

Article

Underwater Chatter for the Win: A First Assessment of Underwater Soundscapes in Two Bays along the Eastern Cape Coast of South Africa

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Abstract: In 2014, the South African government launched ‘Operation Phakisa’ under which port developments play a significant role in supporting ocean economic growth. These developments will likely increase vessel traffic to and from South African ports, making it imperative to monitor for changes in underwater sound budgets with potential negative effects on marine life. However, no soundscape studies have been conducted around South Africa, resulting in an absence of baseline measurements. This study provides a first description of the underwater soundscape in St. Francis Bay and Algoa Bay, Eastern Cape. Soundscape measurements identified major soundscape contributors, temporal patterns in broadband sound levels, and underlying environmental drivers. Applicability of modelled vessel noise and wind noise maps to predict large-scale spatial variation in sound budgets was assessed. Our study shows that sounds from biological sources and wind dominated at all recording sites, with fish choruses driving temporal patterns as a function of time of year and position of the sun. Sound from vessels was present at all sites but most notable in long-term spectral levels measured in Algoa Bay. Sound propagation models predicted a further increase in the contribution of vessel noise towards shipping lanes and east Algoa Bay. Our study provides a building block to monitor for shifts in sound budgets and temporal patterns in these two bays under a developing ocean economy. Furthermore, our study raises concerns that vessel noise is likely a significant contributor in shallow waters elsewhere along the South African coast where vessel density is known to be higher (i.e., Durban and Cape Town).

Keywords: marine soundscape; vessel noise; wind noise; flow noise; biophony; temporal patterns; sound budgets; South Africa

1. Introduction

Soundscapes provide an acoustic representation of the environment and comprise signals from animals (i.e., biophony), geological processes (i.e., geophony), and human activities (i.e., anthropophony). Soundscape studies have rapidly increased over the last ~20 years [1,2], revealing that natural soundscapes are integral to the support of ecological processes [3]. However, soundscape studies also resonate the alarming message that natural soundscapes are disappearing because of the presence of anthropophony (e.g., [4,5]). Anthropophony is present even within the deepest parts of the oceans (>10,000 m; [6]) and under the Arctic and Antarctic ice (e.g., [7–9]). In fact, underwater noise (i.e., unwanted sound) has raised concerns for decades [10] and has now been recognised as a potential form of pollution [11–13] that can have adverse effects on marine life (for a collection of studies see: [14–16]). As visibility under water is limited, many aquatic species have evolved to use acoustic signals as the principal mode of information transmission

(e.g., [17–19]). Sound is therefore recognised as the most important factor to support the life functions of marine animals through its use for communication, navigation, and environmental sensing (e.g., [5,19,20]). To maintain these life functions, it is paramount that the soundscape is able to facilitate the use of sound by animals with little to no interference from anthropogenic noise.

Soundscape monitoring can aid identification of long-term changes in the contribution of anthropogenic noise to sound budgets (i.e., representation of the relative contribution of different sound sources) over time and space, and so detect potential negative effects on marine life. However, detection of long-term changes requires an understanding of baseline soundscape metrics and how these vary over temporal and spatial scales [21,22]. In any soundscape, sound levels change over time. These changes may occur because of various factors, including, but not limited to, human activities and natural changes in weather patterns, the presence/absence of migrating species, and animal behaviour [23]. While weather patterns and the presence of migratory species are often seasonal, changes in animal behaviour may be linked to a variety of temporal scales, including diurnal, tidal, and lunar scales—resulting in recognisable patterns in soundscape metrics. The complexity of these patterns varies with location but generally increases in shallow-water soundscapes where multiple prominent sound sources may contribute to similar frequency bands [24].

The ocean is naturally noisy. Wind is the primary contributor to underwater noise levels between 100 Hz and 20 kHz in the absence of biophony and anthropophony [25]. Rain can also contribute to underwater sound levels, peaking between 1 and 20 kHz [26,27]. Ocean currents *per se* are not noisy, but currents flowing past stakes and ropes in moorings may set these into vibration and thus cause tonal noise from tens of hertz to kilohertz. Moreover, currents flowing over a hydrophone create hydrodynamic (as opposed to acoustic) pressure fluctuations [28], which are sensed by the hydrophone and thus appear in spectrograms as low-to-mid-frequency pseudo-noise, also called noise artefacts.

The most pervasive and persistent anthropogenic sound in the oceans is that from large commercial vessels (i.e., >300 t), which have increased underwater ambient noise levels in the 10–100 Hz frequency range over the last five decades [29–34]. Within close range, vessels of all sizes also raise sound levels over higher frequencies (i.e., up to 160 kHz [35]). Consequently, vessel noise falls within the hearing and communication range of a wide range of marine animals and so can have potentially negative effects (e.g., [36–38]). How vessels contribute to overall sound budgets varies widely over space and time: from being a pronounced contributor (e.g., [39–41]), to being present in hourly spectrograms without leaving a statistically significant footprint (e.g., [9,42]), to possibly being completely absent [39].

Vessel noise has been of less concern in the southern hemisphere because most of the world's major shipping routes lie in the northern hemisphere [43,44]. Yet, vessel densities may also be high along major shipping routes in the southern hemisphere. South Africa, for example, is situated on an important sea trading route connecting the Indian and Atlantic Oceans. Approximately 3500 large vessels pass around Cape Point per year and follow routes close (i.e., at some points < 10 km) to the 3100 km long coastline [45]. In addition, South Africa operates eight commercial seaports, which registered 7836 port calls in 2020 [46]. In 2014, the South African government launched *Operation Phakisa: Unlocking the Ocean's Economy* [47] to build on the country's strategic location and existing facilities. One aim of *Operation Phakisa* is to expand port capacities and facilities to support maritime transport, manufacturing, and repair services likely resulting in increased vessel traffic to and from South African ports. Under such a development program, it is imperative to monitor for changes in sound budgets. However, to date, no research has been conducted on the underwater soundscape anywhere around the southern African continent apart from on individual species' vocalisations (e.g., [48–51]). Consequently, baseline soundscape descriptions (i.e., sound sources) and metrics to monitor for change are absent. This study describes the measured underwater soundscape of St. Francis Bay and Algoa Bay along the Eastern Cape coast of South Africa and models sound (i.e., statistical modelling and sound

propagation modelling) to explain patterns over time and space. We aimed to provide the first underwater soundscape description for South Africa that can be used as a baseline to monitor for changes in contributors over time during South Africa's strategic ocean economy developments.

2. Materials and Methods

2.1. Study Sites

The shallow waters of St. Francis Bay and Algoa Bay support a rich biodiversity, including marine mammals (e.g., [52–55]); sharks (e.g., [56,57]); reef, demersal, and pelagic fish (e.g., [58–60]); squid [61,62]; and seabirds (e.g., [63,64]). Both bays are shallow, eastward-facing, with a mean depth around 46 m (Figure 1). In the western corner of St. Francis Bay lies Port St. Francis, a privately owned harbour, which is home to recreational vessels and a fleet of approximately 40 small (11–20 m) commercial fishing vessels. The commercial fishing vessels predominantly target squid (*Loligo reynaudii*) and operate around eight months of the year [65]. In the western corner of Algoa Bay lies the Port of Port Elizabeth, a multipurpose port accommodating recreational vessels, commercial fishing vessels, cruise liners, and merchant vessels (i.e., container, bulk, and car carriers). Up to 14 (median = 4) merchant ships arrived in or departed from the Port of Port Elizabeth per day between 2009 and 2017. In the northwest corner of Algoa Bay lies the Port of Ngqura, a deep-water port exclusively accommodating merchant vessels. The Port of Ngqura became operational in October 2009, with a rapidly increasing capacity to handle up to nine (median = 2) ships a day by 2016. Continued port expansions are planned for both Algoa Bay ports [66], and a moratorium on licensing for fuel ship-to-ship bunkering may be lifted in 2022. Both developments will result in increased vessel traffic in Algoa Bay over time. Offshore shipping routes approximately follow the 100 m bathymetry contour.

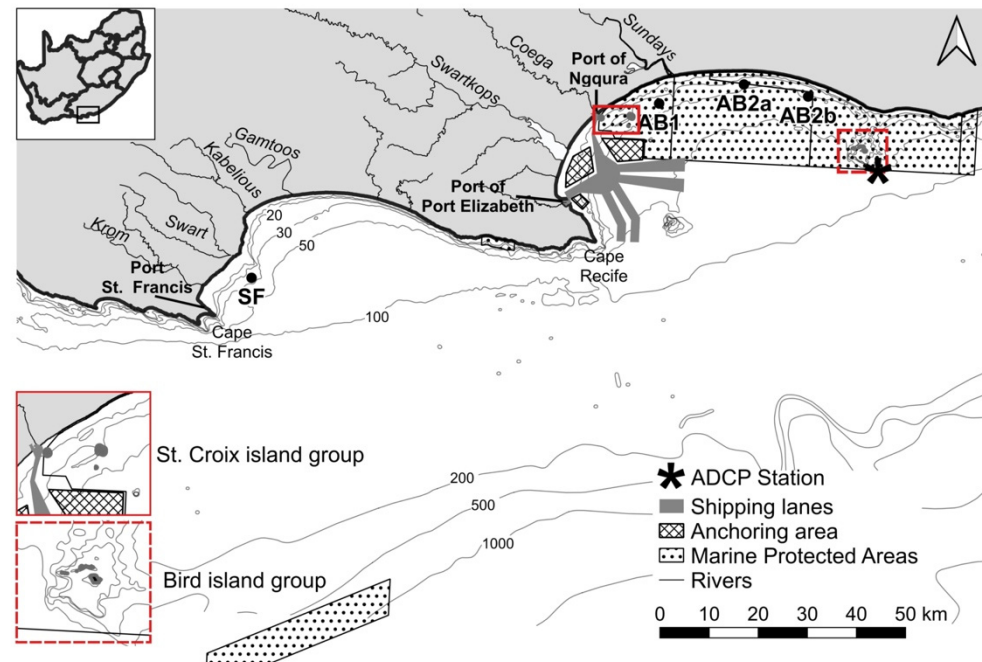


Figure 1. Map of St. Francis Bay (west) and Algoa Bay (east) along the Eastern Cape coast, South Africa. Deployment sites (SF, AB1, AB2a, and AB2b) are shown as large solid dots and the Acoustic Doppler Current Profiler (ADCP) station as an asterisk. Shipping lanes and anchoring areas are depicted in the northwest section of Algoa Bay. Boundaries of Marine Protected Areas (MPAs) are depicted by the dotted boxes.

2.2. Soundscape Measurements

2.2.1. Acoustic Data Collection

Underwater acoustic data were collected between February 2015 and March 2018 with SM2M+ omnidirectional acoustic recorders calibrated by the manufacturer (Wildlife Acoustics Inc., Maynard, MA, USA). The hydrophone sensitivity was -166 dB re 1 V/ μ Pa over 10 Hz– 48 kHz. All deployments were carried out with commercial divers, which restricted our deployment sites to a water depth of <30 m. We found it important to assess the soundscape in a Marine Protected Area (MPA) in more detail and therefore deployed one acoustic recorder (SF) in St. Francis Bay and two (AB1 and AB2a/AB2b) within the Addo Elephant MPA (AEMPA) in Algoa Bay (Figure 1). Site AB2b could not be reached frequently enough to ensure adequate equipment maintenance. Therefore, the recorder was moved 12 km west, to site AB2a, in September 2016.

At all sites, the acoustic recorder was moored to a 100 kg anchor with a 4 m polysteel rope, positioning the hydrophone at 22 m depth. This set-up did not minimise mooring artefacts [40], but was a compromise considering diver deployment constraints, currents, and sediment movement [67]. Recorders monitored underwater sound at a sampling frequency of 48 kHz for 15 min every 60 min in 2015 and for 5 min every 20 min in 2016–2018. We changed the sampling regime to better assess variability within the hour while keeping the duty cycle constant at 20% [68]. The chosen duty cycle was a compromise between battery power, onboard data storage, and fieldwork costs. Weather permitting, data were retrieved and recorders were serviced every three months, with the aim to have all three devices record simultaneously. In practice, simultaneous recordings were challenging and most of the time (i.e., 50%) recordings were obtained from only two recorders because of a flooded recorder at the start of 2015, a lost recorder at the end of 2015, a faulty recorder mid-2016, and prevailing adverse weather conditions.

2.2.2. Identification of Sound Sources

Long-term spectral averages (LTSA) were computed over full recordings and plotted for each year to identify prominent sound sources and their pattern of occurrence (i.e., spatial and temporal occurrence: see Supplementary Material Figure S1). More detailed identification of sound sources and sound source presence–absence data for each site were obtained through aural and visual inspection of every eighth day of recording in Raven Pro (Version 1.6.1.; The Cornell Lab of Ornithology, Ithaca, NY, USA). Visual inspection was carried out at two different spectrogram settings: first with a Discrete Fourier Transform (DFT) of 4096 samples, Hann window, and 50% overlap for mid- to high-frequency sounds and second, with a DFT of $32,768$ samples, Hann window, and 70% overlap for low-frequency sounds.

We obtained hourly wind speed data from the NASA MERRA-2 data set [69] and assessed the contribution of wind with Spearman rank correlation analyses between 0.1 m/s wind speed bins and $1/3$ octave band levels (OBL, 10 – $19,953$ Hz centre frequencies [70]). As the study area received only sporadic and light rainfall in 2015–2018, a correlation analysis between rainfall data and measured sound levels was excluded.

2.2.3. Flow Noise Artefacts

Cross-correlation analyses were used to reveal potential relationships between current speed and $1/3$ OBL time series from 10 to 200 Hz [71]. Relationships were subsequently tested for significance with Granger causality tests. Current velocity data were measured with an Acoustic Doppler Current Profiler (ADCP) near Bird Island (33.869° S and 26.303° E; Figure 1) that was supplied by the South African Environmental Observation Network (SAEON). The ADCP was nearest to site AB2b (~ 19 km) which meant that only current velocity data from 2015 and acoustic data from AB2b were used.

2.2.4. Temporal Patterns

We used a Whittaker–Robinson periodogram analysis on each deployment to detect periodic cycles in broadband sound pressure levels (i.e., SPL). We subsequently used a regression tree analysis on the whole data set for each site to identify prominent drivers of variability. Regression trees provide a visual representation of the most important predictor variables for a given dataset and are particularly useful to analyse complex datasets (e.g., non-normally distributed data, nonlinear relationship, missing values etc. [72]). Variables included in the regression tree analyses were month, wind speed, and significant periodic (i.e., diurnal, tidal, and/or lunar) variables identified by the periodograms. Diurnal periods were represented by dawn (i.e., position of the sun: -18° to 0° below horizon), day (i.e., from sunrise to sunset), dusk (i.e., position of the sun: 0° to -18° below the horizon), and night (i.e., position of the sun $< -18^\circ$ below the horizon). Tidal periods were represented by high (i.e., within an hour of high tide), falling, low (i.e., within an hour of low tide), and rising tide. Finally, lunar periods were represented by full moon (i.e., $>90\%$ of moon illuminated), new moon (i.e., $<10\%$ of moon illuminated), and partial moon (i.e., $10\text{--}90\%$ of moon illuminated). Diurnal and lunar information was extracted with the R Statistical Software (V1.4.1; [73]) package *suncalc* [74], while regression trees were created with the package *rpart* [75]. Tidal data was obtained from the South African Navy Hydrographic Office (SANHO). It should be noted that regression trees were not created with the aim to predict values of future measurements, but purely with the aim to identify prominent drivers of the presented dataset.

2.3. Sound Budgets

Based on the underwater acoustic recordings, a power spectral density (PSD) percentile plot overlain with a power spectral probability density (PSPD) plot, together referred to as a PSD%PD plot, provides a detailed visual representation of the contribution of various sound sources to the soundscape—presenting the statistical variability of noise levels over time at a range of frequencies and the probability of levels occurring at the recorder location [76]. Acoustic recordings, however, only provide spot measurements in space and time, and sound budgets may vary even over short spatial scales [24]. Sound propagation models can provide insight into the spatial variation of sound sources with known source levels (e.g., [39,77–80]) and so assist in predicting variation in sound budgets over larger spatial scales. Therefore, we assessed the spatial variation in sound budgets between sites with PSD%PD plots and used sound propagation modelling of wind and vessel noise to evaluate how sound budgets may change over broader scales. MATLAB (Version 2019a; The MathWorks Inc., Natick, MA, USA) was used to both create PSD%PD plots and perform acoustic modelling.

2.3.1. Power Spectral Density Percentile and Power Spectral Probability Density Plots

PSD%PD plots were created for each site with a year-round dataset from 2015 (SF and AB2b) or the closest year without large data-gaps (AB1 and AB2a). PSD plots were created for each site from LTSAs computed in 60 s windows at 1 Hz resolution—one plot for the whole year and one plot for April–June. Percentiles were smoothed by averaging PSD in adjacent $1/3$ octave bands. We furthermore calculated the probability of how often each level was reached, based on histograms of sound levels within each frequency bin (i.e., PSPD [76]). We labelled and identified the dominant sound sources in the PSD%PD plots by comparison with the LTSAs and our manual (visual and aural) inspection of spectrograms.

2.3.2. Wind Noise Model

We estimated cumulative levels (i.e., C-SEL) of wind noise with hourly wind speed data ($0.5^\circ \times 0.625^\circ$ resolution) retrieved from the NASA MERRA-2 data set [69]. Wind C-SEL was calculated at the same resolution as the raw data points by applying Wenz wind source spectra [25] to wind speed bins and integrating mean-square pressure over time

(see [39]). C-SELs were converted to linear values, plotted in QGIS (Version 3.10; QGIS Development Team, <http://www.qgis.org> accessed on 27 February 2022), and interpolated over the propagation grid. Gridded values were subsequently converted back to dB re $1 \mu\text{Pa}^2 \text{ s}$. This process was completed twice: once for the whole of 2015 and once for April–June alone. The average wind mean-square SPL for 2015 and April–June was computed by subtracting $10\log_{10}(T)$ from the respective C-SEL values, where T equals the number of seconds in 2015 and April–June, respectively (i.e., 75 and 69 dB re 1 s for 2015 and April–June, respectively).

2.3.3. Vessel Noise Model

Vessel noise was modelled based on Automatic Identification System (AIS) data (on vessel position, size, type, and speed) obtained from FleetMon (JAKOTA Cruise Systems GmbH, Rostock, Germany, www.fleetmon.com accessed on 29 April 2022). Data included all vessels up to 80 km offshore from Cape St. Francis and covered the period from 01-Jan-2015 to 31-Dec-2015. Data were first filtered to remove data points with a speed <2 knots, as these vessels often appeared to drift around their mooring location. Data were then split into size classes based on vessel length: $\leq 10 \text{ m}$, $>10\text{--}\leq 25 \text{ m}$, $>25\text{--}\leq 50 \text{ m}$, $>50\text{--}\leq 100 \text{ m}$, $>100\text{--}\leq 200 \text{ m}$, and $>200 \text{ m}$. For each vessel class, we then calculated the cumulative seconds of vessel traffic on a grid with $500 \text{ m} \times 500 \text{ m}$ cells by (1) plotting AIS data points and joining points in chronological order by vessel identification number, (2) summing the length of vessel tracks within each grid cell, and (3) calculating a median vessel speed for each grid cell. Underwater source spectra were computed for each vessel class with the Research Ambient Noise Directionality model (RANDI [77,81]), using the mean vessel length (i.e., 9, 22, 34, 68, 183, and 274 m, respectively) and mean vessel speed in each class (i.e., 6, 6.4, 5.9, 9.6, 11.7, and 11.8 kn, respectively). Linear noise spectra were subsequently integrated into 1/3 OBL. Broadband source levels for the six vessel classes were 141, 150, 152, 171, 187, and 192 dB re $1 \mu\text{Pa m}$, respectively.

Bathymetric, hydroacoustic, and geoaoustic information was collected from sources detailed in Table 1. This information was used to divide the propagation grid into 25 acoustic zones with similar categorical sound propagation characteristics. Dividing the grid into zones allowed sound propagation to be modelled more efficiently from one smaller region at a time. A table with properties for the 25 zones can be found in Supplementary Material Table S1. All spatial analyses were performed in QGIS.

We then imported the grid into MATLAB to identify all source cells (i.e., grid cells with cumulative vessel time $> 0 \text{ s}$) for one vessel class, within one acoustic zone, at a time. From each source cell, 36 source-receiver transects were cast at 10° azimuth resolution. Bathymetry was extracted along every source-receiver transect in 500 m steps over a maximum range of 80 km. The mean distance between two random points in a $500 \text{ m} \times 500 \text{ m}$ square was inserted at the start of the bathymetry transect and used to estimate received levels within the source cell (i.e., 261 m [82]). All transects for one vessel class within a zone were clustered into 64 groups with an unsupervised neural network (i.e., Self-Organizing Map, SOM [83]) and subsequent k -means clustering (see Supplementary Material Figure S2 for an example plot of clustered bathymetry profiles). More detail may be found in Erbe et al. [39]. For each cluster, a cluster centroid (i.e., mean bathymetry transect) was computed, along which sound propagation was modelled.

Sound propagation was modelled for the 24 centre frequencies of 1/3 octave bands between 10 Hz and 2 kHz with RAMGeo in AcTUP (Version 2.8: [84]; <https://cmst.curtin.edu.au/products/underwater/> accessed on 21 February 2022). Models used zone-specific acoustic environments comprising a water column, an unconsolidated sediment layer, and a consolidated sediment layer. Water column properties included a sound speed profile and a water density profile. Sound speed profiles were calculated from the hydroacoustic parameters following the formula in Mackenczie [85]. Water density profiles were calculated following the UNESCO formulae for sea water density [86]. Unconsolidated sediment properties (i.e., compressional sound speed, shear sound speed, compressional

absorption coefficient, shear absorption coefficient, and density) were computed following Hamilton [87–89] and Jensen et al. [90]. Consolidated sediment properties were derived from Jensen et al. ([90]: siltstone) and Rathje et al. ([91]: quartzite). Because RAMGeo is for fluid seabeds, models were run for approximate equivalent-fluid environments [92]. Finally, models used a source depth that increased with vessel length: 1.5 m for Class 1, 3 m for Class 2, 6 m for classes 3 and 4, and 7 m for classes 5 and 6. See Supplementary Material Figure S3 for example plots of propagation loss over 64 bathymetry cluster centroids.

C-SELs per ship class over the entire area were calculated by (1) stepping through each source cell to match source-receiver transects with cluster centroids, (2) retrieving the matching propagation loss matrix for each transect, (3) calculating the received levels (dB re 1 μPa^2) along each transect, for each frequency modelled, by subtracting the propagation loss from the octave band source level plus the cumulative time (i.e., $10\log_{10}(T)$ with T in seconds), (4) interpolating received levels to the noise model grid, and (5) summing linear sound exposures within each grid cell, from all sources, and converting them to dB re 1 $\mu\text{Pa}^2\text{s}$ to represent C-SEL [39]. We further computed the maximum C-SELs over the top 100 m for the entire 12 months. The annual average vessel SPL for each grid cell was computed by subtracting 75 dB re 1 s from C-SEL (i.e., $10\log_{10}$ of the 12-month duration in seconds). Because vessel noise was not modelled for April–June separately, we assumed that the average vessel SPL for April–June was equal to the annual average SPL.

Table 1. List of parameters and their categories (if applicable) used to establish 25 acoustic zones.

Zone Features	Parameters	Categories	Source
<i>Bathymetric</i>	Depth [m]	<150	South African Navy Hydrographical Office (SANHO)
		150–4000	
		>4000	
<i>Hydroacoustic</i>	Temperature profile [$^{\circ}\text{C}$]	<i>Both available for four regions:</i> Continental shelf bay Continental shelf offshore Continental slope Deep ocean	[93]
	Salinity profile [psu]		[94]
<i>Geoacoustic</i>	Unconsolidated sediment	Medium to fine silt	<i>Inside bay:</i> Algoa Bay Sentinel Site for LTER of the South African Environmental Observation Network <i>Outside bay:</i> [95]
		Coarse silt	
		Fine sand	
	Unconsolidated sediment thickness [m]	Medium to fine sand	[96,97]
		Medium sand	
	Consolidated sediment	Fine pebbles	[98,99]
		Medium pebbles	
		na	
		Quartzite	
		Sandstone	

2.3.4. Predicted Spatial Changes in Sound Budgets

It is important to validate modelled levels with measured levels to assess the suitability of noise maps for making large-scale predictions [39,79,80]. We therefore compared modelled levels of vessel and wind noise with measured levels and identified sound sources at each site. For each site, LTSAs were computed over full recordings and subsequently integrated over frequency and time. Measured levels were integrated over 30 Hz–2 kHz to reduce flow noise artefacts. Model evaluation results were used to predict spatial changes in sound budgets.

3. Results

3.1. Soundscape Measurements

3.1.1. Sound Sources

We visually and aurally inspected a total of 100, 69, 66, and 31 days to identify sound sources at SF, AB1, AB2a, and AB2b, respectively. Sources of biophony and geophony were similar between sites, while anthropophony differed. LTSAs for each site can be found in the Supplementary Material Figure S1.

Biophony

Snapping shrimps (*Alpheidae* sp.) were the prevalent source of biophony at frequencies > 3 kHz, audible year-round at all sites. Fish were the dominant source of biophony at 50–750 Hz, with six distinct choruses recorded throughout the year. All fish choruses were recorded at all sites, although their presence was not always concurrent. Chorus I comprised a tonal call with a fundamental frequency around 75 Hz and harmonic overtones extending to 800 Hz (Figure 2a). Chorus I was prevalent at SF in the evenings from mid-February to end-March, while only recorded sporadically in Algoa Bay. Chorus II also comprised a tonal call with harmonic overtones (Figure 2b) and was present throughout the night at all sites from as early as mid-March until the end of July. Over the season fundamental frequencies generally increased from 111 Hz to 140 Hz. Chorus III, with a lower fundamental frequency (i.e., 57 Hz; Figure 2c) and more harmonic overtones than choruses I and II, was recorded during the evening at all sites from mid-July until early September. Chorus IV covered frequencies between approximately 250 and 650 Hz (Figure 2d) and was present nearly year-round at all sites in Algoa Bay, with a variable time of peak calling. In contrast, Chorus IV was only recorded during the night in December and January at SF. Chorus V comprised a series of pulsed signals (main energy 200–300 Hz; Figure 2e) with variable repetition, which were recorded at all sites from October until March. Calls were generally recorded from late afternoon to evening (i.e., 16:00–19:00), although choruses continued into the night at peak calling times. Chorus VI comprised tonal calls with a variable fundamental frequency between 40 and 135 Hz and harmonics up to 340 Hz (Figure 2f). Chorus VI was recorded in the evenings from mid-July until mid-April at all sites in Algoa Bay—always in conjunction with Chorus IV.

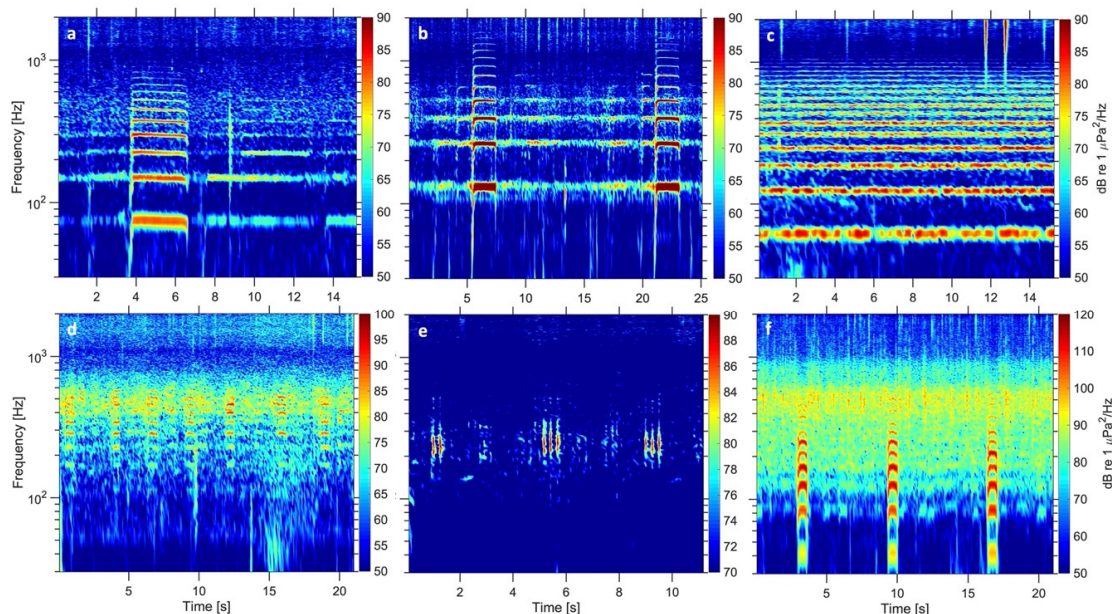


Figure 2. Spectrograms of fish choruses I (a), II (b), III (c), IV (d), V (e), and VI (f). Spectrogram of chorus VI also contains chorus IV in the background. Note that the frequency range is the same for all subfigures, while the colour bar differs in range for subfigures (d) and (f).

In addition to fish, an intense chorus of pulsed signals (main energy 300–500 Hz, Figure 3) was observed at all sites from mid-November until mid-March. This chorus was generally present from sunset until midnight, although at its peak, it was recorded all night. Individual signals were heard throughout the year. Iversen et al. [100] recorded similar sounds in the Pacific and suggested squid (i.e., *Thysanoteuthis rhombus*, *Symplectoteuthis ovalaniensis*, *Onychoteuthis banksi*, or a combination of species) as the responsible sound source. Because both St. Francis Bay and Algoa Bay are well-known spawning grounds for squid (*Loligo reynaudii*) with peak spawning in summer [101–103], we believe that this chorus was produced by squid.

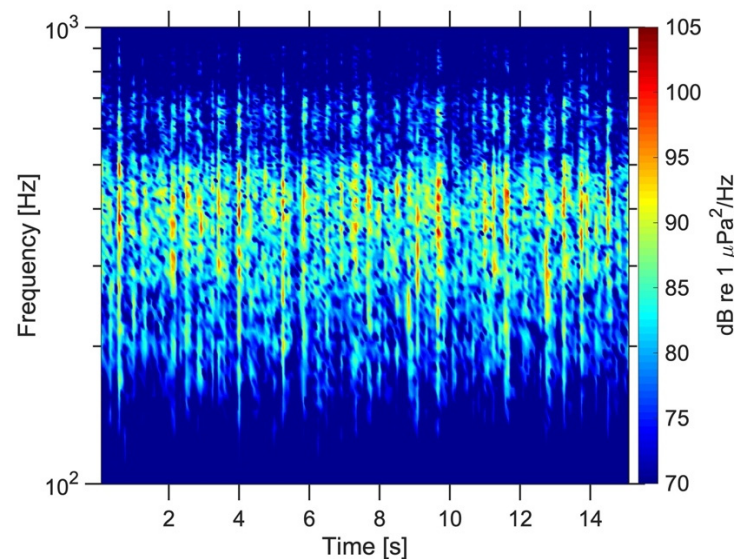


Figure 3. Chorus of pulsed signals likely produced by squid.

Frequency-modulated tones (whistles, 6–24 kHz) and pulsed sounds (clicks and burst pulses, 7–24 kHz) produced by dolphins were detected year-round at all sites, but in <10% of inspected samples. Humpback whales (*Megaptera novaeangliae*) were recorded from mid-June until mid-December, with more extensive vocalisations in Algoa Bay than in St. Francis Bay. Energy from calls and songs was most intense between 100 Hz and 1 kHz. Humpback whale vocalisations were occasionally combined with non-vocal sounds produced by surface behaviours (Figure 4a, [104]). Less frequent marine mammal vocalisations recorded in both bays included southern right whale (*Balaenoptera australis*) calls detected between June and August. The most frequent call was a broadband pulse with energy extending up to 24 kHz, also known as the gunshot sound [105]. Occasionally, low-frequency (<100 Hz) Bryde’s whale (*Balaenoptera edeni*) vocalisations were also recorded (Figure 4b, call Be6 in [106]).

In Algoa Bay, we also detected two calls and one chorus of unknown origin: a wide-band 30 Hz constant-wave call, with overtones up to 400 Hz (Figure 5a), a harmonic down-sweep with the fundamental typically starting at 500 Hz (Figure 5b), and a low-frequency chorus (i.e., 20–80 Hz, Figure 5c). Both calls were predominantly detected from March until June in 2015, while the chorus was only detected at AB2a in March–April and December 2017. Occasionally, bird-like calls were detected (Figure 5d), which may be in-air vocalisations produced by the African penguin (*Spheniscus demersus*: P. Pistorius and A. Thiebault, personal communication, 16 June 2020).

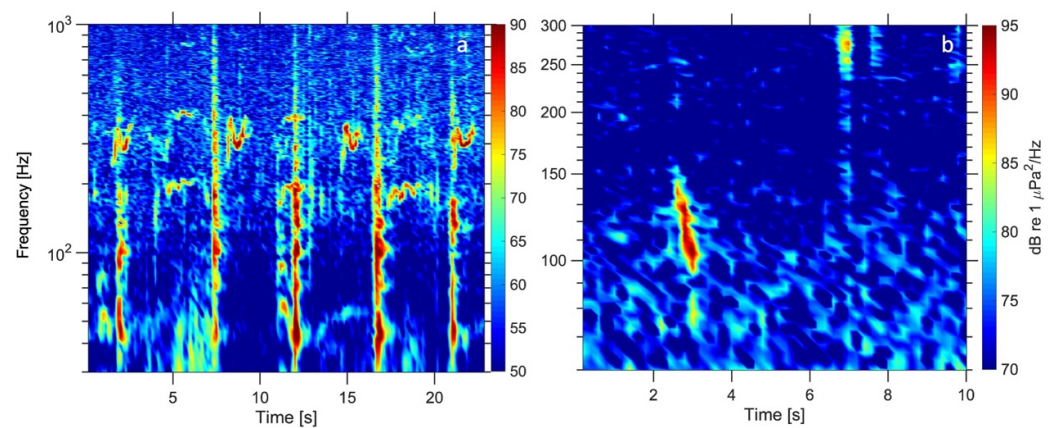


Figure 4. Spectrograms of humpback calls (300 Hz) with non-vocal sounds from surface behaviours (40–100 Hz; **a**) and a Bryde’s whale vocalisation (**b**). Note that the frequency axis and colour bars have different ranges.

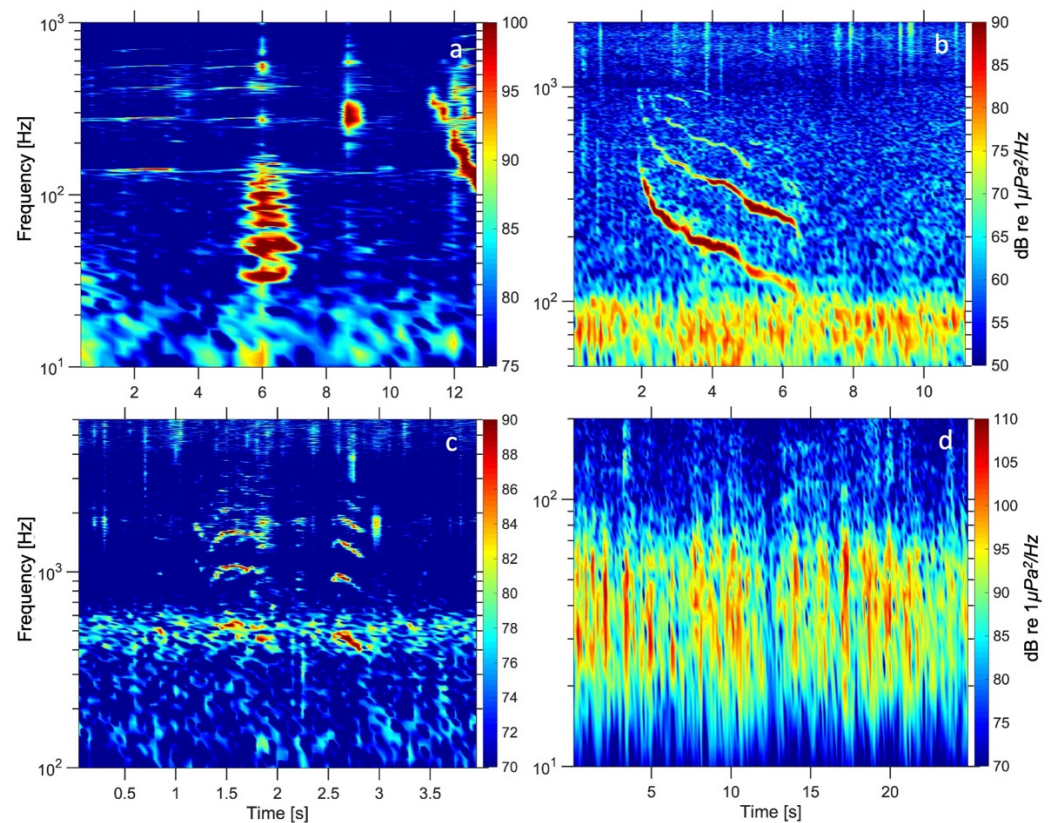


Figure 5. Spectrograms of a wide-band constant-wave call (**a**) and a harmonic down-sweep of unknown origin (**b**), vocalisations likely produced by the African penguin in air (but recorded under water: **c**), and a chorus with unknown origin (**d**). Note that the frequency axis and colour bars have different ranges.

Geophony

Sources of geophony included thunder, temporally increasing sound levels at frequencies up to 10 kHz, and rain, raising sound levels at frequencies > 12 kHz. There was a marked presence of biophony in the study area from July to March and so, only wind and sound level data from April to June were included in the correlation analyses between wind speed and sound levels. Sound levels from 1000 to 2512 Hz 1/3 octave bands revealed strong correlations (i.e., correlation coefficients > 0.7) at SF, AB1, and AB2b; and moderate

(i.e., correlation coefficients 0.4–0.7) correlations at AB2a. In addition, at SF, correlations were strong from 158 to 794 Hz and weak to moderate (i.e., ≤ 0.7) from 50 to 126 Hz. At AB1, strong correlations were also seen ≤ 200 Hz, whereas weak to moderate correlations were seen from 100 to 316 Hz at AB2a and AB2b. All three sites in Algoa Bay indicated a negative correlation between wind speed and sound levels at 501 Hz.

Anthropophony

Vessels were the most prevalent source of anthropophony in 11%, 13%, 18%, and 28% of samples at SF, AB1, AB2a, and AB2b, respectively. Detected vessels were categorised as small, large, or unknown based on acoustics (i.e., higher spectral peak/pitch for small vessels) and behaviour (i.e., irregular speed and faster transits for small vessels). At SF, 87% of detected vessels were transient small vessels, producing main energy < 10 kHz (Figure 6a). At AB1, 74% of vessels could not be identified, while 21% were classified as large. At AB2a, an approximately equal number of small (28%), large (36%), and unknown (36%) vessels were recorded. At AB2b, 52% of detected vessels comprised large commercial vessels, increasing sound levels between 20 and 100 Hz (Figure 6b), while a further 42% were unknown. Two additional sources of anthropophony were detected at AB1: chain noise, presumed to originate from the nearby anchoring area, and airplanes, which temporarily raised sound levels up to 400 Hz (Figure 6c).

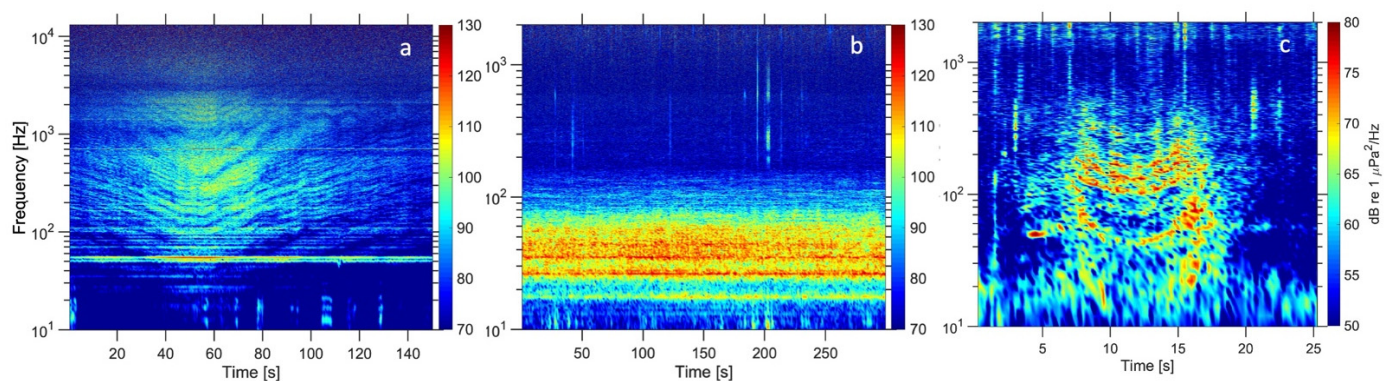


Figure 6. Sources of anthropophony from left to right: small vessel (a), large vessel (b), and airplane flying overhead (c). Note that the frequency axes and colour bars have different ranges.

Mooring noise was present as brief pulses with energy between 10 Hz and 600 Hz. This noise was removed prior to further data analyses with a custom-written detection function applied in MATLAB.

3.1.2. Flow Noise Artefacts

The presence and effect of flow noise were only assessed in recordings from April to June to minimise acoustic interference from biophony. Current velocity data ranged from 0.3 to 67.0 cm/s. While cross-correlation analyses suggested correlations between current velocity and all OBLs, the Granger causality tests only identified current velocity as a predictor for sound levels within the 10 Hz and 13 Hz OBLs. However, LTSA plots of site SF, for which no current velocity data were available, suggest that flow noise occasionally extended up to 110 Hz (see Supplementary Material Figure S1).

3.1.3. Temporal Patterns

Results of the periodogram and regression tree analyses are summarised in Table 2. Figures of the periodograms and regression tree for each site can be found in the Supplementary Material Figures S4–S7 and Figure S8, respectively. Whittaker–Robinson periodograms identified significant semi-diurnal (12 h) and diurnal (24 h) periods in every deployment for all sites. Diurnal period harmonics were typically recognisable along most, or all, of the periodogram. Additional 6 h and 8 h periods were present at SF in deployments covering

peak austral summer months (i.e., December/January). In Algoa Bay, 6 h periods were only detected in the summer of 2016 and 2017 at AB2a and AB1, respectively. In contrast, 8 h periods were common at both AB1 and AB2a. Larger periods were most common at SF but did not indicate a clear pattern in relation to time of year. Deployments at SF covering February–October generally had one short multi-day period (i.e., ~3.4 or ~4.5 days) and one or two long multi-day period(s) (i.e., ~15, ~18, ~20.5, and/or ~27 days). Deployments covering peak summer only revealed long multi-day periods, including ~11.5, ~23, and ~37 days. Deployments with periods of ~15 days sometimes revealed weaker periods at ~7.2 days. In Algoa Bay, periods of ~6.2 and ~14.2 days were found in February–June 2015 at AB2b, while periods of ~5.5 and ~9.5 days were found in February–October 2017 at AB1 and AB2a.

Table 2. Summary of significant periods revealed by periodogram analyses performed on each deployment (columns 4–6) and of variables included in the most parsimonious regression tree for each site. The number behind predictor variables reflects the relative importance of that variable to improving the overall tree prediction error (i.e., root-mean-squared error). R^2 indicates the percentage of variation in the data explained by the regression tree.

Recording	Start Date	End Date	<1 Day [h]	Short Multi-Day	Long Multi-Day	Predictor Variables (Importance)	R ²
SF							
Set 1	3 April 2015	5 August 2015	12, 24	~4.5	~15, ~20.5	Month: 0.75 Diurnal: 0.19 Lunar: 0.05 Wind: 0.01	0.23
Set 2	25 September 2015	4 February 2016	6, 8, 12, 24		~37		
Set 3	15 May 2016	25 August 2016	12, 24	~4.5	~15, ~20.5		
Set 4	21 September 2016	14 January 2017	6, 8, 12, 24		~15		
Set 5	31 January 2017	5 June 2017	12, 24	~3.4	~20.5		
Set 6	7 July 2017	26 October 2017	12, 24	~3.4	~18, ~27		
Set 7	17 November 2017	28 February 2018	6, 8, 12, 24		~11.5, ~23		
AB1							
Set1	10 December 2015	8 April 2016	8, 12, 24			Month: 0.54 Diurnal: 0.42 Lunar: 0.01 Wind: 0.03 Tidal: 0.01	0.40
Set2	14 April 2016	28 August 2016	8, 12, 24				
Set3	22 February 2017	14 June 2017	8, 12, 24		~9.5		
Set4	14 June 2017	4 September 2017	12, 24	~5.5	~9.5		
Set5	21 October 2017	5 February 2018	6, 8, 12, 24				
AB2a							
Set1	8 September 2016	23 January 2017	6, 8, 12, 24			Month: 0.52 Diurnal: 0.46 Wind: 0.02	0.43
Set2	23 January 2017	15 May 2017	8, 12, 24		~9.5		
Set3	14 Jun 2017	21 October 2017	12, 24	~5.5			
Set4	21 October 2017	13 March 2018	8, 12, 24				
AB2b							
Set1	27 February 2015	10 June 2015	12, 24	~6.2	~14.2	Month: 0.86 Diurnal: 0.12 Lunar: 0.01 Wind: 0.01	0.50
Set2	30 June 2015	4 November 2015	8, 12, 24				
Set3	30 November 2015	22 December 2015	12, 24				

Regression tree analyses identified month of the year and the position of the sun as the most important SPL predictor variables at all sites (Table 2). SPL generally increased at dusk and at night, with peak levels over the summer months. Sound levels at dawn and during the day peaked in early summer (i.e., October–November). Wind speed also occurred in each regression tree, suggesting an increase in SPL at higher wind speeds in at least some circumstances. Finally, trees for SF, AB1, and AB2b suggested moon phase related changes in summer. However, regression trees only explained 23–50% of variation in the data (Table 2).

3.2. Sound Budgets

3.2.1. Power Spectral Density Percentile and Power Spectral Probability Density Plots

PSD%PD plots are depicted in Figure 7. The n th percentile of a PSD indicates the sound levels that were exceeded $n\%$ of the time. PSD%PD plots for all data sets identified flow noise as the principal contributor to sound levels < 30 Hz. At SF, annual measured broadband SPL (i.e., 30 Hz–24 kHz) were dominated by sound sources between 30 Hz and 100 Hz approximately 25% of the time (i.e., upper three percentiles in Figure 7a). Small vessels accounted for the highest levels in this frequency range (i.e., first percentile), but wind was the most common driver. The remaining 75% of the time, annual broadband SPL was predominantly driven by snapping shrimps > 3 kHz, followed by other sources of biophony (i.e., squid, fish, and humpback whales) between 100 and 800 Hz. In contrast, biophony between 200 and 800 Hz was the prominent driver of annual broadband SPL approximately 50% of the time at AB1 (Figure 7c) and 100% of the time at AB2a (Figure 7e). Snapping shrimps > 3 kHz dominated the other 50% of the time at AB1. At AB2b, biophony between 50 Hz and 800 Hz was the dominant contributor to annual broadband SPL levels approximately 50% of the time, while snapping shrimp dominated the remaining 50% (Figure 7g). Large vessels dominated sound levels < 2 kHz 25% of the time, seen as a spectral hump between 20 and 150 Hz in the lower three percentiles of Figure 7g.

Over April–June, the sound budgets at SF and AB1 were similar to the annual sound budgets (Figure 7b,d). Fish choruses dominated broadband SPL for 5% of the time at AB2a, while wind and snapping shrimps dominated for the remaining 95% of the time (Figure 7f). At AB2b, the contribution from biophony over the 150 Hz–1 kHz frequency range reduced considerably over April–June (Figure 7h). Large vessels dominated the soundscape for 5% of the time while snapping shrimp dominated the remaining 95% of the time. Fish choruses were seen as spectral peaks between 200 and 700 Hz, but the percentiles in this range never exceeded those at both lower and higher frequencies at the same time.

Probability densities indicated that sound levels between 10 Hz and 1 kHz were uniformly spread between the 1st and 99th percentiles at SF, AB1, and AB2b. In other words, all values of SPL between the 1st and 99th percentile levels were equally likely to occur. Above 1 kHz, the most probable (common) sound levels matched the median level. At AB2a, the most probable (common) levels equalled the median levels over the entire frequency range.

3.2.2. Wind Noise Model

Maps of modelled wind noise over 2015 are shown in Figure 8. Modelled wind noise in 2015 ranged from 97 to 101 dB re $1 \mu\text{Pa}^2$, with lowest received levels modelled for St. Francis Bay. A comparison between sites revealed a ~ 1 dB increase in wind-driven noise from west to east with an SPL of 98 dB re $1 \mu\text{Pa}^2$ modelled for SF and AB1, and an SPL of 99 dB re $1 \mu\text{Pa}^2$ modelled for both AB2 sites (Table 3). Wind models over April–June showed a decrease of ~ 1 dB in both bays. Consequently, the pattern of increased wind noise at the recording sites from west to east was also seen in April–June (Table 3). While this trend of increasing wind noise from west to east directly related to the increase in observed wind speed (i.e., the input data into our wind noise model), the 1 dB difference was small compared to the uncertainty in absolute wind noise levels. Modelled wind noise depends on the altitude above the sea surface at which wind speed is measured, on the water depth, and on the seafloor composition. However, with all of our acoustic recording sites in shallow water close to shore, these factors would have had the same effect at all sites.

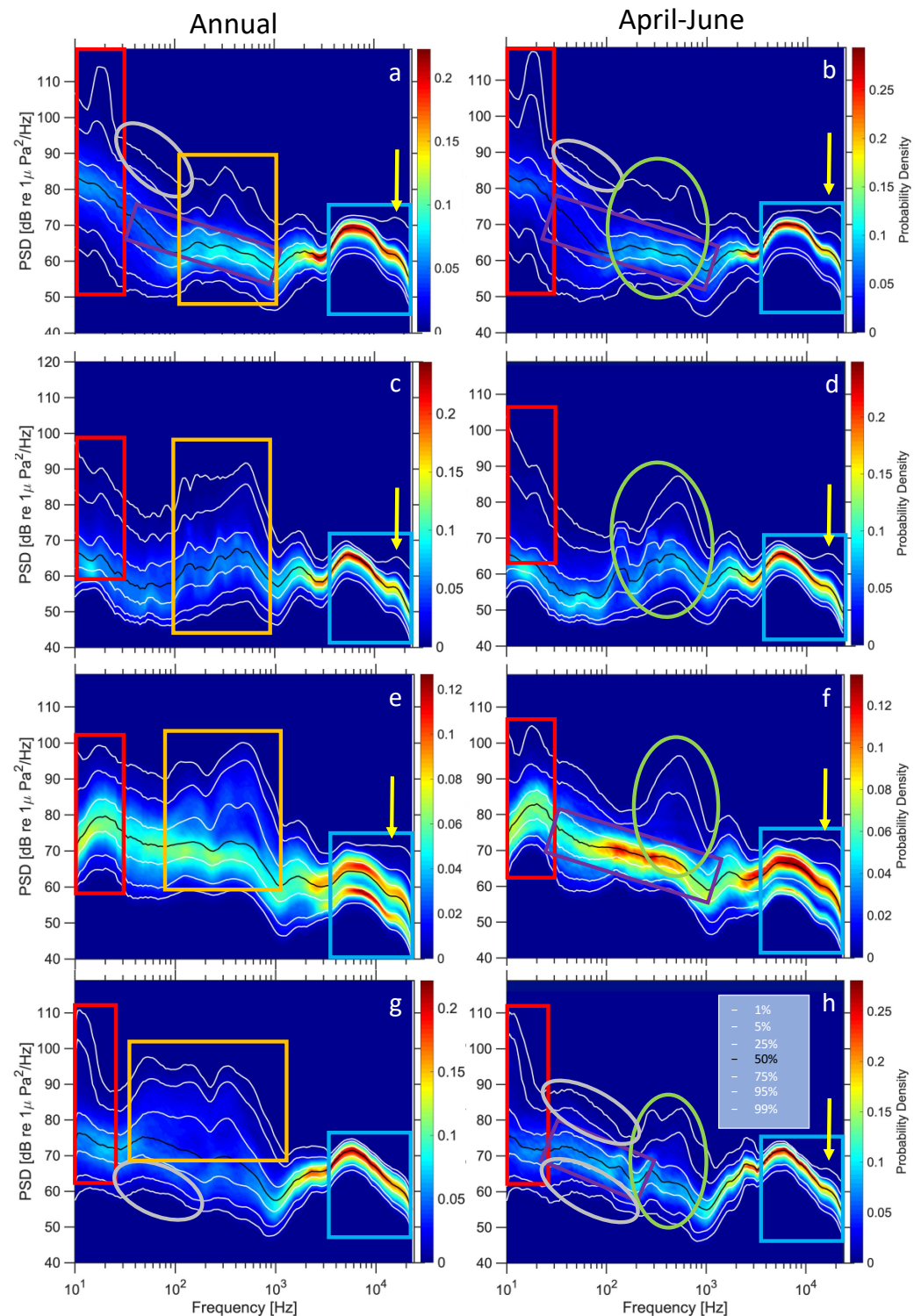


Figure 7. Power spectral density (PSD) percentile and power spectral probability density (PSPD) plots for SF (a,b), AB1 (c,d), AB2a (e,f), and AB2b (g,h) from top to bottom, respectively. Left panels are based on annual data, right panels are based on data for the same year, but only from April to June. Flow noise (red boxes), wind (purple boxes), combined biophony (i.e., squid, fish, and humpback whales overlapping in frequency: orange boxes), snapping shrimp (blue boxes), and dolphin buzzes (yellow arrows) were the main contributors to measured sound levels. Biophony between 100 Hz and 1 kHz in April-June was dominated by fish choruses (green ellipses). Vessels contributed to sound levels at all sites but could only be identified in plots for SF (a,b) and AB2b (g,h: grey ellipses).

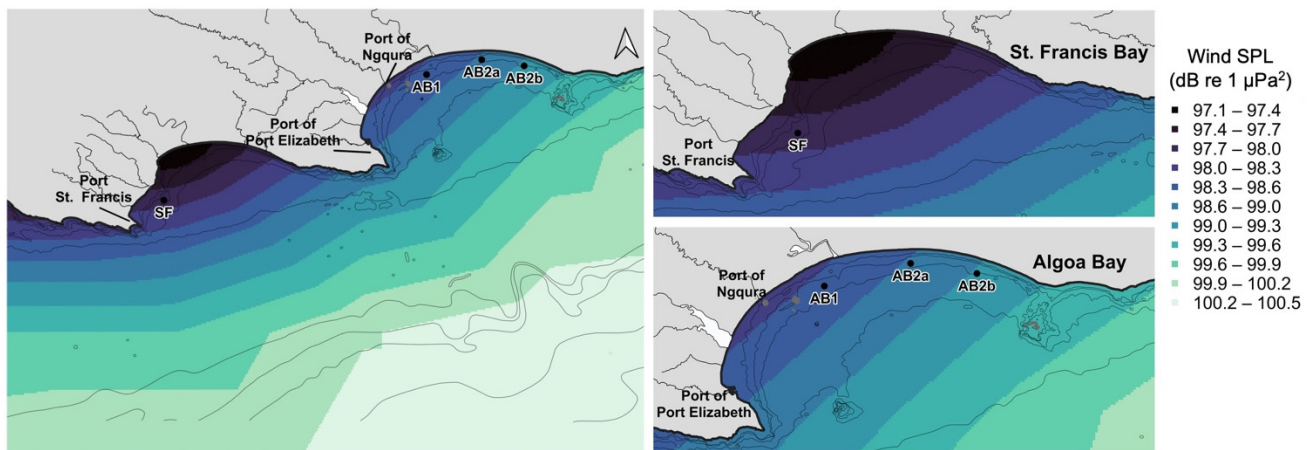


Figure 8. Modelled average wind noise levels (SPL) in St. Francis Bay and Algoa Bay over the whole of 2015. Modelled levels were similar over April–June.

3.2.3. Vessel Noise Model

A map of modelled vessel SPL over all classes is shown in Figure 9, while maps for individual vessel classes are available in the Supplementary Material Figure S9. Lowest received levels were modelled for the northwest–north coastal waters of St. Francis Bay (76–80 dB re 1 μPa^2) and along the northern coast of Algoa Bay (87–90 dB re 1 μPa^2). Highest received levels were modelled for the shipping lanes approaching the Port of Port Elizabeth and the Port of Ngqura. Vessel noise was also high around the eastern side of the Algoa Bay mouth, where vessels transit over quartzite consolidated sediment with a thin layer of sand. Modelled levels (for all classes combined) at the recording sites revealed a small (i.e., ≤ 5 dB) decrease in vessel noise from west to east, with an SPL of 99, 98, and 94 dB re 1 μPa^2 modelled for SF, AB1, and both AB2 sites, respectively (Table 3). However, modelled levels between recording sites varied by 1–23 dB for classes 1–4 (Table 3). We assumed average received levels over April–June to approximate annual average received levels.

Table 3. Comparison of measured sound pressure level (SPL), modelled vessel SPL, and modelled wind SPL for each site over a period of a year and over April–June. All SPL values are mean-square sound pressure, averaged over 12 and 3 months (April–June), respectively. Vessel and wind noise model results are based on data from 2015. Measured SPL were calculated from data recorded in or nearest to 2015 and integrated over 30 Hz–2 kHz. * We assumed that vessel noise SPL over April–June was equal to vessel noise SPL over the whole year.

Site	Data Set	Annual SPL Measured [dB re 1 μPa^2]	Annual SPL Modelled [dB re 1 μPa^2] <i>Vessel</i> All Classes (Class1 Class2 Class3 Class4 Class5 Class6)	<i>Wind</i>	<i>Vessel & Wind</i>	Annual SPL Difference [dB] <i>Measured- Modelled</i>	April-June SPL Measured [dB re 1 μPa^2]	April-June SPL Modelled * [dB re 1 μPa^2] <i>Wind</i>	<i>Vessel & Wind</i>	April-June SPL Difference [dB] <i>Measured- Modelled</i>
SF	2015–2016	112	All classes: 99 (47 62 70 83 95 97)	98	102	10	101	98	102	−1
AB1	2015–2016	106	All classes: 98 (24 45 58 67 92 97)	98	101	5	101	98	101	0
AB2a	2017	114	All classes: 94 (38 44 47 65 89 92)	99	100	14	108	98	99	9
AB2b	2015	109	All classes: 94 (29 46 50 78 88 92)	99	100	9	101	99	100	1

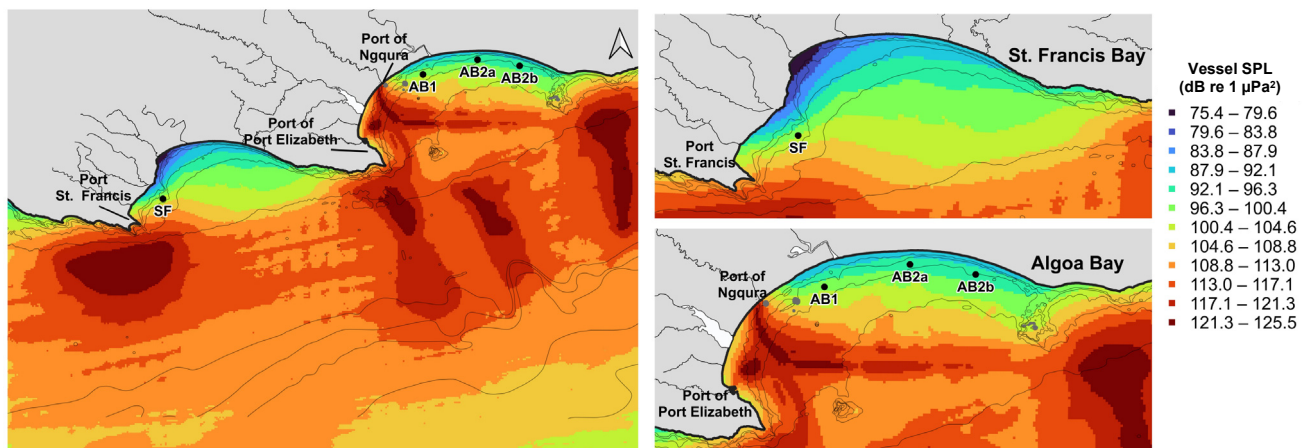


Figure 9. Modelled average received mean-square sound pressure level (SPL) from all vessel classes combined, in St. Francis Bay and Algoa Bay, Eastern Cape, South Africa. Levels represent the maximum over the top 100 m from vessels traversing up to 80 km from Cape St. Francis (i.e., headland south of Port St. Francis).

3.2.4. Predicting Spatial Changes in Sound Budgets

Table 3 summarises the comparison between average measured (30 Hz–2 kHz) and modelled SPL (i.e., model validation). Annual measured SPL exceeded both modelled vessel and wind SPL. A comparison between modelled annual wind and vessel SPL at each site (Table 3 and Figure 10) revealed that modelled vessel and wind noise were approximately equal at SF and AB1. At both AB2 sites, modelled wind noise exceeded modelled vessel noise by ~5 dB. Annual results for AB2a and AB2b agreed well with the identification of sound sources from manual inspections and annual PSD%PD graphs. Agreement was less strong for SF and AB1. The annual PSD%PD graph for SF identified wind as the dominant contributor to underwater noise levels < 2 kHz and so the wind noise model likely underestimated wind noise at SF. In addition, modelled SPL from large vessels at SF exceeded modelled SPL from smaller classes and modelled SPL from the same class at sites AB2a and AB2b. This was in contrast with our manual spectrogram analyses, which identified small vessels (i.e., <50 m) as the main source of vessel noise at SF and large vessels as a more important contributor at AB2a and AB2b. Modelled vessel SPL from classes 5 and 6 at AB1 also exceeded those modelled for both AB2 sites where large vessels were more often detected. It is therefore likely that our vessel noise model overestimated received SPL from large vessels (i.e., classes 4–6) at SF and AB1. Similar conclusions can be drawn from the comparison of April–June levels.

Disagreements between modelled and measured levels indicate that inference on changes in sound budgets over large spatial scales should be made with caution. However, the contribution of vessel noise generally increases towards shipping lanes and from our modelled and measured levels it is evident that vessel noise was more pronounced on the eastern side of Algoa Bay. While modelled wind SPL also increased towards shipping lanes and the eastern side of Algoa Bay, modelled vessel SPL exceeded modelled wind SPL throughout most of Algoa Bay (Figure 10). We therefore predict an increase in the contribution of vessel noise to noise budgets moving south from the deployment sites in Algoa Bay and moving east from site AB2b towards the Bird Island group.

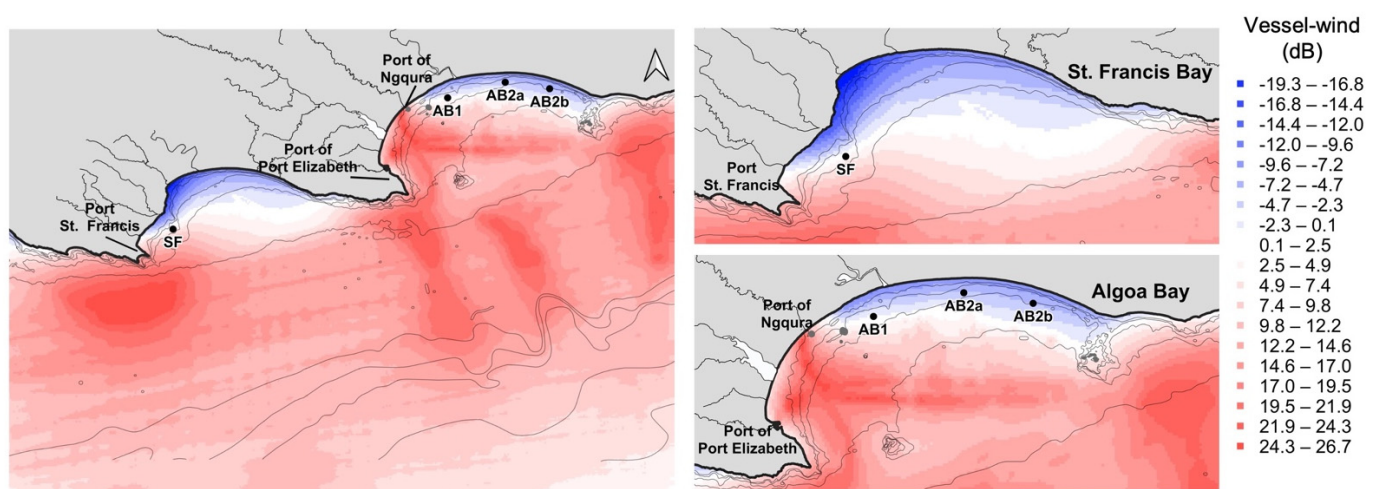


Figure 10. Modelled vessel noise less modelled wind noise in St. Francis Bay and Algoa Bay. Blue shades indicate areas where wind noise exceeded vessel noise, white area indicates the transition phase where vessel noise started to dominate wind noise, and red shades indicate areas where vessel noise exceeded wind noise.

4. Discussion

This study provides a first underwater soundscape description for the shallow marine environment in two South African bays through acoustic measurements and modelling. At all sites, the prominent sources of biophony, geophony, and anthropophony were biological signals and choruses (i.e., humpback whales, fishes, squids, and snapping shrimps), wind, and vessels, respectively. Temporal fluctuations in broadband sound levels (i.e., 30 Hz–24 kHz) were primarily driven by time of year and time of day, with higher levels in summer and at dusk/night. Inspections of annual PSD%PD plots for each site identified biophony and wind as principal drivers of these temporal patterns. The contribution of wind became more prominent over April–June at SF and AB2a, while both wind and vessel noise became more prominent at AB2b. Based on measurements and sound propagation modelling, we predict an increase in the contribution of vessel noise to noise budgets moving south of our Algoa Bay recording sites and towards the Bird Island group on the eastern side of Algoa Bay.

Biophony and wind were the principal contributors to annual sound budgets at all sites, suggesting that these two sound sources drive variability in SPL (30 Hz–24 kHz) with time of year and time of day. However, wind speed was not identified as an important predictor variable in our regression tree analyses. Although historical data for our study area identified October–December as the windiest months [107], a more recent study has reported a changing trend with below-average wind speeds in summer and above-average wind speeds in winter [108]. These changes may have resulted in a more uniform wind speed pattern throughout the year, explaining the absence of clear wind-driven patterns in SPLs. The increase in SPL in summer and year-round presence of a diurnal period was most consistent with the diversity and intensity of choruses in summer (i.e., three fish choruses and squid chorus) as well as the typical presence of choruses from dusk until midnight. The increase in SPL at dusk/night was generally less pronounced over the winter months, which can be explained by the presence of strong humpback whale vocalisations throughout the day. Similar biophony-driven temporal patterns have been observed in New Zealand [109,110] and the eastern Taiwan Strait [111]. Nevertheless, our periodogram analyses also identified shorter (i.e., 6 h and 8 h) and multiday periods, while regression trees included the moon, tide, and wind as less important predictor variables. Our PSD%PD plot for April–June further indicates that wind became a more important component of the soundscape in the absence of humpback whales and multi-species choruses. Hence, variability in SPLs was likely the result of more complex interactions between predictor

variables and individual soundscape contributors, which are easier to assess over smaller time scales (e.g., time scale over which a specific chorus occurs [112]) and separate frequency bands [24,113].

Although natural sound sources were the principal contributors to sound budgets at all sites, large vessels were identified as a prominent sound source at AB2b between 30 and 100 Hz for 25% of the time. Manual inspections of sound files verified that these large vessels contributed to noise levels over extended periods of time (i.e., full length of recording sample). In addition, propagation models predicted an increase in vessel noise contribution near shipping lanes and towards the Bird Island group on the eastern side of Algoa Bay. This is of concern because our results stress that vessel noise is present within the AEMPA in which the Bird Island group provides an important breeding habitat for various marine species (i.e., Cape gannets, *Morus capensis*; South African fur seals, *Arctocephalus pusillus*; and South African penguins: [52,63,114,115]). Specifically, seals and penguins may be sensitive to underwater vessel noise with potential negative effects on breeding success. It should also be noted that, irrespective of vessel noise not distinctly featuring in most of our PSD%PD plots, vessel passages did change sound levels over periods of time at SF, AB1, and AB2a too. Thus, vessels may have a potential negative effect (e.g., masking of communication signals, increased stress, and behavioural changes [36–38]) on marine species in both bays. Under a developing ocean economy (i.e., *Operation Phakisa*), the contribution of vessel noise to sound levels within the study area can be expected to increase over time. In addition to a likely increase in offshore vessel traffic, container vessel traffic inside Algoa Bay can be expected to increase by a factor of six within the next 40 years because of a six-fold increase in berth capacity at the Port of Ngqura [66], potentially resulting in an 8 dB increase in vessel noise. Furthermore, future ship-to-ship bunkering activities (potentially starting in 2022) will increase noise levels from continuous dynamic positioning.

Disagreements between modelled and measured received vessel noise were partially caused by a generalisation of ship source levels based on the median speed of all vessels within one vessel class. Vessels reduce speed in their approach to port, resulting in decreased source levels [81,116,117] with a consequent overestimate of our modelled received levels [118–120], in particular at site AB1 because of its proximity to the Port of Coega. We further used the RANDI model to calculate the source level for each vessel class, which is based on vessel size and speed alone. Other studies have found that source levels also depend on vessel type [116,117,121]. In particular, the RANDI model was found to overpredict source levels for container vessels and bulk carriers [116], which were the predominant vessel types calling on port in Algoa Bay. In terms of the sound propagation environment, our model used range-independent geoacoustic properties (i.e., propagation was modelled based on the geoacoustic properties of the source-cell), which may explain the overestimated received levels from large vessels at SF. Site SF is for ~75% of neighbouring grid cells enclosed by areas with an unconsolidated sediment-layer thickness of ~8 m and sees a ~22 m layer of accumulated sand ~9 km south of the recording site. Yet, the propagation of sound from large vessels farther offshore (i.e., 15–80 km away) were modelled with a 0.5 m thick unconsolidated layer of sand. These thicker layers of sand complicate interference patterns in transmission loss at higher frequencies and thus yield variable received levels over relatively short spatial scales [122]. Further model disagreement originated from the limited AIS coverage of small vessels, which may contribute significantly to coastal soundscapes [123]. Private vessels are not fitted with an AIS system and although small commercial vessels (e.g., fishing vessels) generally possess an AIS system, the system is not always in use. Finally, it should be noted that our model did not include noise from vessels outside of our modelled area and therefore underestimated noise levels at the far east boundary of the AEMPA.

With regards to the wind model, we have to note that wind can be a prominent contributor to lower frequencies (i.e., <200 Hz) in the absence of vessel noise [124]. Yet, because low-frequency dependency on wind varies more over space and time than the

mid-frequency dependency [25,125], we used source spectra > 200 Hz based on the Wenz curves [25]. Consequently, our wind noise model may have underestimated wind-driven noise. We furthermore interpolated wind speed measurements via linear interpolation and thus assumed gradual changes in wind speed between measurement points, while ignoring effects of wind direction. In practice, wind speed in coastal areas changes at more irregular patterns because of interactions with land features (e.g., venturi effects or wind shadows).

It should be noted that we have only discussed expected spatial changes in sound budgets with respect to changes in wind and vessel noise. This is because we were able to model the sound propagation from these sources with relatively well-documented data on source location and source levels. In reality, sound budgets also change because of changes in biophony. The choruses from fish and squid, for example, typically propagate over distances < 2 km [126,127], and so originate from species near the recording site. If their calling behaviour is specific to the habitat surrounding the recording site, then their contribution to the sound budget, and thus the contribution from biophony, may change rapidly when moving away from the recording site. Humpback whales produce strong calls, which have the potential to propagate over larger ranges depending on environmental conditions [128]. Their contribution to the sound budget is, therefore, less likely to change over very short spatial scales.

We encourage additional soundscape studies in Algoa Bay to obtain a better understanding of spatial variation in noise budgets, with a focus around the Bird Island group and busy shipping areas. Temporal variations should be studied in more detail (i.e., smaller spatial scales and frequency bands) to tease apart interactions between different sound sources and between sound sources and predictor variables, which will provide a better base to monitor for changes in sound budgets [24]. An attempt should also be made to improve vessel and wind noise propagation models so that they can aid identification of additional areas where soundscape monitoring and management may be required [129,130]. Furthermore, we encourage an extension of soundscape studies to other places along the South African coast. Although our study area may be representative of other bays along the South African coast, there are several locations where vessel pressure is expected to be noticeably greater (i.e., Cape Town and Durban with larger ports) or smaller (i.e., west coast with vessel routes farther offshore).

5. Conclusions

Our study has provided baseline information on soundscape contributors, temporal patterns in broadband SPL, and noise budgets in two bays along the Eastern Cape coast of South Africa. We have shown that the soundscape is generally pristine, but that vessel noise is present in both bays—with significant contributions in the centre and on the eastern side of Algoa Bay. Our study provides a building block to monitor for shifts in sound budgets and changes in temporal patterns in these two bays under a developing ocean economy. Furthermore, the Port of Port Elizabeth and the Port of Ngqura only receive a fraction of vessel traffic in comparison to the Port of Durban and Port of Cape Town and so our study raises concern that vessel noise is likely a significant contributor in other shallow water soundscapes.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse10060746/s1>, Figure S1: Long-term spectral averages for each site per year with shorter LTSA snippets to illustrate choruses and vessel presence; Table S1: Table with bathymetric, hydroacoustic, and geoacoustic properties for the 25 acoustic zones; Figure S2: Example plot of clustered source-receiver transects; Figure S3: Example plots of propagation loss along bathymetry cluster centroids; Figures S4–S7: Whittaker–Robinson periodograms for all deployments; Figure S8: Regression trees for each recording site; Figure S9: Maps of average received vessel noise (i.e., SPL) per vessel class.

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Data Availability Statement: Long-term spectral average figures; a table with bathymetric, hydroacoustic, and geoacoustic properties for each zone; periodograms for each deployment; regression trees for each site; and figures with modelled vessel noise per vessel class are available in the supplementary material. A shapefile with modelled vessel noise is available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

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