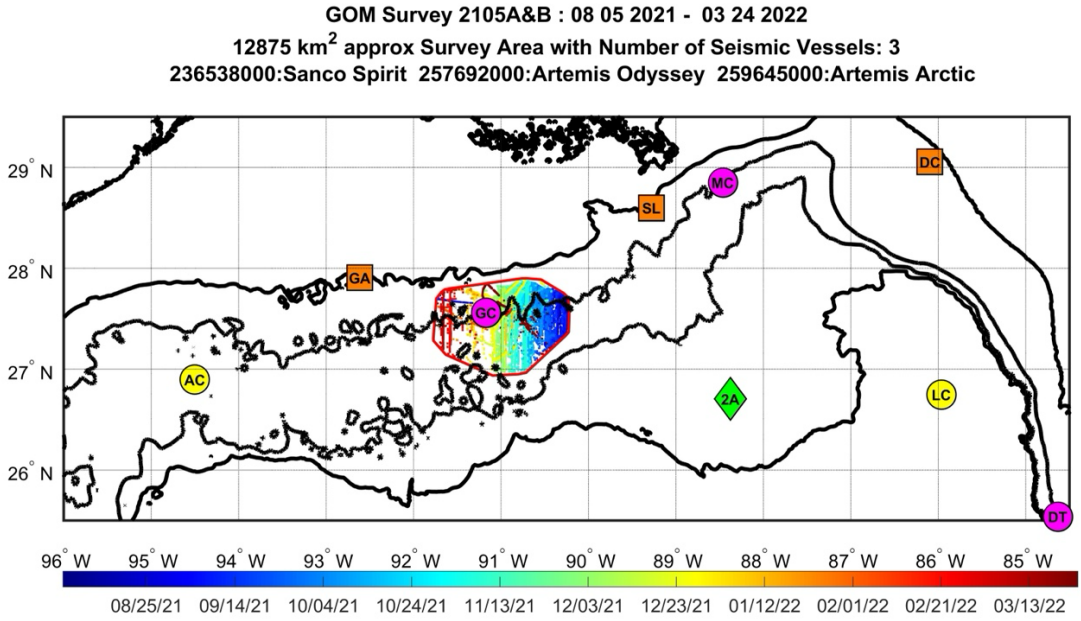

Figure 19. Map of survey 2105A and B vessel AIS tracks.
Survey 2105 area coverage was ~12,200 km. Track color indicates date/time spanning ~8 months. Bathymetric contours are at 300, 1,000, 2,000, and 3,000 m depth.

Surveys 2103, 2102, and 2005

Surveys 2103 used two seismic vessels: *Artemis Odyssey* and *Artemis Arctic*, the same two as the preceding and following surveys 2102 and 2105 (Fig. 20). Sound levels at sites DT and CE were similar if not a bit higher for 2103 compared to 2102 and 2105, suggesting all three used similar source arrays. Survey 2103 duration was about 4 weeks and covered ~1,600 km^2; whereas survey 2102 lasted about 6 weeks and 1,500 km^2. Survey 2005 also used two vessels: *Artemis Odyssey* and *Sanco Spirit*, with a duration of about 7 weeks covering ~2,000 km^2 and unknown sources (Fig. 13). Final PSO reports are not available for this set of surveys, therefore detailed information is lacking.

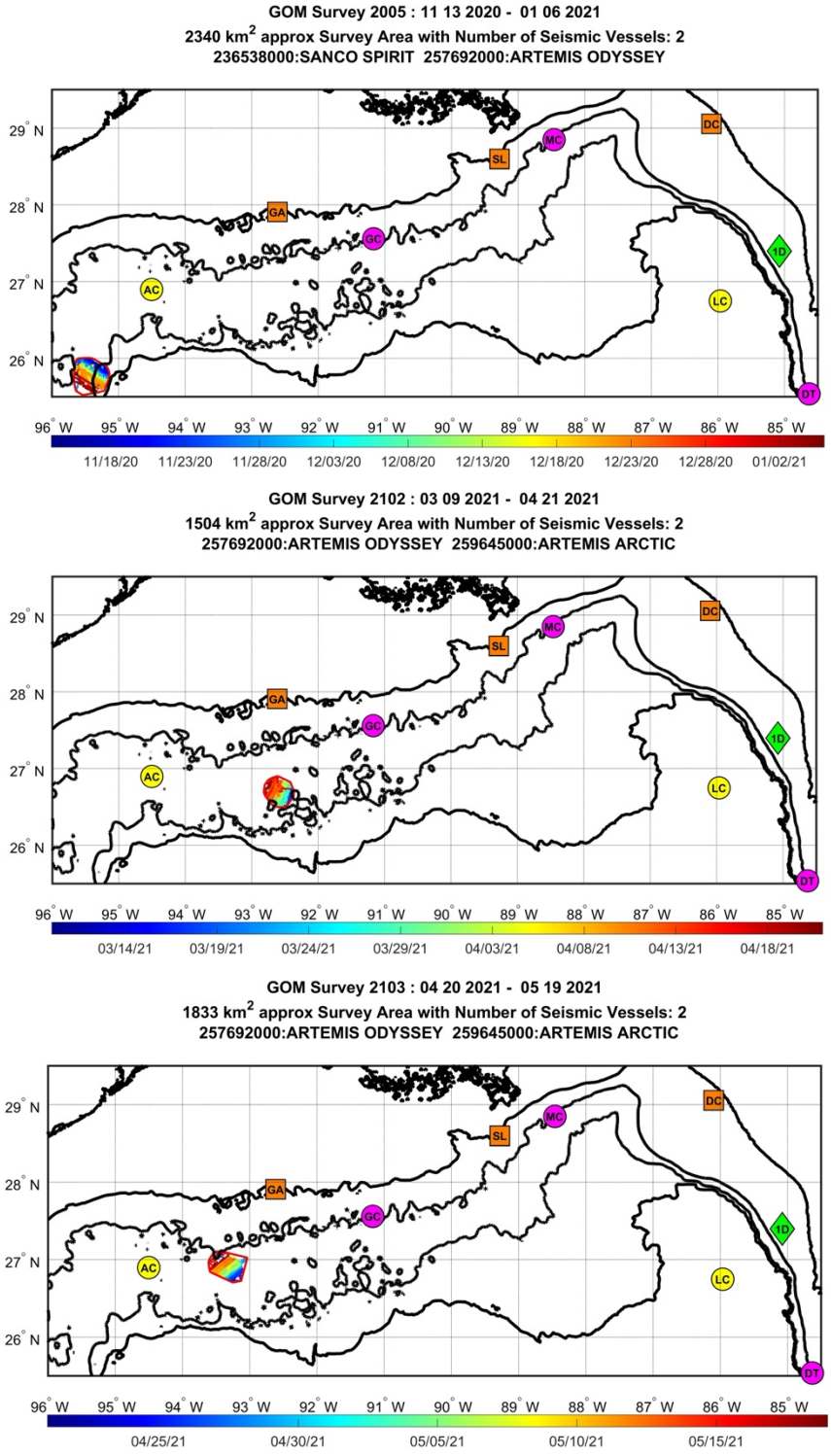

Figure 20. Maps of surveys 2005, 2102, and 2103 vessel AIS tracks.
Survey area coverage ranged from 1,500~2,300 km^2. Track color indicates date/time spanning ~4-6 weeks each. Three survey ships *Artemis Odyssey, Artemis Arctic*, and *Sanco Spirit* participated in these surveys, with two airgun ships active per survey. Bathymetric contours are at 300, 1,000, 2,000, and 3,000 m depth.

C. Sound Propagation

Survey 2103 (Figs. 12-14 & 20) was conducted at a location and period that provided insight on how sound propagation in the GOM was affected by different bathymetric conditions. Sound levels recorded at the different sites were not a simple function of range from the source (e.g. following geometric spreading loss models), such that longer paths did not always result in lower received sound levels. For example, one site (CE) at over 500 km from the survey 2103 area recorded sound levels a few dB above recordings at a site (GA) only ~130 km away (Figs. 21-22). The similarity in sound levels indicates differences in propagation loss along the transmission paths, which can be explained by the amount of seafloor interaction the sound ray paths incur while propagating from source to receiver (Dosso & Chapman, 1987).

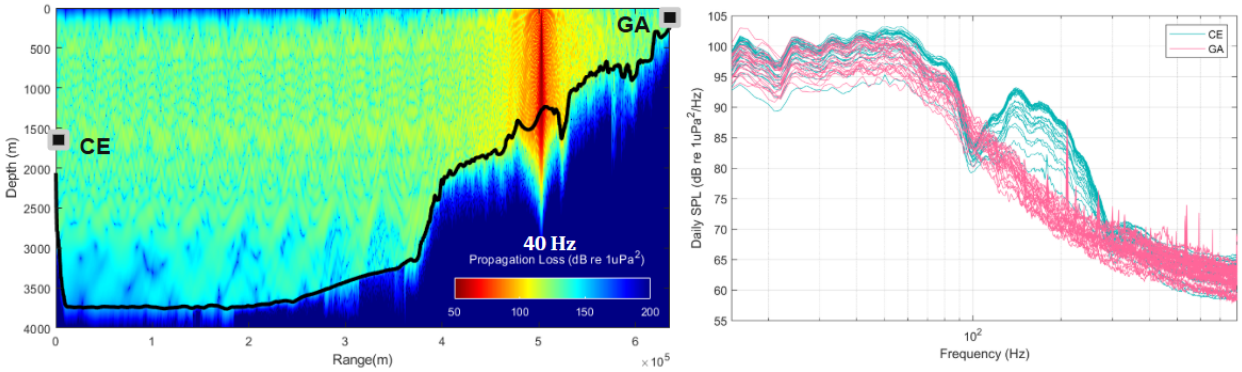

Figure 21: Propagation from survey 2103 to CE and GA with associated DASPL measurements. Bidirectional propagation loss model, using a PE algorithm, from the center of survey 2103 to HARP sites CE and GA for 40 Hz and 12-meter source depth (left). Daily average SPL during survey 2103 (right) recorded at sites CE (blue) and GA (pink).

In seismic surveys, the source energy is directed at the seafloor for penetration into the strata and imaging petroleum reserves. Because seismic airgun sounds are produced at low-frequencies and high intensities and travel long ranges (100s to more than 1,000 km, the depth of the GOM (<4 km) makes it a "shallow water" waveguide. The shallower the water, the more seafloor/sea surface (SFSS) reflections occur causing more sound propagation loss as the sound travels in this type of waveguide. Upslope propagation has the highest losses due to increased SFSS reflections with range. Along-slope sound path propagation also results in high losses, but with less SFSS reflections and less loss than upslope; whereas, downslope propagation has the lowest loss and can result in the sound ray paths entering the water column sound channel (~1000 m for GOM) and propagating in a refractive "deep water" waveguide across the basin with much lower losses than in shallower water, similar to cylindrical spreading (i.e., $TL \sim 10*\log_{10}(Range(m))$).

Survey 2103 occurred during a period without any other surveys and was recorded at 13 sites (Figs. 14, 22). Survey 2103 provided all three types of SFSS interactions (up, along, and down slope) including down slope conversion of the sound ray paths into the water column sound channel waveguide with low loss propagation (Fig. 21). Shallow water sites GA, SL and DC were upslope or along slope from survey 2103 and had high propagation losses as did along slope deep water sites AC and GC. All other deep-water sites (Y1D, LC, DT, Y1B, CE, Y1C, and MR) had low losses that varied based on total distance and how much the propagation paths were on the slope or in the sound channel across the deep basin (Fig. 23).

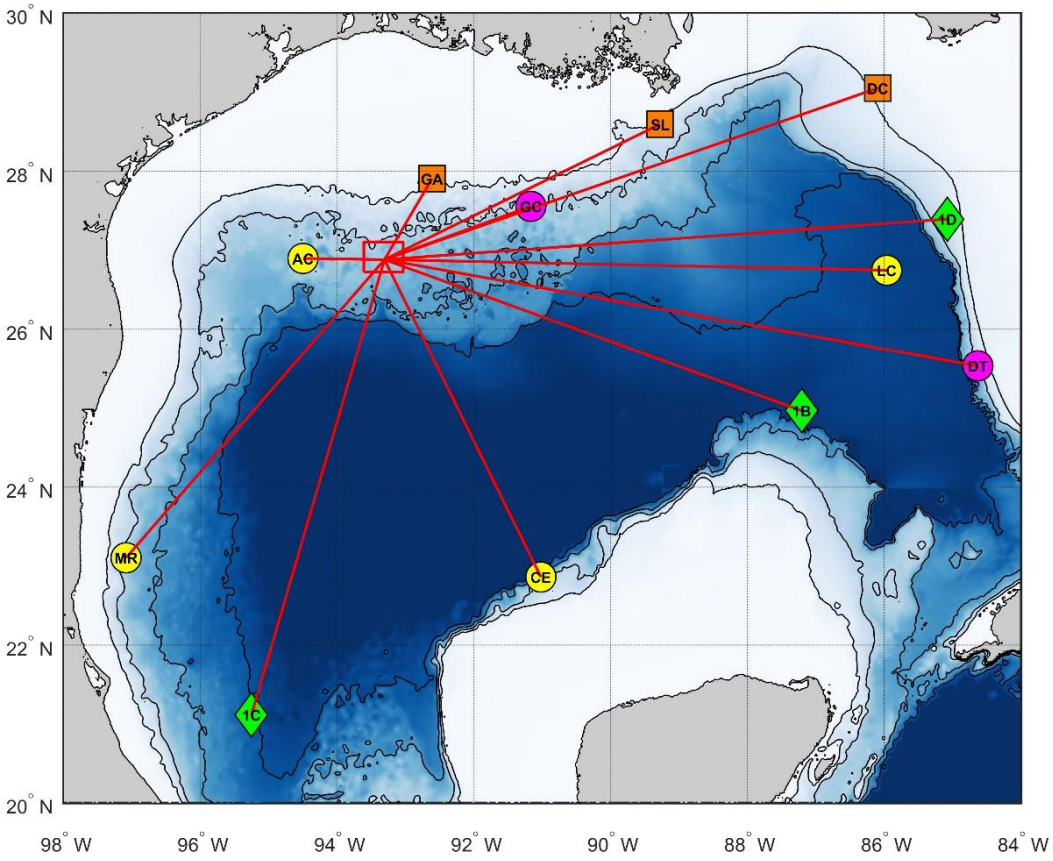

Figure 22. Survey 2103 sound path map.
Survey 2103 (red box): 12 source-to-receiver sound paths (red lines) on NGOM bathymetric map. Bathymetric contours are at 300, 1,000, 2,000, and 3,000 m depth.

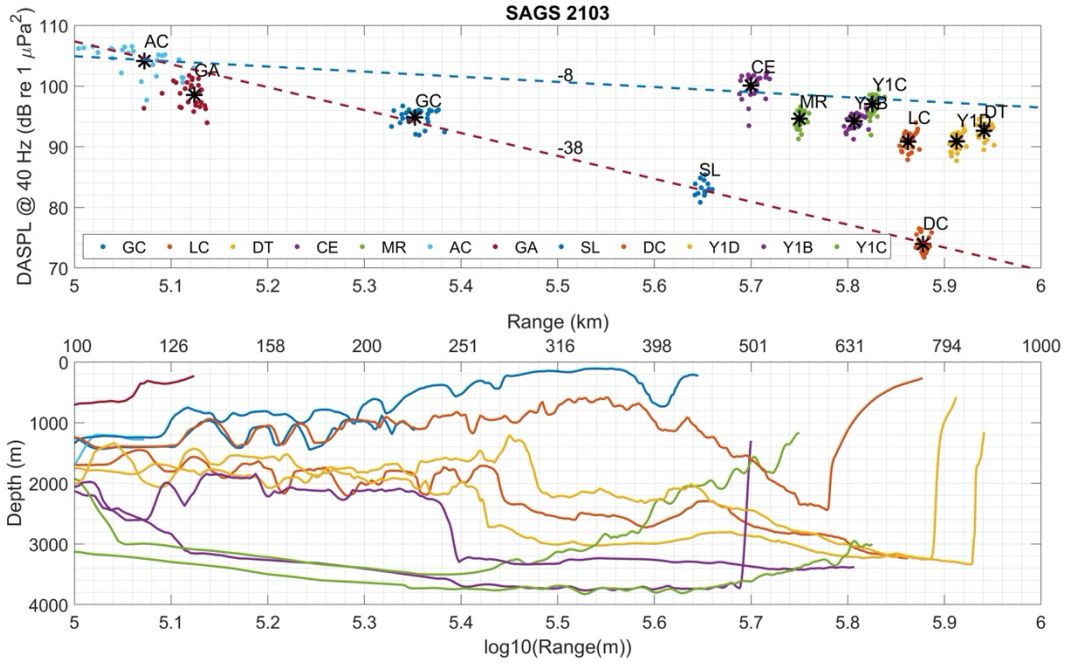

Figure 23. Survey 2103 DASPL@40Hz as a function of range.
Survey 2103 DASPL@40Hz vs log10(Range) from 100 to 1,000 km for 12 receivers (top panel) and bottom bathymetry as depth vs log10(Range) for the corresponding sound path shown in Fig. 19 (bottom panel). Range values are also provided in km for reference (top of lower panel). Red and blue dashed lines are meant to approximate two observed TL scenarios: the sites with relatively deep water and down slope sound paths have lower transmission loss (TL regression coefficient ~-8, red line is fit to mean DASPL@40Hz from sites AC, CE and Y1C). Shallow water and up slope sound paths have far greater TL (TL regression coefficient ~-38, blue line is fit to sites AC, GC and DC). AC is used in both fits, because it is the closest site to survey 2103, however it should be noted that AC is somewhat obstructed (short light blue path in the lower panel), and therefore the slope of the red line is an underestimate. Site DASPL@40Hz value colors in top panel correspond to site sound path depths in bottom panel. * indicates mean DASPL@40Hz and distance values in top panel.

To better understand the nuances in sound propagation observed for survey 2103, Parabolic Equation (PE) modeling was used to investigate how low-frequency sounds propagate long ranges accounting for water column and seafloor properties such as sound speed, density, and bathymetric relief (Fig. 24). Received level estimates from PE modeling along each of the source-to-receiver paths for survey 2103 (Fig. 25) were compared to actual received levels from our recordings at each HARP site (Fig. 23) to further develop our understanding of seismic survey sound propagation loss in the GOM. To model airgun propagation specifically, a 40 Hz frequency was used with a source depth of 12 m, the approximate source depth of an airgun in an array.

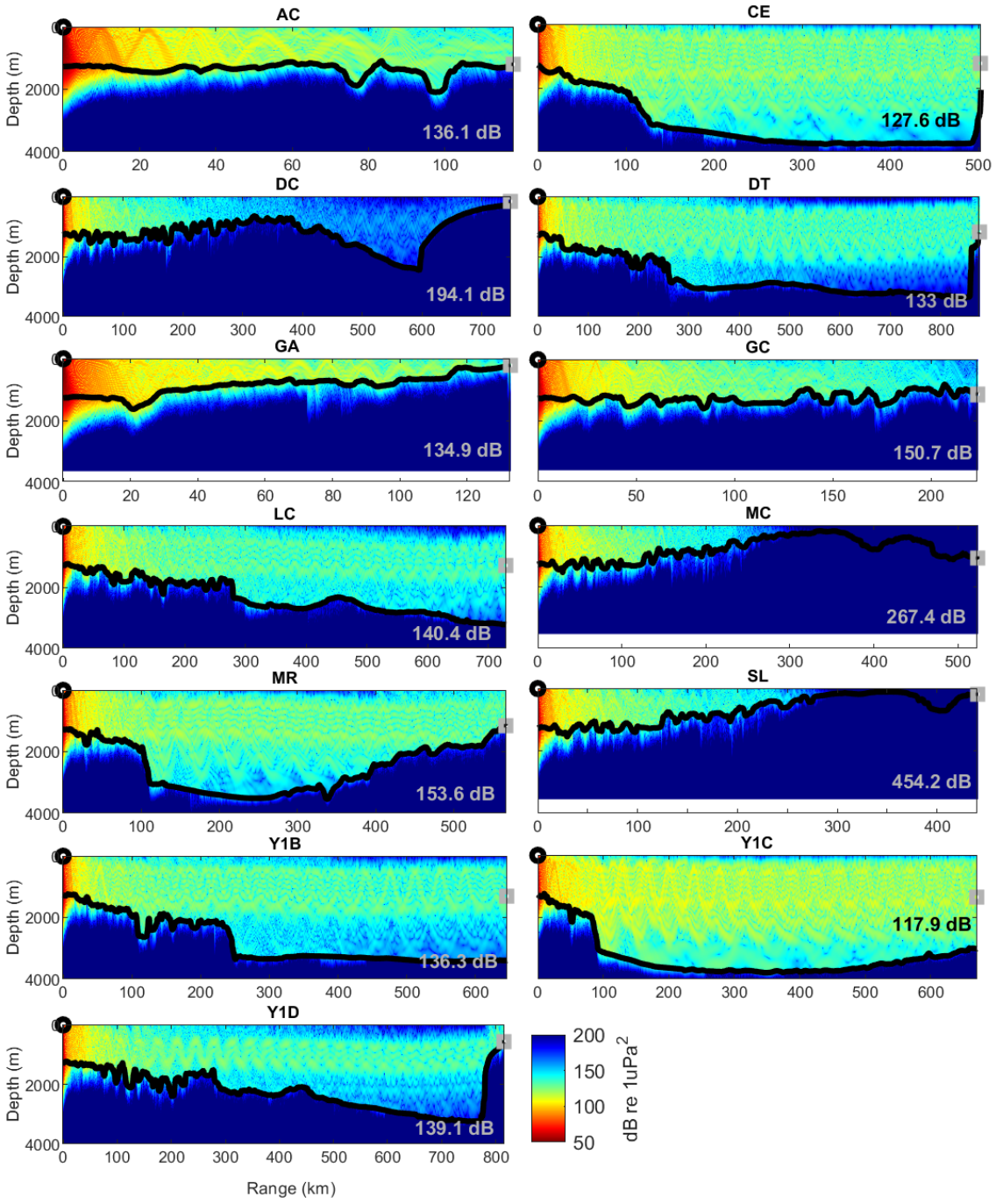

Figure 24: Sound propagation from survey 2103 to HARP sites.
Range vs. depth profiles showing modeled propagation loss (color) from the center of Survey 2301 to 13 HARP sites (includes two additional shipping lane HARPs, SL and GA, in shallow water). Propagation models were run for 40 Hz with 12 meters source depths. Black circles indicate simulated source position, and gray boxes indicate the receiving HARP position. A dark black line indicates the seafloor boundary. Inset values indicate model-estimated propagation loss between the source (seismic survey) and receiver (HARP). Note that the range scale (x-axis) differs between subplots.

Preliminary results from the PE modeling show some similar patterns as the measured propagation loss such as large losses at sites GC and DC, and low losses for CE, Y1C, Y1B, Y1D, LC and DT, but differences also are apparent. For example, PE modeling found larger losses at DC and MR and smaller loss at Y1C than measured sound levels show (Figs. 23 & 25). Of note, each site contains sound sources beyond the single surveys that may contribute to DASPL values recorded by HARP measurements, which may in part explain discrepancies between single survey modeling and measurement of the full acoustic environment. Additional work is needed to account for these differences, including modeling of a variety of different sound sources that occur within the GOM, including ships, airgun surveys, and natural sounds. Experimentation with PE model implementation details such as model resolution and the specification of ocean bottom layers may also be necessary.

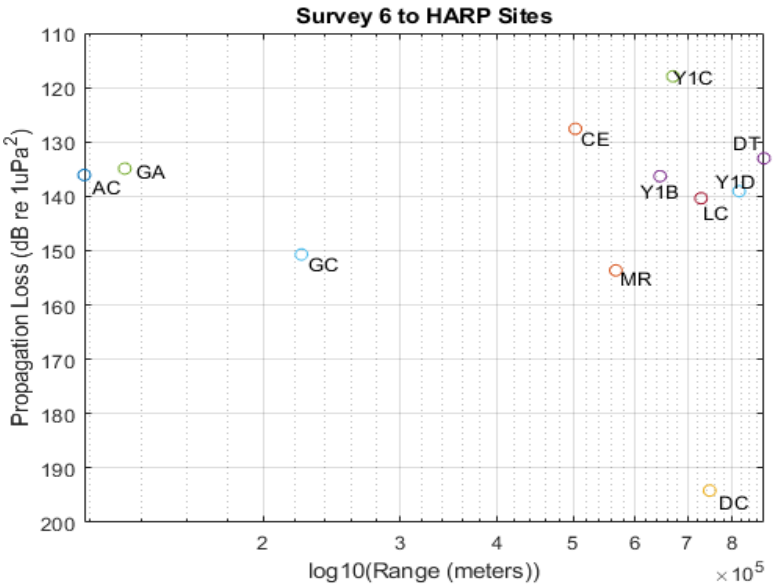

Figure 25. Survey 2103 PE modeling propagation loss as a function of range.
Propagation loss vs log10(Range) from PE modeling shows similar patterns to measured sound levels (Fig. 23), but differences between the measured and modeled losses need to be resolved.

To support a generalized understanding of the influence of survey position on measured sound levels across the array, a simplified TL model for long range (>100 km) propagation of seismic survey sounds originating on the northern continental slope was considered as three log10-space linear regions concatenated together with range (R) providing a piecewise TL model (Fig. 26). The first section goes from near the source (i.e., theoretically 1 m, but likely 10 m or more for array configurations) out to R1 and is or nearly is spherical (TL= 20*log10(R1 / 1 m)). R1 is approximately equal to the water depth or could be a few km's farther, depending on water depth, sound energy/seafloor interaction, and refraction. The second section, continuing from R1 to R2, is mostly affected by sound energy interaction with the seafloor and is dominated by the slope angle, seafloor material properties (i.e., density, sound speed, porosity, etc.), and seafloor roughness. Losses in this section are high, especially for upslope paths and paths over long distances on the slope, and have TLs up to ~40*log10(R2/ R1) or more. The third section may or may not occur, depending on the location of the receiver and the sound path. Many of the recording sites are separated from seismic survey locations in the northern GOM by a third section R3, extending across the deepwater basin (Fig. 4). A water column sound channel exists in this region. Sound

traveling downslope can enter and propagate into the channel with much lower loss, similar to cylindrical spreading (i.e., TL= 10*log10(R3 / R2)). In this simplified model, the path on the slope to R2 and the TL regression coefficient for the second section is the most variable and has the largest impact on received sound levels as shown in Figs. 21 and 23. Because of the long range of propagation and low frequencies of seismic airgun sounds, attenuation due to chemical absorption and viscosity should also be considered.

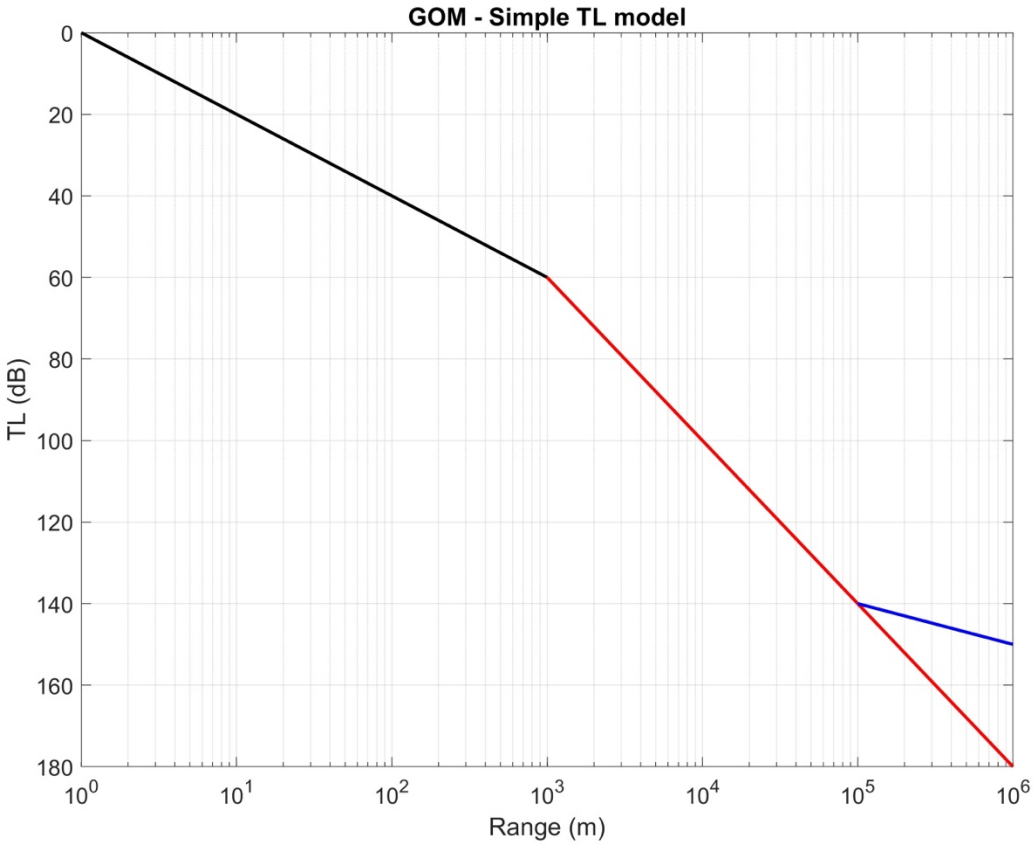

Figure 26. Simplified TL model for seismic surveys in GOM.
Simplified three-section piecewise TL model. The first (black: closest to source) section is nearly spherical with the TL regression coefficient ~20 and the third section (blue: closest to receiver across the deep basin) is cylindrical with the coefficient ~10. The middle section (red) is the most variable in slope (regression coefficient) and start and end ranges, and is a function of bathymetric slope angle (positive/negative), seafloor material properties, and roughness.

D. Directivity

Although simulations of seismic survey footprints often assume that the signals are omnidirectional, industry documentation describing seismic airgun source spectra indicates that directivity is expected at higher frequencies. Above ~50 Hz, the Gundalf airgun array modeling for a 22-gun array shows directivity differences in spectrum level such that along the direction of travel for the seismic survey vessel (inline) the side lobes are lower level, have more peaks, more complexity, and are asymmetric (forward to aft) compared to crossline directional spectrum (Fig. 2). At dip angles >45 degrees, the modeled crossline first side lobe peak at ~175 Hz is 10 – 15 dB lower than the peak spectrum level at ~40

Hz; whereas, the inline side lobes near the same frequency are about 20-25 dB lower than the peak, and are less well-defined.

The effects of the airgun array directivity are observed in the HARP recordings. As an example, survey 2025A transited primarily N/S during the survey, which was inline with HARP site CE, and approximately crossline to site DT (Fig. 16). The averaged spectrum levels for one day (January 20, 2023 – Fig. 17D) during survey 2205 at sites CE and DT show different shaped spectrum levels above ~70 Hz with ~8 side lobe peaks recorded at site CE and only two side lobe peaks at site DT (Fig. 27). Additionally, the first side lobe at site DT (~145 Hz) was at a higher spectrum level than site CE even though CE was closer to the source and had higher spectrum levels below ~100 Hz than site DT (Figs. 4 & 14).

A differenced spectrum (Fig. 27) shows ~8-10 dB higher levels at CE than at DT from 5-20 Hz and gradual decrease in difference to ~5 dB higher levels at 65 Hz; then the change in differences (i.e. the 2nd difference) increases until 200 Hz due to the primary side lobe of the crossline signal at DT. The minimum differenced spectrum occurs at ~160 Hz and is about -5 dB at the peak of the primary side lobe at DT. The second side lobe peak is ~250 Hz but the differenced spectrum is about +1 dB. The inline side lobes recorded at CE can also be observed in the differenced spectrum from ~80-400 Hz.

The crossline first lobe may be important to consider when evaluating how the transit direction of seismic survey sounds may affect Rice's whale. Crossline surveys relative to Rice's whale locations may result in higher-than-expected sound levels in the Rice's whale calling band (~70-150 Hz) than would be expected for an omni-directional source.

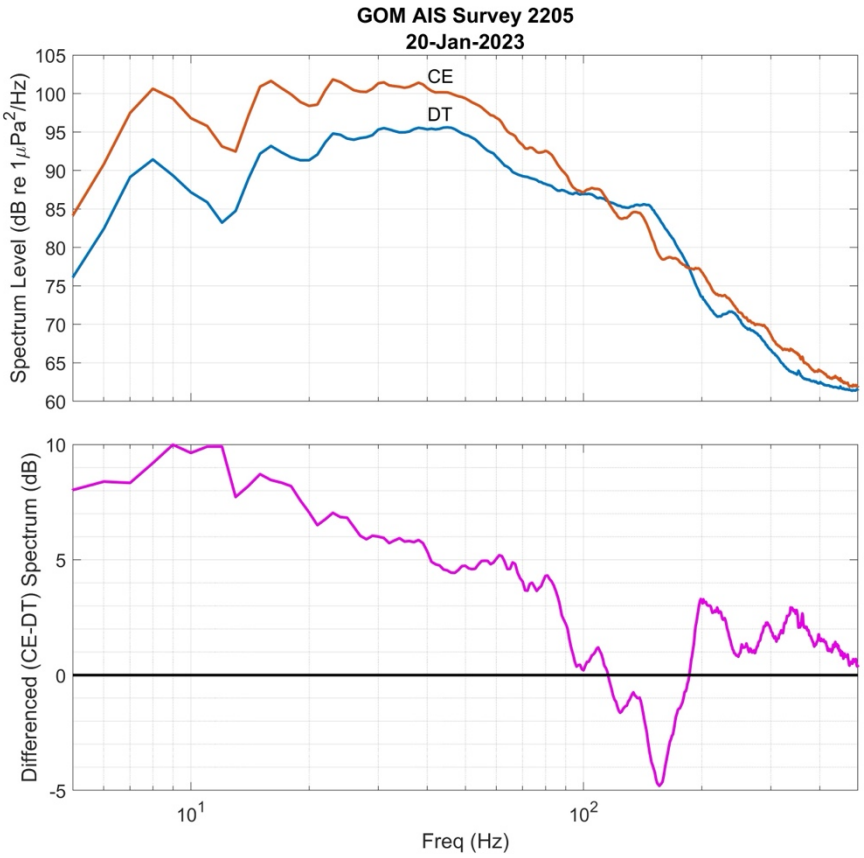

Figure 27. Seismic survey 2205 sound pressure spectrum levels for sites CE and DT.
Seismic survey 2205 daily average spectrum levels for one day (January 20, 2023, Fig. 16D) show directivity above 70 Hz in airgun shots (top panel) as measured crossline at site DT (blue) with two side lobes and inline at site CE (red) with ~8 side lobes. Differenced spectrum (bottom panel) provides a clearer distinction between inline and crossline directions. Note that the first side lobe recorded at site DT ~145 Hz had a higher sound level than for site CE which is closer to the source with higher overall sound levels.

DISCUSSION

The purpose of this report was to provide an overview of seismic airgun survey activity and opportunistic acoustic recordings during our underwater acoustic recording effort in the Gulf of Mexico starting in 2010. The overview provides a basis from which to launch more in-depth analyses investigating temporal, spatial, sound level, spectrum level, and other survey and acoustic parameters, potentially leading to the development of models to aid with our understanding of these high sound level, basin-wide, nearly omni-present sounds and the impacts of this chronic noise source on the marine environment. The acoustic, AIS-based, and permit-informed analyses conducted over a 14-year period provide a rare and valuable long-term view of seismic survey activity and its acoustic footprint in the deepwater GOM. While prior studies have documented the prevalence of airgun-generated noise, this work represents one of the most

comprehensive efforts to directly associate spatial-temporal patterns of seismic vessel operations with calibrated passive acoustic recordings at a basin-wide scale.

The overview, including analysis and plotting software, original data files, and resulting plots, figures, and charts also provides a type of table of contents of the identified surveys and related recordings, and the ability to find other AIS related surveys and sound sources, including future surveys. This information is not readily available or easily integrated, rather, finding, extracting, and synthesizing the information in this report represents a multi-year effort by many of the co-authors. While this report represents our current best understanding of seismic survey activities, it relies essentially on detective work; additional insight and greater accuracy could likely be achieved through the inclusion of seismic survey documentation that is not currently publicly available.

A. Surveys

A key result from the AIS and PSO-derived data is a clear downward trend in the number of seismic surveys and the number of ships used per year since 2010. However, this reduction in effort does not correspond to a proportional decline in underwater noise. Instead, long-term HARP recordings show that daily average sound pressure received levels at 40 Hz, a frequency representative of peak airgun output, have remained elevated and, in some cases, have increased in recent years. This finding suggests that while fewer surveys are being conducted, they are acoustically more intense, likely due to larger arrays, higher source levels, or higher pulse rates. For example, recent surveys such as survey 2205 and 2301 employed multi-vessel operations with arrays comprising over 60 airguns per ship, pushing source levels to or above 266 dB re 1 µPa-m peak-to-peak.

Visualizations conducted by BOEM (BOEM 2021-005) show that there has likely been a correlation historically between economic factors, namely the price of oil, and seismic survey activity. In a number of cases, when the price of oil increased, historically, survey activity picked up 18 months later. However, this relationship is loose and breaks down over time. It does not explain more recent trends since 2016.

We hypothesize that observed changes in survey activity and behavior since 2010 are at least partially attributable to changes in seismic survey technologies, strategies, and survey goals. Survey styles have changed over this period, with a general trend toward some smaller, more highly focused surveys in recent years. Additional investigation is required to understand the details of each of the 95 seismic surveys identified. Based on the seven high amplitude surveys reviewed in greatest detail, it appears that airgun volumes, number of guns, firing rates, and source levels may have increased over time. Moreover, although the total number of survey days has declined in recent years, the data show that surveys have been scheduled sequentially rather than overlapping. As a result, this reduction has not yielded an increase in quiet periods.

More detailed post-survey reporting would be useful, as actual activities and technologies appear to differ from pre-survey filings, based on a limited comparison with PSO reports, which were the main source of post-cruise information available. In particular, the descriptions of sources used vary in detail and content between reports, making comparisons difficult. Additionally, the quality of publicly available AIS data varies between years, and can be intermittent offshore, which has implications for survey footprint analyses and identification of participating vessels. The reasons for interannual and inter-vessel variability in AIS data quality are unclear. Acoustic-based analyses to localize seismic survey sounds could also provide some of these details, potentially along with other information not yet considered.

Our analysis focused on seismic surveys that were prominent in the AIS data and acoustic recordings. However, many smaller surveys, including possible tests of new technologies or methodologies, and shelf surveys are evident in the AIS and acoustic data. Investigation of these smaller surveys could yield additional insight into marine seismic airgun use, trends, and technological changes in the GOM.

B. Recordings

(1) Long-term array 2010-2024

The number of seismic survey vessels used per year in the GOM has declined over the past 14 years likely due to advancements in seismic survey techniques and efficiencies resulting in lower at-sea operational costs. However, despite this reduction in the number of active survey vessels, noise levels in GOM due to seismic surveys have only fluctuated by a few dB over the past 14 years and appear to be increasing in the last few years during certain months.

Deep water seismic surveys generally appear to use fewer vessels running for long periods (months) each towing multiple string arrays with more airguns per array. An alternating pattern between arrays appears to be used to maintain a high firing rate and higher acoustic output from fewer vessels. The fact that noise levels due to seismic surveys has been steady or increasing while in number of active vessels has declined suggests that fewer seismic survey vessels are now generating more noise per vessel.

We note that seismic surveys revisit certain regions year after year, but that survey designs and footprints change. A comparison of the acoustic characteristics of these successive surveys at particular locations could provide insight on the progression of seismic survey activities and differences in associated noise levels.

(2) Large aperture array 2020-2024

The large aperture array data reviewed in this report provides new insight into the Gulf-wide propagation of seismic survey signals. Although prior studies have shown long range propagation of these signals, the ability to correlate seismic survey noise between these widely spaced sensors provides opportunities to localize sources, develop and validate models for Gulf-wide sound propagation, estimate source levels for different survey types, and explore source signal directionality.

In this initial analysis, seismic survey noise is clearly correlated for large surveys across the entire array spanning the whole deepwater Gulf, with received sound levels heavily influenced by the survey location, bathymetry, and ocean bottom composition. Temperature and salinity also likely have range-dependent influences on observed received levels, and the interactions between all of these factors is a rich topic for further investigation.

A general intuition about the propagation of these signals is gained by studying the relationship between bathymetric profiles between surveys and the recording locations. For example, deepwater sites DT and CE, as far as 500 km away across the GOM basin from the primary survey region, consistently recorded signals from distant surveys even when nearby up- or along-slope sites did not. Modeling and empirical analysis confirm that downslope propagation benefits from more efficient transmission into the deep sound channel, whereas upslope or along-slope paths are subject to greater losses due to increased sea surface–seafloor reflections and seafloor interactions. The simplified three-stage TL model introduced here captures these dynamics and provides a foundation for more robust sound field predictions.

C. Sound Propagation

Preliminary parabolic-equation modeling reproduced the broad pattern of greater acoustic propagation loss at upslope/shallower sites compared to downslope/deeper sites. Range-depth propagation plots indicate that sound at deep water, downslope sites tends to become trapped within the deep sound channel, resulting in minimal interaction with (and associated losses from) the sea floor, and in some cases, potential enhancement of sound from slope-related reflections. In contrast, propagation at upslope sites show significant interaction with the seafloor, where complex and dynamic bathymetry may contribute to increased energy loss. Additionally, seafloor composition may also contribute to sound propagation characteristics, with muddier sediment likely absorbing more acoustic energy than harder, rockier seafloors. More up-to-date compilations of sediment type in the GOM may help constrain the effects of reflection and absorption at the seafloor in future propagation loss modeling efforts.

The sound levels modeled from Survey 2103 to each HARP site captured some of the general spatial patterns observed in the measured DASPL values. However, DASPL values represent the integration of contributions from millions of sound sources including ships, airguns, wind, waves, and biological sounds. At monitoring sites located beneath major shipping lanes (example: SL), the DASPL values are significantly higher than the modeled levels, likely due to additional contributions of ship traffic not accounted for in the single shot model. To more accurately represent acoustic conditions within the GOM, future modeling efforts should incorporate a broader range of sound sources to better understand measured sound levels and identify key drivers of long-term acoustic trends across monitoring sites.

While water column property and sediment data exist for the GOM, many are outdated or lack the comprehensive parameterization needed to fully characterize the acoustic environment. Additionally, knowledge of sound source location, source level, and behavior is incomplete. To advance acoustic modeling in this region, future efforts could leverage in situ HARP measurements with machine learning algorithms that incorporate physics-based loss functions. Such an approach like spatial-domain physics-informed neural networks (SPINNs) could be used to iteratively refine sound pressure level field predictions across depths and space. This approach may improve the accuracy and utility of ocean noise model predictions in spatially-dependent oceanic scenarios.

D. Directivity

Seismic array signal directivity has not been widely recognized (but note Duncan 2017), and has important implications for sound exposure assessments. Our acoustic recordings confirm a representative operator's simulation predicting pronounced side lobes above ~70 Hz. Airgun arrays exhibit notable spectral variation based on vessel heading, and these differences are persistent over long ranges. Crossline directions tend to generate stronger, broader side lobes in the 100–200 Hz band compared to inline directions, potentially enhancing exposure in lateral directions. Spectral comparisons at sites like CE and DT during identical survey periods clearly illustrate these directional effects: during days when vessel heading was nearly perpendicular to the recorder bearing, site DT showed a single dominant lobe at ~145 Hz that was 5 dB louder than the same lobe recorded 100 km closer at site CE when viewed inline. This directivity is particularly relevant for Rice's whales, which vocalize in the 70-150 Hz range and whose core habitat is exposed to seismic survey noise. The orientation of surveys may have a large impact on their level of exposure.

To investigate the directivity of airgun activity further, future efforts may analyze individual airgun pulses in addition to DASPL, for a fine-scale spectral and temporal comparison across monitoring sites.

Incorporating AIS may also help distinguish between inline and crossline survey orientations relative to HARP locations, providing context for interpreting directional differences in single shot SPL. Additionally, modeling the source-level directivity of airgun arrays and simulating propagation toward different site bearings may reveal how energy is distributed directionally, and how SPLs vary as a function of angle from the survey track.

E. Data-Handling Achievements and Limitations

Compiling >1 PB of passive-acoustic data, identifying 130 AIS vessel tracks and extracting parameters from >300 PSO logs required extensive manual data reconciliation. Incomplete AIS from certain chartered vessels and the absence of PSO final reports prior to 2020 limit source-parameter certainty for ~40 % of surveys. Biweekly PSO reports were not available for the period from 2020 to the present, and these would have provided insight on shot times, facilitating efforts to link the acoustic measurements with specific surveys and survey vessels. Despite these gaps, daily average metrics proved robust for basin-scale pattern detection, and provide a tractable platform for the finer-scale pulse-level analyses now recommended.

CONCLUSION

This report provides an unprecedented 14-year overview of seismic survey activity and associated acoustic signatures in the GOM, using calibrated, spatially distributed passive acoustic monitoring data. Long-term, basin-scale monitoring, paired with vessel movement records, observer reports, and modeling expands our understanding of seismic airgun use in the GOM and how surveys impact the region, as well as unanticipated patterns in the generation and propagation of airgun noise.

Key takeaways from this initial study include:

- Noise levels have not decreased in tandem with the number of seismic surveys. In fact, some of the most intense acoustic events have occurred in recent years, as surveys appear to have become more efficient, and more acoustically powerful. Fewer surveys do not translate into less noise, and additional metrics including source level, firing rate, and survey duration must be considered.

- Propagation loss between survey locations and regions around the GOM are highly dependent on the bathymetry and slope orientation between them. Down-slope transmission into the deep sound channel allows survey signals to travel >1000 km with relatively low loss, exposing large portions of the GOM to seismic noise, while nearby up- and across-slope regions may be less exposed.

- Seismic array signals exhibit clear directionality at frequencies above 70 Hz, which may result in higher-than-expected exposure in lateral directions. This may be particularly relevant for Rice's whale conservation. Relevant information related to sound sources used including model predictions for different survey equipment types and configurations likely exists and is needed to support further analyses and mitigation efforts.

- Assembling and interpreting this dataset required significant effort, particularly in reconciling AIS, PSO, and acoustic data sources. We highlight the need for better integration, transparency and quality in survey metadata collection and availability.

This initial synthesis of the available data highlights the value of long-duration, basin-wide passive acoustic monitoring for understanding the full scope of seismic survey operations in the GOM. Data-driven insights from these in situ measurements not only illuminate current acoustic conditions but also inform the development of effective strategies to mitigate chronic noise impacts. As airgun technologies evolve and interest in low-frequency anthropogenic noise intensifies, continued monitoring will be essential, both for tracking ongoing impacts and for uncovering new and often unexpected dimensions of this otherwise opaque industry.

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REFERENCES

BOEM 2021-05. Deepwater Gulf of Mexico December 31, 2019. U.S. Department of the Interior Bureau of Ocean Energy Management. Gulf of Mexico Office. New Orleans January 2021.

BOEM L21-024. Letter of Authorization Application – Addendum to G&G Permit Application Long Form. BOEM CONTROL NUMBER: L21-024. Accessed June 28th, 2025.

Barkaszi, M.J. and C.J. Kelly. 2018. Seismic survey mitigation measures and protected species observer reports: synthesis report. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Gulf of Mexico OCS Region, New Orleans, LA. Contract No.: M17PD00004. OCS Study BOEM 2019-012. 220 p.

Carey, W. M. (1986). Measurement of down-slope sound propagation from a shallow source to a deep ocean receiver. *The Journal of the Acoustical Society of America*, 79(1), 49-59.

Collins, M. D. (1995). User's Guide for RAM Versions 1.0 and 1.0 p. Naval Research Lab, Washington, DC, 20375, 14.

Duncan, A. J. (2017). Airgun arrays for marine seismic surveys-physics and directional characteristics. *Proceedings of ACOUSTICS* 2017, 1-10.

Hamilton, E.L. and Bachman, R.T., (1982). Sound velocity and related properties of marine sediments. *The Journal of the Acoustical Society of America*, *72*(6), pp.1891-1904.

Heaney, K. D., & Campbell, R. L. (2019). Parabolic equation modeling of a seismic airgun array. *IEEE Journal of Oceanic Engineering*, 44(3), 621-632.

Hildebrand, J., Wiggins, S., Cornuelle, B., & Frasier, K. (2025). Using seismic sources of opportunity to investigate sound propagation in the Gulf of Mexico. The Journal of the Acoustical Society of America, 157(4_Supplement), A178-A178.

Landrø, M. (1992). Modelling of GI gun signatures. *Geophysical Prospecting*, 40(7), 721-747.

Li, G., Cao, M., Chen, H., & Ni, C. (2011). Modelling the signature of clustered airguns and analysis on the directivity of an airgun array. *Journal of Geophysics and Engineering*, 8(1), 92.

Lin, Y. T. (2021). Three-dimensional propagation of seismic airgun signals in the Mississippi Canyon area of the Gulf of Mexico. JASA Express Letters, 1(2).

Long, A.S., Pramik, W., Fromyr, E., Laurain R., & Page, C. (2006) Multi-Azimuth and Wide-Azimuth lessons for better seismic imaging in complex settings, ASEG Extended Abstracts, 2006:1, 1-5.

Jones, J. M., Westdal, K. H., Ootoowak, A. J., Wiggins, S. M., & Hildebrand, J. A. (2023). Impact of ship noise on the underwater soundscape of Eclipse Sound in the northeastern Canadian Arctic. *Marine Pollution Bulletin*, *195*, 115534.

Mackenzie, K.V. (1981). Nine-term Equation for Sound Speed in the Oceans. *The Journal of the Acoustical Society of America*, 70(3), 807 - 812.

McDonald, M. A., Hildebrand, J. A., Wiggins, S. M., & Ross, D. (2008). A 50-year comparison of ambient ocean noise near San Clemente Island: A bathymetrically complex coastal region off Southern California. *The Journal of the Acoustical Society of America*, *124*(4), 1985-1992.

National Centers for Environmental Information. (2011). *Gulf Data Atlas*. NOAA. https://www.ncei.noaa.gov/maps/gulf-data-atlas/atlas.htm. Accessed Jan 15, 2024.

Newcomb, J., Fisher, R., Field, R., Rayborn, G, Kuczaj, S., Ioup, G., Ioup, J. & Turgut, A. (2002, October). Measurements of ambient noise and sperm whale vocalizations in the northern Gulf of Mexico using near bottom hydrophones. In OCEANS'02 MTS/IEEE (Vol. 3, pp. 1365-1371). IEEE.

NOAA National Centers for Environmental Information. 2022: ETOPO 2022 15 Arc-Second Global Relief Model. NOAA National Centers for Environmental Information. https://doi.org/10.25921/fd45-gt74 . Accessed Jan 15, 2024.

RPS (2022). BOEM OCS Permit L21-039 Survey 2022: Protected Species Observer Report. Final. Prepared for BP Production and Operations, 29 November. 2022.

RPS (2023a). BOEM OCS Permit L21-002 WesternGeco Engagement IV 3d OBN Survey: Protected Species Observer Report. Final. Prepared for WesternGeco, 16 November. 2023.

RPS (2023b). BOEM OCS Permit L21-041 Shell Momentum 3D OBN Survey: Protected Species Observer Report. Final. Prepared for Magseis Fairfield (TGS), 28 November. 2023.

RPS (2023c). BOEM OCS Permit L22-004 WesternGeco Engagement III Survey: Protected Species Observer Report. Final. Prepared for WesternGeco, 29 June. 2023.

Shen, H., Tao, C., Elboth, T., Wang, H., Zhou, J., Qiu, L., Liu, Y., Chen, J., and Jin, X. (2020). Optimizing spatial distribution to minimize the inline directivity for a marine air-gun source. Geophysics 85(3) P37-P44.

Schuster, G. T. (2010). Basics of Seismic Imaging. Cambridge University Press. 105pp.

Sidorovskaia, N. A., & Li, K. (2016, July). Decadal evolution of the northern Gulf of Mexico soundscapes. In *Proceedings of Meetings on Acoustics* (Vol. 27, No. 1). AIP Publishing.

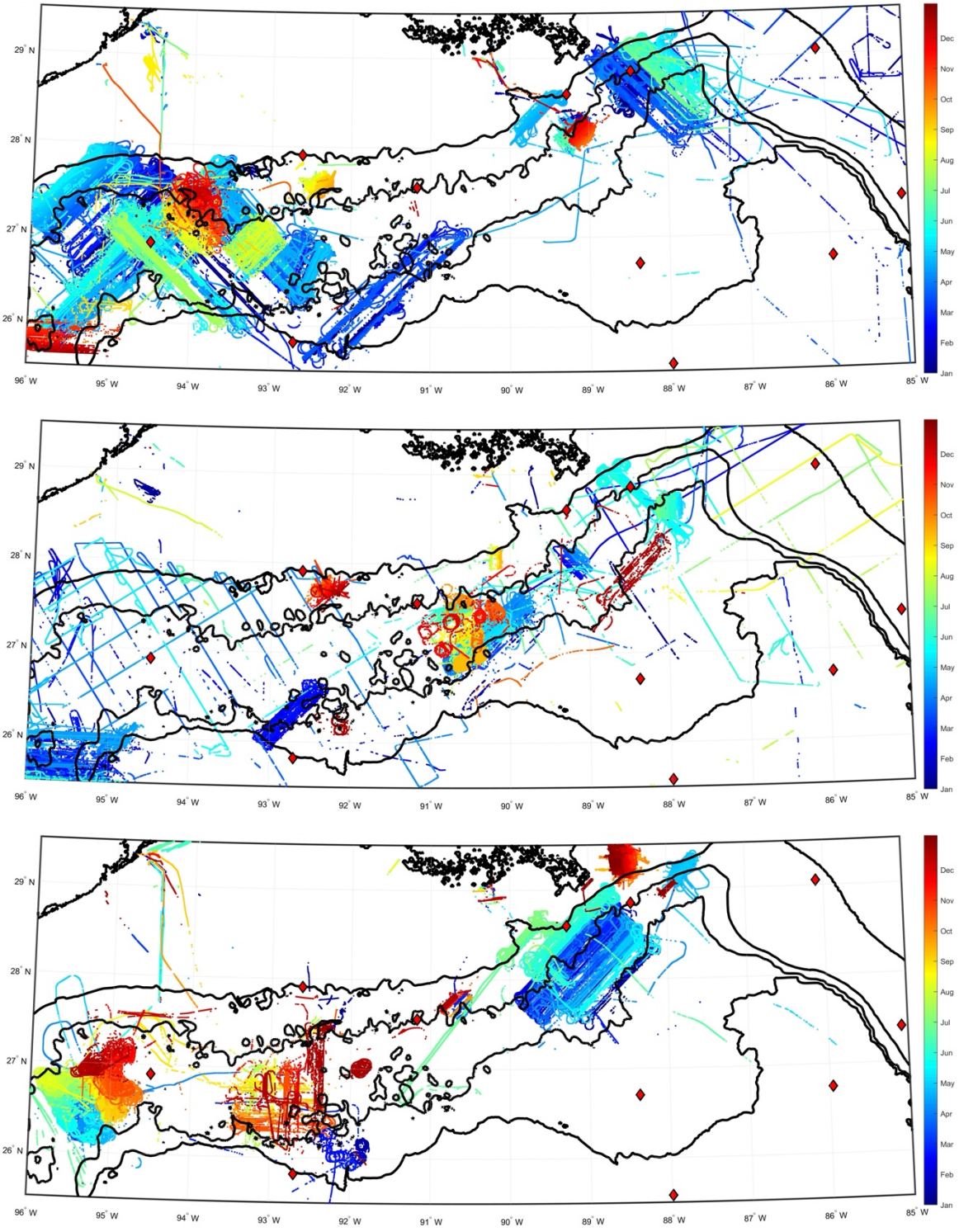
Snyder, M. A., & Orlin, P. A. (2007, September). Ambient noise classification in the Gulf of Mexico. In *OCEANS 2007* (pp. 1-10). IEEE.

Tashmukhambetov, A. M., Ioup, G. E., Ioup, J. W., Sidorovskaia, N. A., & Newcomb, J. J. (2008). Three-dimensional seismic array characterization study: Experiment and modeling. *The Journal of the Acoustical Society of America*, 123(6), 4094-4108.

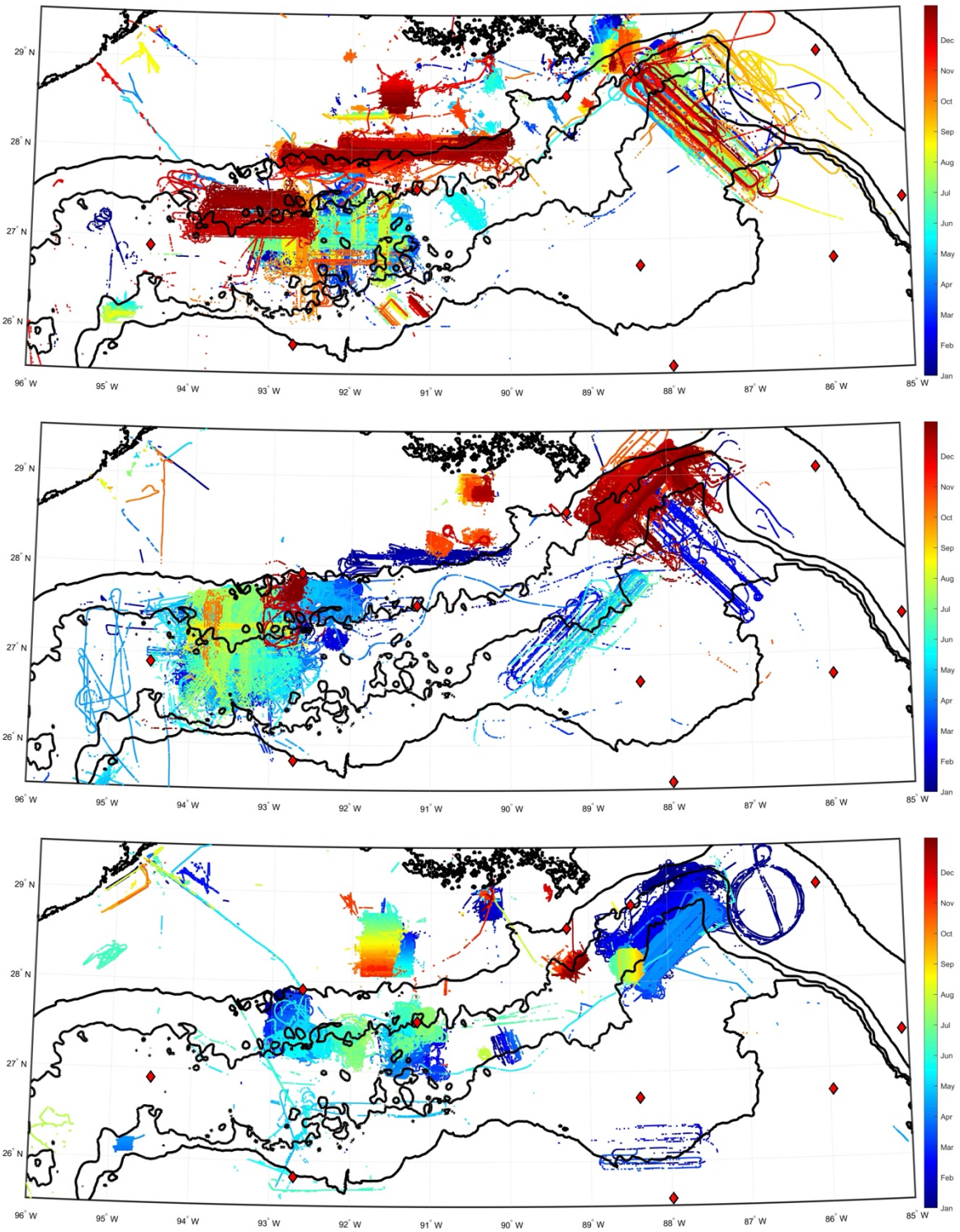
Udengaard, C., Brookes, D., Flores, H., & Rocke, M. (2024). An enhanced frequency source for modern marine seismic surveys. In 85th EAGE Annual Conference & Exhibition (Vol. 2024, No. 1, pp. 1-5). European Association of Geoscientists & Engineers.

Wiggins, S. M., Hall, J. M., Thayre, B. J., & Hildebrand, J. A. (2016). Gulf of Mexico low-frequency ocean soundscape impacted by airguns. The Journal of the Acoustical Society of America, 140(1), 176-183.

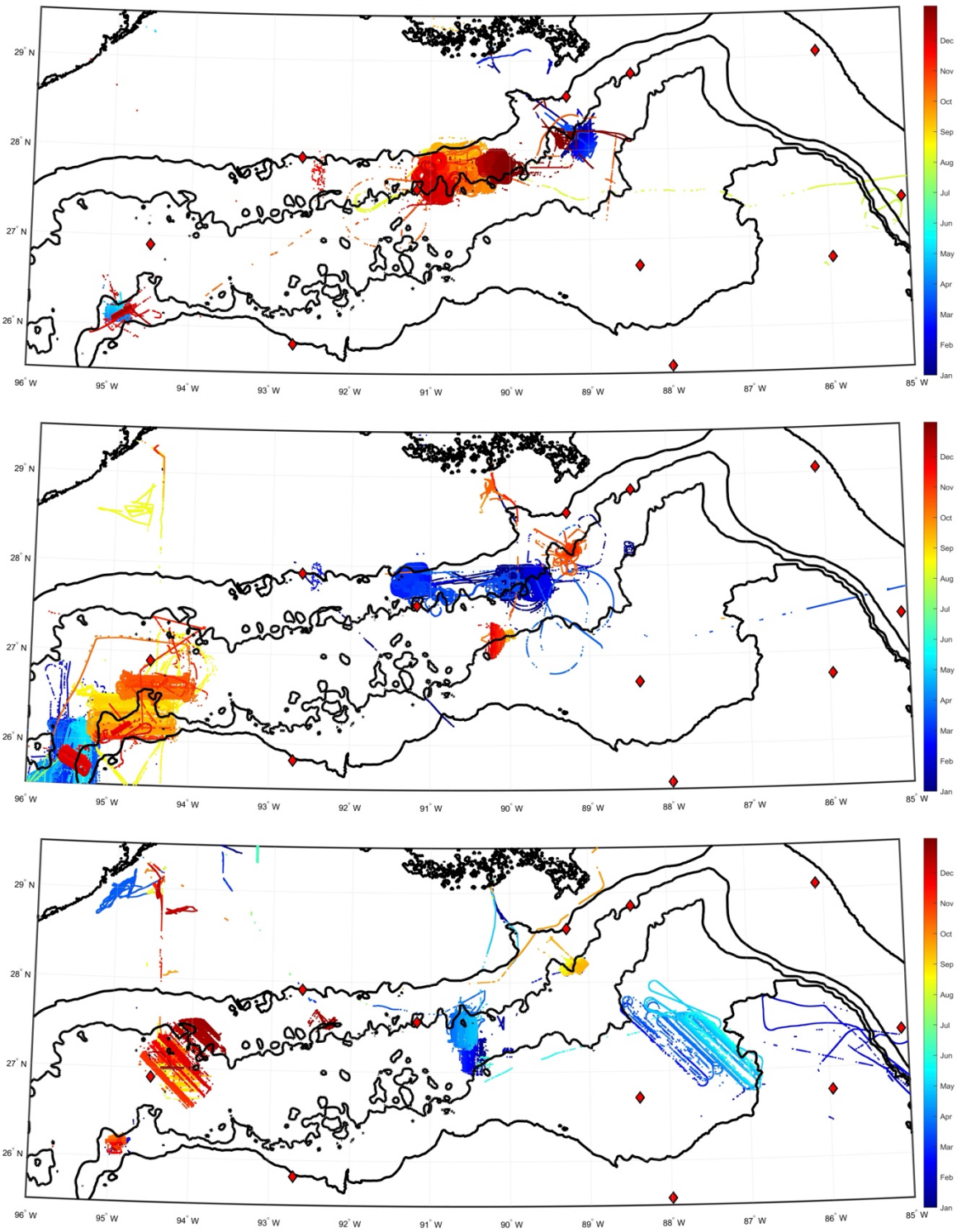
Supplementary Figures



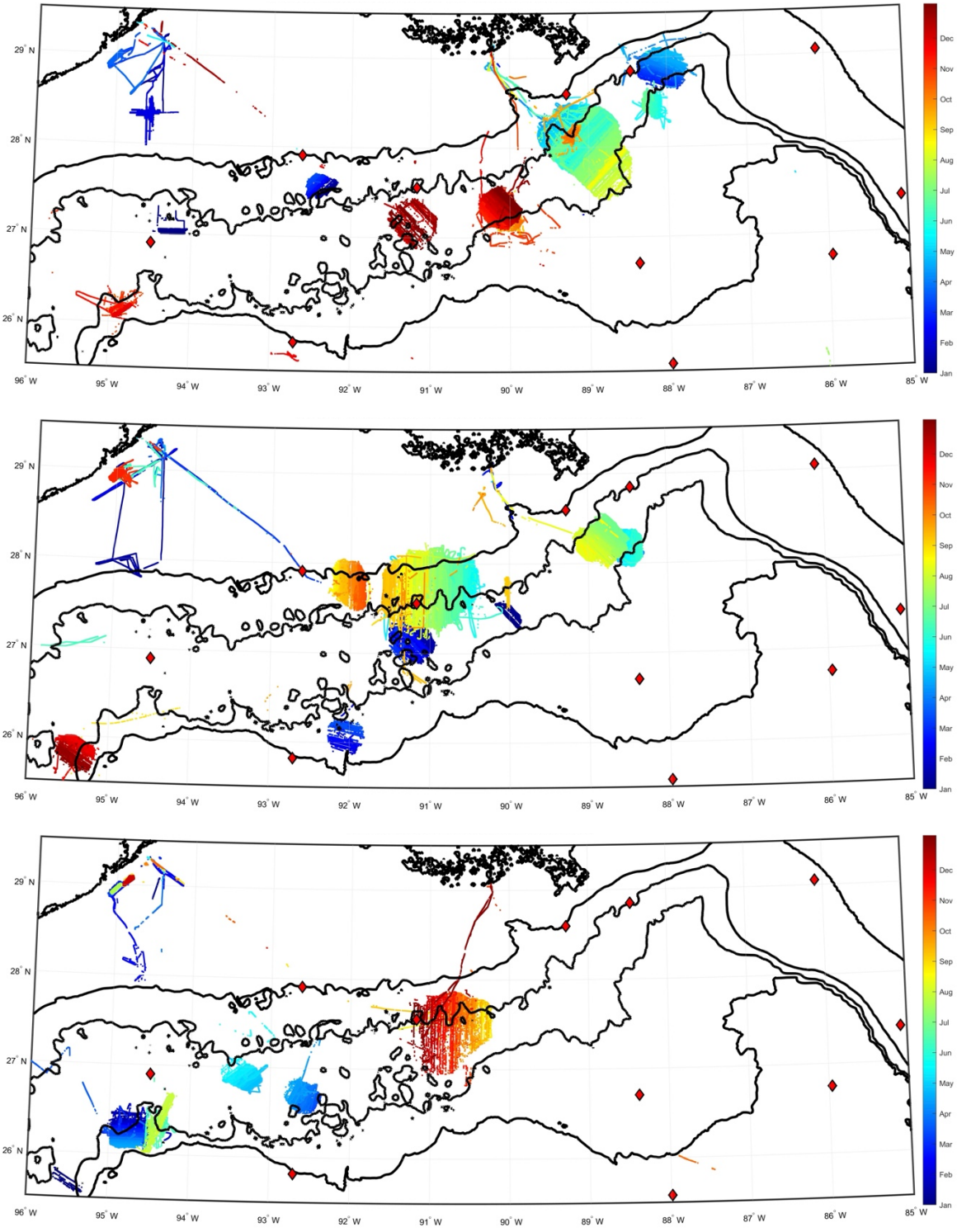
Supplementary Figure 1. Seismic survey vessel AIS positions, filtered by known survey vessel MMSIs - 2010-2012. Top to bottom: 2010, 2011, 2012. Color represents month of the year.



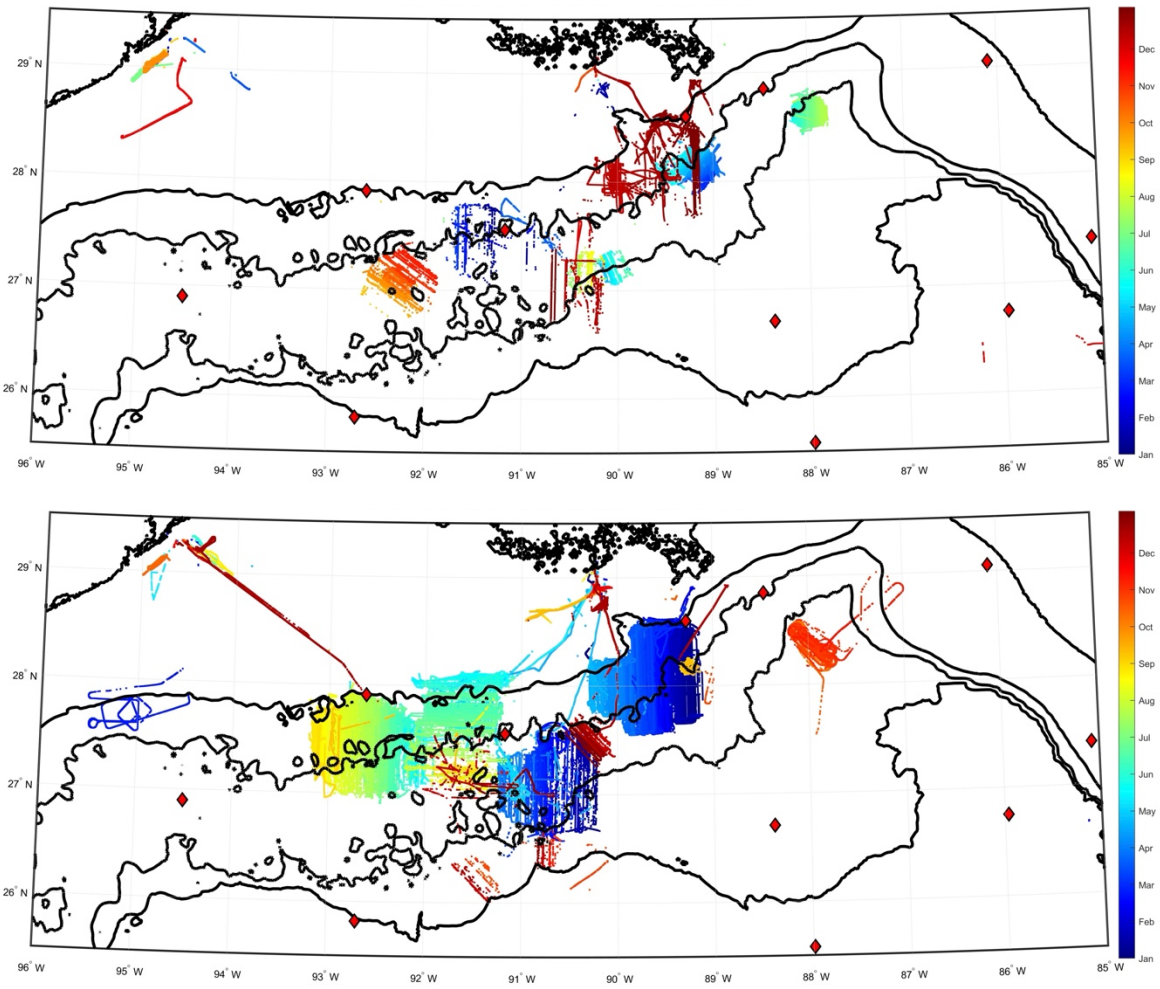
Supplementary Figure 2. Seismic survey vessel AIS positions, filtered by known survey vessel MMSIs - 2013-2015. Top to bottom: 2013, 2014, 2015. Color represents month of the year.



Supplementary Figure 3. Seismic survey vessel AIS positions, filtered by known survey vessel MMSIs - 2016-2018. Top to bottom: 2016, 2017, 2018. Color represents month of the year.



Supplementary Figure 4. Seismic survey vessel AIS positions, filtered by known survey vessel MMSIs - 2019-2021. Top to bottom: 2019, 2020, 2021. Color represents month of the year.



Supplementary Figure 5. Seismic survey vessel AIS positions, filtered by known survey vessel MMSIs - 2022-2023. Top to bottom: 2022, 2023. Color represents month of the year.