Gulf of Mexico low-frequency ocean soundscape impacted by airguns

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(Received 12 February 2016; revised 6 June 2016; accepted 20 June 2016; published online 12 July 2016)

The ocean soundscape of the Gulf of Mexico (GOM) has not been well-studied, although it is an important habitat for marine mammals, including sperm and beaked whales, many dolphin species, and a potentially endangered baleen whale species. The GOM is also home to high levels of hydrocarbon exploration and extraction, heavily used commercial shipping ports, and significant fishery industry activity, all of which are known contributors to oceanic noise. From 2010–2013, the soundscape of three deep and two shallow water sites in the GOM were monitored over 10 – 1000 Hz. Average sound pressure spectrum levels were high, >90 dB re 1 μPa^2/Hz at <40 Hz for the deep water sites and were associated with noise from seismic exploration airguns. More moderate sound pressure levels, <55 dB re 1 μPa^2/Hz at >700 Hz, were present at a shallow water site in the northeastern Gulf, removed from the zone of industrial development and bathymetrically shielded from deep water anthropogenic sound sources. During passage of a high wind event (Hurricane Isaac, 2012), sound pressure levels above 200 Hz increased with wind speed, but at low frequencies (<100 Hz) sound pressure levels decreased owing to absence of noise from airguns.

[http://dx.doi.org/10.1121/1.4955300]

[JAC] Pages: 176–183

I. INTRODUCTION

Ocean soundscapes have both anthropogenic and natural sources, and often vary across frequencies, locations, and time-periods (Hildebrand 2009). At low frequencies (i.e., 10–1000 Hz), ship propulsion, seismic exploration, whale calls, and wind are all common sound sources, but with different levels of occurrence and intensity depending on measurement location and period. For example, at a deep-water site in the northeastern Pacific it was shown that sound pressure spectrum levels at 40 Hz have increased about 3 dB per decade over the last 40 yr, attributed primarily to an increase in commercial shipping and to the site's deep-water exposure to the Pacific Ocean basin (McDonald *et al.*, 2006). Conversely, at a nearby shallow-water site shielded from deep ocean noise, 40 Hz sound pressure levels remained relatively constant over the past 50 yr and were lower by ~20 dB (McDonald *et al.*, 2008).

The ocean soundscape has been studied offshore of the U.S. in the Pacific and Atlantic Oceans, showing that the highest sound pressure levels are usually in the 10–100 Hz band, and are typically dominated by commercial shipping (Wenz, 1962); although in some regions, seismic exploration also makes significant contributions to this band (Nieukirk *et al.*, 2004; Roth *et al.*, 2012). At frequencies from ~200 Hz to 20 kHz, wind agitates the sea surface and is correlated with ambient noise levels (Knudsen *et al.*, 1948). While these general relationships also hold for the soundscape in the Gulf of Mexico (GOM), few measurements have been reported for this important ocean basin.

During 2004–2005 in the GOM, Snyder (2007) recorded ambient noise in the 10–1000 Hz band for over 1 yr at a site approximately 300 km south of Panama City, FL at about 3000 m depth, near local shipping lanes. Spectrum levels were computed in 1/3-octave bands from calibrated hydrophones. Mean sound pressure spectrum levels were approximately 90 dB re 1 μPa^2/Hz at 25–50 Hz, ~80 dB re 1 μPa^2/Hz at 100 Hz sloping down to about 60 dB re 1 μPa^2/Hz near 1000 Hz with highest variability at 25 Hz and at frequencies above ~200 Hz. At the lowest frequencies, these high levels are similar to sites with exposure to heavy commercial shipping, both distant and local (Andrew *et al.*, 2002; Chapman and Price, 2011), and at the higher frequencies variability was associated with local wind. Also, for approximately 1 month in 2001 in the northern GOM, Newcomb *et al.* (2002) recorded similar sound pressure spectrum levels using similar equipment to Snyder (2007), although at shallower depths on the continental slope at 600–1000 m. Their results

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included sound pressure spectrum levels from periods before, during, and after the passage of tropical storm Barry, which showed variability associated with wind and sea state at frequencies above 200 Hz, and ships and seismic exploration below 100 Hz. While these studies are important as apparently the only ones for documenting ambient noise sound levels in the GOM, measurements from other locations throughout the Gulf are needed for comparison and to provide a more complete picture of the GOM soundscape.

Starting in 2010, in response to the Deepwater Horizon oil spill, autonomous acoustic recorders were deployed at five sites around the northern and eastern GOM: three in deep water (∼1000 m) and two in shallow water (∼100–250 m). In this study, we compare low-frequency (10–1000 Hz) sound pressure spectrum levels from over 3 yr of recordings and show site-specific differences in levels and spectrum shape along with similarities within each of the two site types: shallow and deep. Also, wind is shown to be well-correlated to sound pressure levels at the higher end of our bandwidth, including the passage of a hurricane. Airguns are a constant source of noise in the GOM, and during the hurricane passage, low frequency sound pressure levels actually decreased owing to the absence of seismic airgun activity.

II. METHODS

During 2010–2013, five high-frequency acoustic recording packages (HARPs) sampling at 200 kHz continuously were deployed for 2–9 months per deployment in the GOM at sites with names based on the Bureau of Ocean Energy Management (BOEM) lease blocks in which the sites were located: Green Canyon (GC), Mississippi Canyon (MC), Main Pass (MP), DeSoto Canyon (DC), and Dry Tortugas (DT) (Fig. 1; Table I). Sites GC, MC, and DT were deep water sites at 1100, 980, and 1300 m depths, respectively; and MP and DC were shallow water sites at 90 and 260 m depths, respectively.

HARPs are seafloor-mounted, long-term autonomous acoustic recorders consisting of a hydrophone tethered above

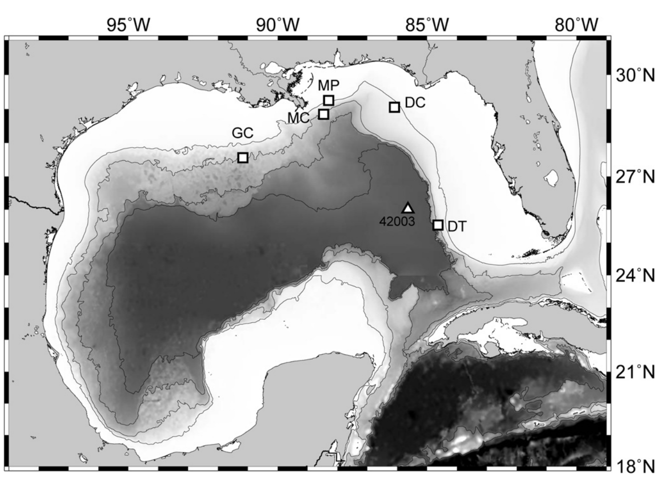

FIG. 1. HARP locations (see Table I) shown as squares with site names. NOAA NDBC weather buoy station 42003 shown as triangle northwest of site DT. GOM bathymetric map with contours at 100, 1000, 2000, and 3000 m depth.

TABLE I. HARP deployment location, depth and number of full days used for sound pressure spectral averages.

Site	Latitude (N)	Longitude (W)	Depth (m)	Full days[a]
GC	27° 33.4′	91° 10.0′	1100	1011
MC	28° 50.8′	88° 27.9′	980	1075
MP	29° 15.3′	88° 17.8′	90	957
DC	29° 03.2′	86° 05.8′	260	818
DT	25° 31.9′	84° 38.2′	1300	786

[a]Number of complete recording days between May 2010 and October 2013.

a data logger, batteries, flotation, acoustic release, and ballast weight (Wiggins and Hildebrand, 2007). The frequency response of each hydrophone electronics circuit board was measured at Scripps Institution of Oceanography, and select hydrophone/data logger pairs were full-system calibrated at the U.S. Navy's Transducer Evaluation Center in San Diego, CA. The hydrophones were composed of two channels, one for low-frequency (<2 kHz) and the other for high-frequency (>2 kHz), although we focus on only the low-frequency band for this paper. Six Benthos AQ-1 lead-zirconium-titanate (PZT) ceramic hydrophone elements (www.teledynebenthos.com) were used for the low-frequency channel of each hydrophone. Typical hydrophone sensitivity was measured to be −188 dB re V/μPa with a single pole high-pass filter corner frequency around 20 Hz. A 34 dB gain preamp and a four-pole low-pass filter with a corner frequency around 2 kHz were added for signal conditioning. These calibrations were used to convert all recordings to sound pressure levels. Signal clipping level was around 160 $\mathrm{dB_{pp}}$ re 1 $\mu\mathrm{Pa}^2$ and the noise floor was approximately 54 dB re 1 $\mu\mathrm{Pa}^2$/Hz at 10 Hz and 27 dB re 1 $\mu\mathrm{Pa}^2$/Hz at 1000 Hz.

Acoustic data were recorded in a standard wav audio format and were processed and analyzed with *Triton*, a MATLAB-based (www.mathworks.com) software package for large acoustic data sets (Wiggins and Hildebrand, 2007). Because the recordings were sampled at 200 000 samples s^{-1}, the waveforms were decimated by a factor of 100 to provide compact files for ease of processing and an effective sample rate of 2 kHz. Consecutive, 5 s waveforms were transformed into sequential sound pressure spectral density estimates with 1 Hz bins using the Welch method (Welch, 1967). During recording sessions, HARPs write sequential 75 s acoustic records to standard laptop-style computer hard disk drives such that there were 15, 5 s spectra for each 75 s acoustic record. However, system self-noise can be present when the HARP is writing to disk (12 s out of each 75 s record), so the first three 5 s spectra were not used for averaging. Averages were computed per day, with partial days and days with deployment/recovery ships sounds or with known instrument self-noise problems discarded. The sequential 5 s spectra were further analyzed with custom MATLAB-based software to provide average and percentile sound pressure spectrum levels for the five sites over the study period in addition to long-term spectrograms and sound pressure level time series for specific frequency bands.

One-hour averaged wind speeds were obtained from the National Oceanic and Atmospheric Administration (NOAA)

National Data Buoy Center (NDBC) for station 42003 (26.007′N 85.648′W), located ∼115 km northwest of site DT (Fig. 1) with anemometer height at 5 m above sea level (http://www.ndbc.noaa.gov/station_page.php?station=42003). Corresponding 1 h averaged sound pressure levels were calculated with recordings from site DT at 40 and 900 Hz for wind speed comparison over 5 days in August 2012 when tropical storm/hurricane Isaac was present, and additional averaging over 1 day was computed to compare wind speeds to sound levels over a 1 yr period from 1 August 2012 through 31 July 2013. Tropical storm and hurricane positions and wind speeds were provided by NOAA's National Climate Data Center (NCDC) International Best Tracks Archive for Climate Stewardship (IBTrACS) (Knapp *et al.*, 2010).

Daily averaged sound pressure levels at 40 Hz over the deployment period were used to compare the temporal variability of airgun activity at and between the five sites. Example time series waveforms and spectrograms for two periods at site GC, one with low and one with high sound pressure levels, show how these sound levels relate to individual airgun pulses.

III. RESULTS

Between 786 and 1075 daily averaged sound pressure spectrum levels were used to compute long-term spectrograms over the deployment period for each of the five sites (Table I and Fig. 2). Each site has unique sound pressure spectrum characteristics with varying intensities in different frequency bands and over various time intervals. For example, at frequencies below 100 Hz, site DT shows a relatively smooth decrease and then increase in levels over the whole deployment period compared to site MP where sound pressure levels increase and decrease over a greater range and over shorter periods of about one week or less. The vertical striations shown in all of the long-term spectrograms are caused by discrete events, such as wind and storms for frequencies above 200 Hz and airgun surveys for lower frequencies.

Average deployment period sound pressure spectrum levels (Fig. 3) show similar spectral shapes for the deep water sites (GC, MC, and DT) over the entire band. The two shallow water sites (MP and DC) likewise share similar spectral levels below 30 Hz but diverge at higher frequencies. In general, the deep water sites had higher levels than the shallow water sites below 100 Hz (Figs. 2 and 3). All sites have high average levels >90 dB re 1 μPa^2/Hz at 10 Hz; and at 100 Hz, sound pressure spectrum levels are around 80 dB re 1 μPa^2/Hz for all sites except DC which is at 64 dB re 1 μPa^2/Hz. Also, the levels at the other shallow site, MP, are 5–10 dB less than the deep water sites from 20 to 60 Hz and the spectrum is concaved upward; whereas, the deep water sites are convex over the same band.

At frequencies above 100 Hz, deep water sites GC and MC are similar, and they include tonal signals around 150, 175, 200, 550, and 675 Hz, but the other deep water site, DT, only shows a strong tone at ∼175 Hz and weaker tones around 150 and 200 Hz (Fig. 3). Neither of the shallow water sites have these distinct tones, but MP shows weak tonal structure from about 60–200 Hz. Above 300 Hz, MP has the highest sound pressure spectrum levels; whereas, the other shallow water site, DC, has the lowest levels above 30 Hz.

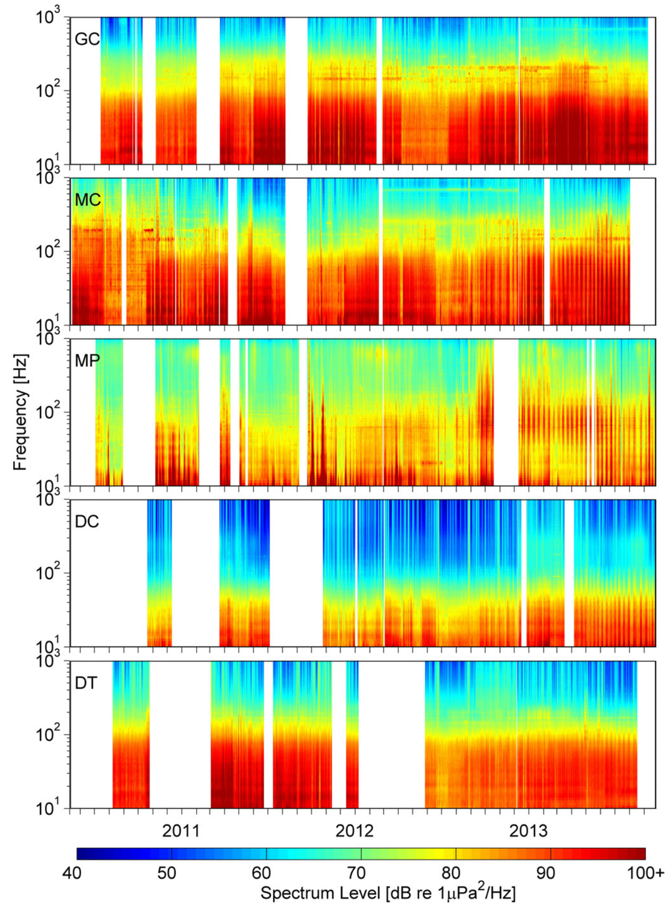

FIG. 2. (Color online) Long-term spectrograms using daily average sound pressure spectrum levels for each site over the deployment period. White regions are gaps between the end of one recording cycle and the start of the next, or due to instrument problems. Time ticks are the beginning of each month with January ticks between "0" and "1" above year label.

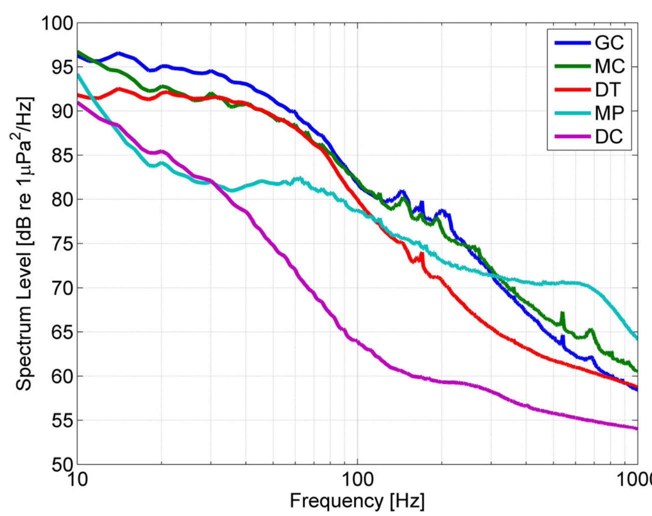

FIG. 3. (Color online) Average sound pressure spectrum levels by site over entire deployment period. See Table I for total number of days used for each average.

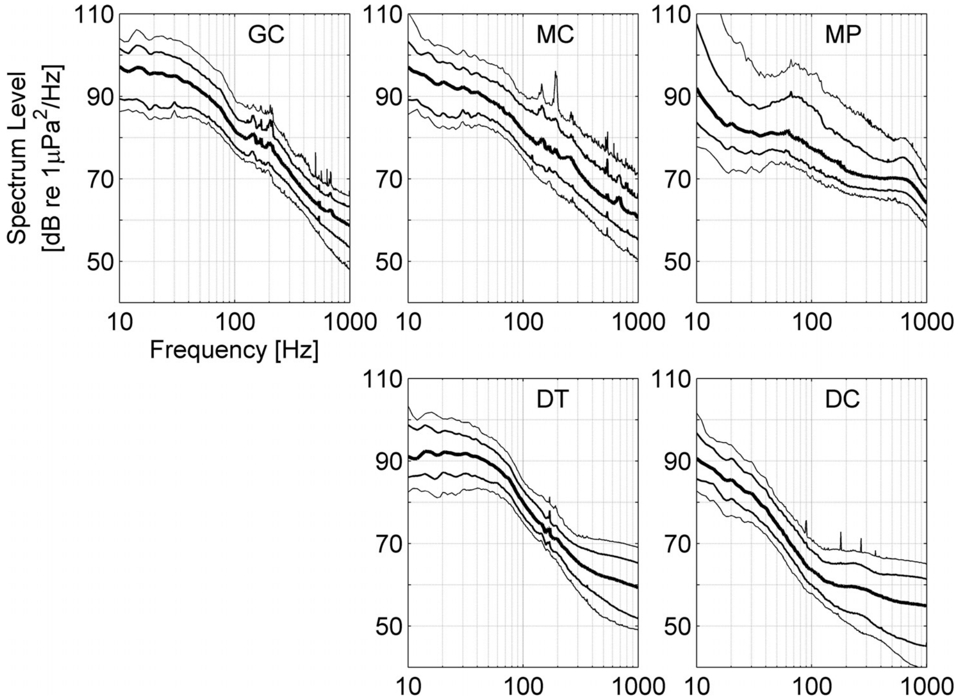

FIG. 4. Distribution of daily average sound pressure spectrum levels as percentiles: 1 (lowest), 10, 50 (thick middle line), 90, and 99% (highest).

Percentile plots for each site over the deployment period show sound pressure spectrum levels that are approximately normally distributed, except for the shallow water site MP which is long-tailed at higher levels (Fig. 4). Both shallow water sites, MP and DC, show the greatest variability between the 1st and 99th percentiles, with 20–40 dB for MP below 100 Hz and over 20 dB for DC above 200 Hz.

One year of daily averages of wind speed from NDBC station 42003 and 900 Hz sound pressure levels from site DT are well correlated (Pearson correlation 0.78, null hypothesis $p = 1 \times 10^{-75}$) with corresponding peaks and troughs, including similar rates of change (Fig. 5). The highest daily average wind speed and sound pressure level measured for the August 2012–July 2013 period occurred in late August and corresponded to the tropical storm and hurricane Isaac which traveled northwest across the GOM from DT to Louisiana (Fig. 6). Also, in early June, tropical storm Andrea traveling from the deep water Gulf northeast over DC corresponded to elevated wind speed and sound pressure levels.

Beginning at 0000 on 27 August 2012, southeast of site DT, tropical storm Isaac's wind speeds were measured to be about 50 kts per IBTrACS (Knapp *et al.*, 2010) and traveling northwest increased to 55 kts at 1200 h above site DT (Fig. 6). About 6 h later wind speeds had reached 60 kts near NDBC station 42003. Isaac continued northwest with increasing wind speeds to 65 kts, becoming a category 1 hurricane at 1200 h on 28 August. Six hours later, Isaac wind speeds reached 70 kts for about 12 h while passing site MC before reaching Louisiana and reduced wind speeds back to tropical storm status as it continued to head northwest over land.

As with the yearlong comparison of wind speed and sound pressure levels for station 42003 and site DT (Fig. 5), hourly averaged wind speed and sound pressure levels at 900 Hz for the 5 days surrounding Isaac's passage show the highest positive correlation with a time lag of 4 h (Pearson correlation 0.72, null hypothesis $p = 1 \times 10^{-20}$), although Isaac took 6 h to travel from DT to station 42003 and the

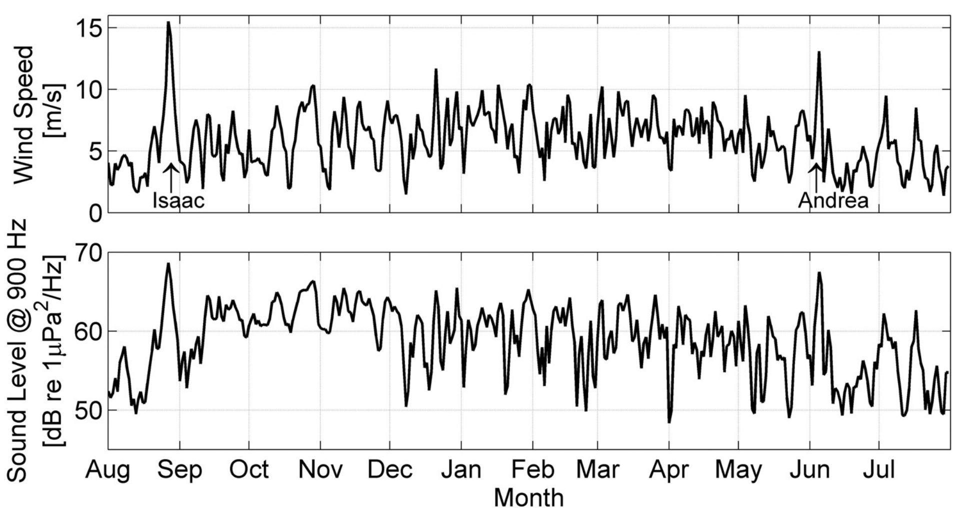

FIG. 5. One year of daily average wind speed from NOAA NDBC station 42003 (top panel) and sound pressure level at 900 Hz for site DT (bottom panel) between 1 August 2012 and 31 July 2013. Peaks, troughs, and rate of change of both measurements are well correlated (Pearson correlation 0.78). Hurricane Isaac appears as the peak at end of August and tropical storm Andrea as the peak in early June.

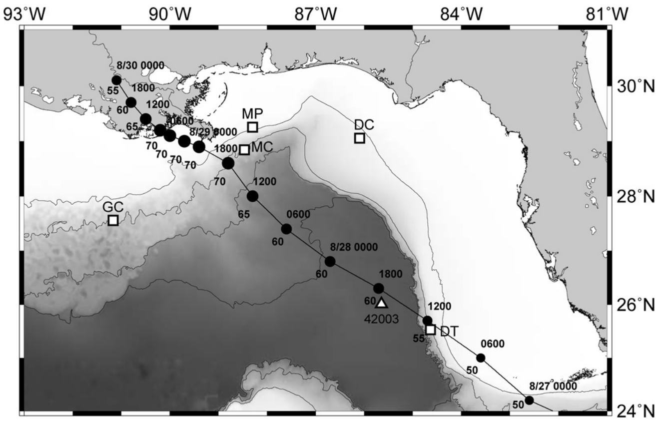

FIG. 6. Tropical storm and hurricane Isaac's track northwest through the GOM 27–30 August 2012 with times (GMT) and wind speed (kts) next to locations (black circles, diameters relative to wind speed). HARP site locations (squares) and weather buoy station (triangle) are also shown.

time difference between the two time series main peaks and following troughs (i.e., eye of the storm) was about 6 h (Figs. 6 and 7). Also, the shape of the wind speed and 900 Hz sound pressure level time series are different around their respective lows. The 900 Hz sound pressure levels peak sharply before the wide low trough and are lower after the trough; whereas, the wind speed is about the same after the low trough as before, and continues to increase for a few more hours. Furthermore, the sound pressure levels at 40 Hz (Fig. 7, third panel) are not correlated with the wind speed, 900 Hz sound levels, nor the storm directly; although, the 40 Hz low (81 dB re 1 μPa^2) ~1200 on 28 August was when Isaac was about 6 h from passing site MC, during a period when airgun actively was non-existent at all sites (Fig. 7, bottom panel). Also, discrete periods of high sound pressure levels from airgun activity lasting ~12 h followed by a few hours with lower levels before increasing again are apparent at and in the band around 40 Hz (Fig. 7).

Daily sound pressure levels at 40 Hz over the deployment period show long-term and short-term variability at and between the five sites (Figs. 2 and 8). As with the average deployment period sound pressure spectrum (Fig. 3), the three deep water sites (GC, MC, and DT) show the highest sound pressure levels at 40 Hz, but all sites show a minimum in the middle of 2012 with increasing levels thereafter until the end of the recordings. Sites MC and MP show a similar pattern over the deployment due to their close proximity to each other, although daily 40 Hz sound pressure levels at MP were about 10 dB lower than at MC. The highest sound pressure levels at each site were investigated and were found to be from intense airgun activity for all sites except MP whose levels above 90 dB re 1 μPa^2 were found to be from mooring strum caused by ocean currents and tides at this shallow water (~90 m) site.

Example 1-min time series and spectrograms from periods of 40 Hz low sound pressure levels (86 dB re 1 μPa^2, 4 June 2012) and high sound pressure levels (103 dB re 1 μPa^2, 23 March 2013) from site GC show how the different intensity and number of airgun pulses were related to the daily averages (Figs. 8 and 9). The low sound pressure level recording shows distant low frequency airgun pulses every 15 s; whereas, the high sound pressure level recording is more complex with higher frequency (150 – 250 Hz) short pulses every 10 s, and close (intense) and distant (moderate) low frequency long pulses every 20 or 30 s.

IV. DISCUSSION

Deployment average sound pressure spectrum levels were found to vary between sites across frequency, but site similarities also were observed. The deep water sites were

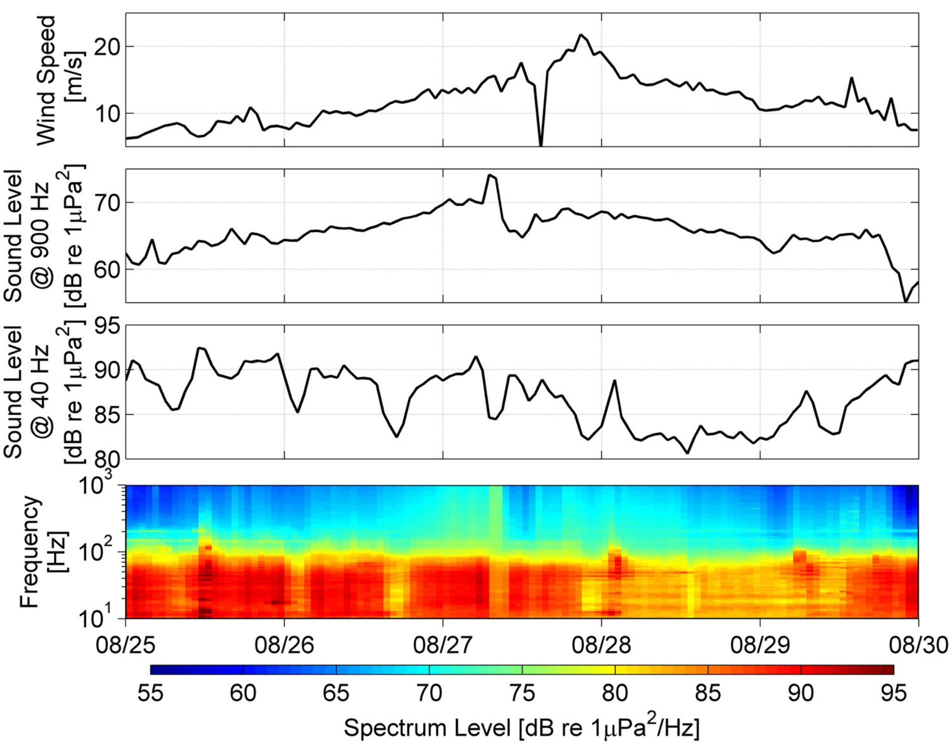

FIG. 7. (Color online) Hourly average wind speed from NOAA NDBC station 42003 (top panel), sound pressure level at 900 Hz (second panel), sound pressure level at 40 Hz (third panel), and spectrogram using 1 h average sound pressure spectrum levels (bottom panel) for site DT during period of tropical storm and hurricane Isaac passage 25–30 August 2012. The storm has ~6 h time lag between site DT and station 42003. The "eye" of the storm is clearly shown as a low in both wind speed and 900 Hz sound pressure levels. The 40 Hz sound pressure levels are largely uncorrelated with the storm, but show over 10 dB of variability in airgun activity over the 5 d.

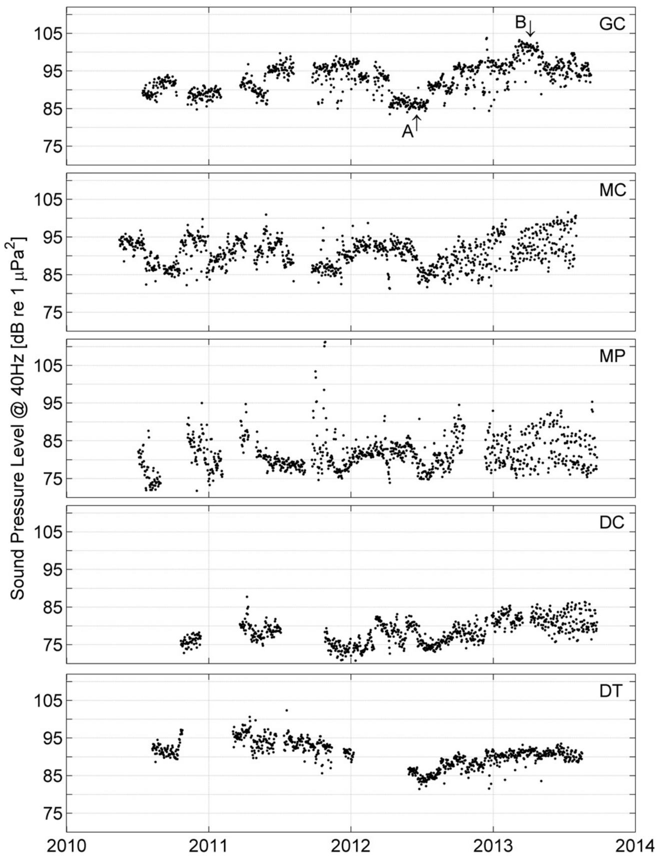

FIG. 8. Daily averaged sound pressure levels at 40 Hz by site (designated in the right-hand upper corner of each panel) over the deployment period. A and B arrows in the top panel (site GC) indicate periods used in Fig. 9 as examples of low (86 dB re 1 μPa^2) and high (103 dB re 1 μPa^2) daily sound pressure levels of airguns, respectively.

most similar with the highest sound pressure levels below 100 Hz. Levels at site DT were similar to a deep water site to the northwest described by Snyder (2007) with 1/3-octave levels from 2005 within 1–2 dB those measured at DT, suggesting minimal change in the eastern deep water GOM ambient soundscape over the 6–8 yr between measurements.

The GOM low frequency deep water ambient noise levels reported here are among the highest measured averages over long periods (Dahl *et al.*, 2007). Below 100 Hz in most regions of the world's oceans, sound pressure levels are dominated by surface ship noise, and deep water sites are well-suited to receive distant ship sounds because of favorable sound propagation conditions, such as low frequency low attenuation and down-slope conversion to the deep sound channel (Ross, 1976). Furthermore, 10 of the top 13 highest ranked U.S. ports for total handled tonnage are on the Gulf Coast, with the majority of the cargo transported via bulk carriers (Strocko *et al.*, 2014). While bulk carriers travel at slower speeds than container and vehicle carriers, their source levels are similar suggesting an overall larger impact on the regional soundscape since the bulk carrier sound levels will remain high for longer periods effectively resulting in higher sound exposure levels (SEL) for a given area (McKenna *et al.*, 2012).

Even though ship traffic is high in the GOM and contributes to the soundscape, airgun pulses from seismic exploration are the dominate source of low frequency, high sound levels in the deep water Gulf (Fig. 9). Nearby ship sounds were observed in the acoustic records, but typically their passages were shorter ($\sim$1 h) than airgun surveys ($>$12 h) and were masked by the airgun sounds at frequencies below 100 Hz. Airgun pulses were observed on the three deep water site recordings on almost every day recorded. Much of the seismic activity appeared distant as a constant band of elevated energy around 10–100 Hz. Moderate received level pulses $\sim$135 dB$_{pp}$ re 1 μPa^2 occurred frequently with energy extending up to 200–300 Hz; whereas, other more intense pulses approached the recording system's clip level at 160 dB$_{pp}$ re 1 μPa^2 and had elevated sound levels up to 1000 Hz. Airgun arrays source levels are as high as 250 – 260 dB$_{pp}$ re 1 μPa^2 at 1 m and are typically fired every 10 to 20 s (Hildebrand, 2009), suggesting that the surveys with high received levels are within $\sim$100 km of the sensor, assuming approximately spherical spreading transmission loss {i.e., 20*log10(Range [meters])}. Low to moderate level surveys are farther away, with the deep sound channel allowing less transmission loss than spherical spreading (Urick, 1983), although whether the survey is conducted in deep water or in shallow water on the continental shelf will also affect its received level owing to differing interaction with the sea bottom. When Hurricane Isaac transited through the GOM in late August, 2012 causing cessation of airgun operations, low frequency sound pressure levels dropped at the deep water sites by over 10 to $\sim$81 dB re 1 μPa^2 at 40 Hz, below their long-term one percentile level (Figs. 4 and 7). A similar trend was observed in a separate study in 2001 when sound pressure spectrum levels $\sim$40 Hz decreased during the passage of tropical storm Barry and rebounded one week later presumably caused by changes in shipping and seismic exploration during and after the storm (Newcomb *et al.*, 2002).

Also common at the deep water sites were tones in the 100 – 200 Hz band. The tones varied in intensity, frequency, and bandwidth over time and were weakest at DT. The origin of these tones is unknown, but they may be related to petroleum extraction or exploration in the GOM. The tones are not likely from ship propulsion because they often last much longer ($\sim$12 h) than transiting ships ($\sim$1 h) and the tones are typically without the blade-rate tonals and spectral-temporal interference patterns that are usually observed from nearby ships (Fig. 2).

The shape of the sound pressure spectrum levels for the two shallow water sites (MP and DC) were much different than the deep water sites, and they were only similar to each other below 30 Hz. Above 100 Hz, levels at site MP were up to 15 dB higher than site DC. MP was the shallowest (90 m) site and was expected to have slightly higher sound pressure levels than DC the deeper (260 m) site because of higher tidal flow noise. However, the primary difference between these sites was their proximity to local anthropogenic activity. The area around MP is a region heavily used by the petroleum and fishery industries with a high level of local vessel noise and many nearby ports in support of these activities; whereas, DC is not near the focus of these activities.

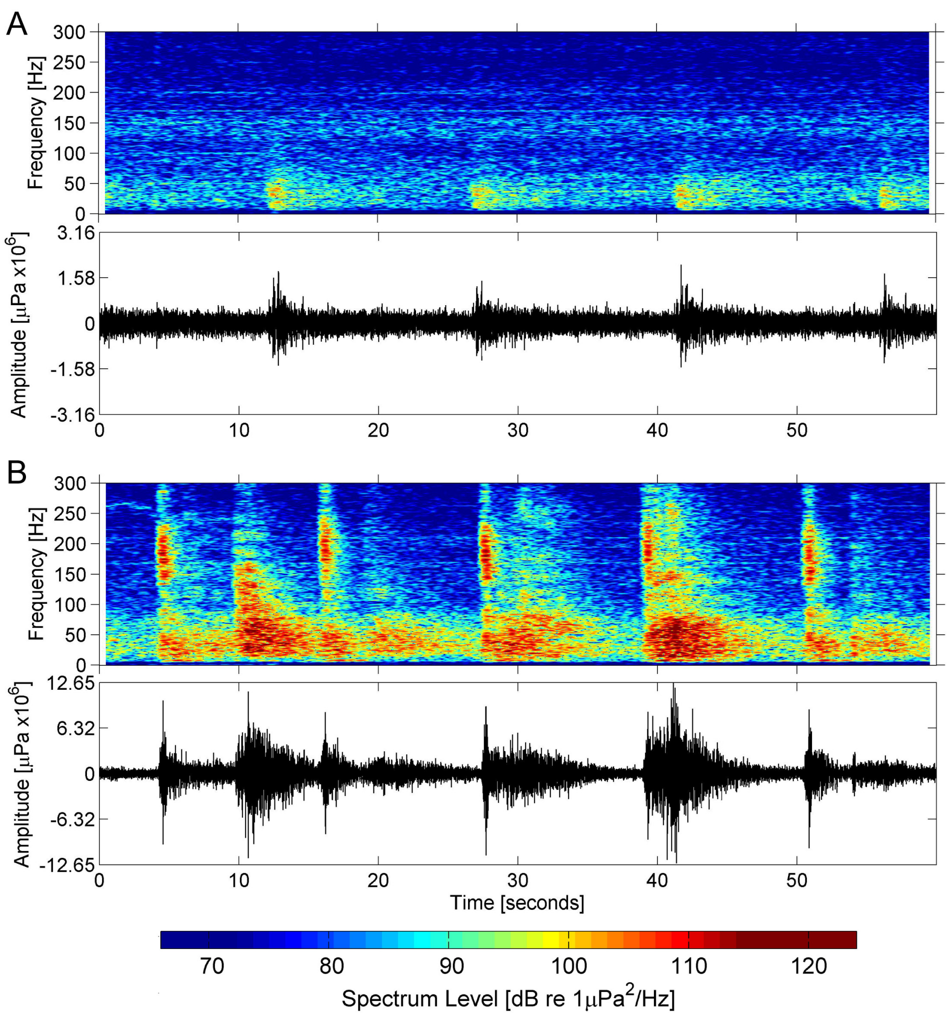

FIG. 9. (Color online) Airgun pulses in 1-min spectrogram (upper panel) and time series (lower panel) from site GC for 40 Hz at (A) low sound pressure levels on 4 June 2012 and (B) high sound pressure levels on 23 March 2013 (see Fig. 8, top panel). Spectrograms are 2000 samples (1 Hz bins) with 95% overlap and use the same sound pressure spectrum level color mapping. Note, time series amplitudes in (B) are four times (12 dB) greater than in (A).

At both the eastern sites, DC and DT, the variability in sound spectrum levels increased at frequencies above 100 Hz (Fig. 4) and were correlated with varying wind speeds. Both sites are distant from anthropogenic activity as found in the north-central Gulf, resulting in lower sound levels at 200–1000 Hz. The shallower site DC had the greatest variability (>25 dB at 1000 Hz) owing to its proximity to wind-generated sea surface noise.

Wind speeds from tropical storm and hurricane Isaac were correlated with sound pressure levels at 900 Hz from site DT (Fig. 7), suggesting passive acoustic techniques as another method for studying extreme weather events (e.g., Traer *et al.*, 2008). A symmetric peak-trough-peak pattern was observed with wind speed, but the 900 Hz sound pressure levels were asymmetric with a high narrow peak followed by a wide trough and moderate peak 5 dB less than the initial peak. This asymmetry may be a result of the storm's wind direction as it passes the hydrophone. As the counter-clockwise rotating storm approaches site DT, the winds are blowing east-to-west which constructively built up breaking sea surface waves in that direction. After the storm passed the hydrophone, the wind direction was west-to-east and in opposite direction of the previously built up seas which reduced the breaking sea surface waves and lowered sound pressure levels.

V. CONCLUSIONS

Multi-year passive acoustic monitoring in the GOM showed high average sound pressure spectrum levels (90–95 dB re 1 μPa^2) for deep (~1000 m) water sites below 50 Hz, caused by a high density of seismic exploration and shipping in the GOM. Two shallow water sites, one on the shelf and the other on the shelf break, show much different sound pressure spectrum levels compared to the deep water sites and compared to each other, primarily a function of proximity to anthropogenic activity.

Sound pressure levels at 900 Hz were well correlated with local wind speeds including a hurricane event. The two eastern Gulf sites showed high sound pressure spectrum level variability above 200 Hz associated with wind events in contrast to the three north-central Gulf sites which have higher local anthropogenic activity.

ACKNOWLEDGMENTS

We thank S. Murawski and S. Gilbert of USF and L. Garrison, K. Mullin, and M. Soldevilla of the SEFSC for project assistance. We thank LUMCON and the crew of the R/V Pelican, as well as I. Kerr and the crew of the R/V Odyssey for assistance with HARP deployments. We thank members of the SIO Whale Acoustic Laboratory including:

T. Christianson, C. Garsha, B. Hurley, J. Hurwitz, J. Jones, E. O'Neill, and E. Roth for assistance with HARP operations and data processing, as well as M. McDonald of Whale Acoustics LLC. Funding for HARP data collection and analysis was provided by the Natural Resource Damage Assessment partners (20105138), the U.S. Marine Mammal Commission (20104755/E4061753), the Southeast Fisheries Science Center under the Cooperative Institute for Marine Ecosystems and Climate (NA10OAR4320156) with support through Interagency Agreement #M11PG00041 between the Bureau of Ocean Energy Management, Environmental Studies Program and the National Marine Fisheries Service, Southeast Fisheries Science Center, and the CIMAGE Consortium of the BP/Gulf of Mexico Research Initiative (SA 12-10/GoMRI-007). The analyses and opinions expressed are those of the authors and not necessarily those of the funding entities. The data used for this study are archived at https://data.gulfresearchinitiative.org/data/R4.x267.180:0009 maintained by the Gulf of Mexico Research Initiative.

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