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Sound Decisions: Moving forward with Acoustics

A passive acoustic survey for marine mammals conducted during the 2019 Antarctic voyage on Euphausiids and Nutrient Recycling in Cetacean Hotspots (ENRICH)

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ABSTRACT

The 2019 ENRICH Voyage (Euphausiids and Nutrient Recycling in Cetacean Hotspots), was conducted from 19 January – 5 March 2019, aboard the *RV Investigator*. The voyage departed from and returned to Hobart, Tasmania, Australia, and conducted most marine science operations in the area between 60°S – 67°S and 138°E – 152°E. As part of the multidisciplinary research programme, a passive acoustic survey for marine mammals was undertaken for the duration of the voyage, with the main goal to monitor for and locate groups of calling Antarctic blue whales (*Balaenoptera musculus intermedia*). Directional sonobuoys were used at 295 listening stations, which resulted in 828 hours of acoustic recordings. Monitoring also took place for pygmy blue, (*B. m. brevicauda*), fin, (*B. physalus*), sperm (*Physeter macrocephalus*), humpback (*Megaptera novaeangliae*), sei (*B. borealis*), and Antarctic minke whales (*B. bonarensis*); for leopard (*Hydrurga leptonyx*), crabeater (*Lobodon carcinophaga*), Ross (*Ommatophoca rossii*), and Weddell seals (*Leptonychotes weddellii*), and for odontocete (low frequency whistles) vocalisations during each listening station. Calibrated measurements of the bearing and intensity of the majority of calls from blue and fin whales were obtained in real time. 33,435 calls from Antarctic blue whales were detected at 238 listening stations throughout the voyage, most of them south of 60°S. Southeast Indian Ocean blue whale song was detected primarily between 47° and 55°S while the southwest Pacific blue whale song was recorded between 44° and 48°S. Most baleen whale and seal calls were detected along the continental shelf break in the study region but some were also detected in deeper waters. Marine mammal calls were uncommon on the shelf, which did not have any ice cover during the survey. Calling Antarctic blue whales were tracked and located on multiple occasions to enable closer study of their fine-scale movements and calling behaviour as well as enabling collection of photo ID, behavioural, and photogrammetry data. The passive acoustic data collected during this voyage will allow investigation of the distribution of Antarctic blue whales in relation to environmental correlates measured during ENRICH, with a focus on blue whale prey.

1 INTRODUCTION

The Euphausiids and Nutrient Recycling In Cetacean Hotspots (ENRICH) voyage focused on understanding predator-prey interactions between whales and krill, krill and phytoplankton, and the effects of these animals on iron recycling. The study was conducted during a 45-day Antarctic voyage on the RV *Investigator* from 19 Jan – 5 Mar 2019, focusing on an area located off East Antarctica in the D'Urville Sea from 60°S – 67°S and between 138°E – 152°E; Figure 1). The ENRICH voyage was multidisciplinary with numerous modes of scientific operation and varied activities conducted during the voyage. A detailed description of each of these modes and the associated activities can be found in the ENRICH Voyage Report (Double 2019). Here we provide a summary of the passive acoustic survey for marine mammals conducted throughout the voyage.

Passive acoustic research during ENRICH expanded upon methods developed during previous Antarctic whale surveys conducted by the Australian Antarctic Division (Gedamke and Robinson 2010; Miller et al. 2015, 2016, 2017). Methods employed during ENRICH involved structured passive acoustic monitoring of marine mammals using sonobuoys (Gedamke and Robinson 2010; Miller et al. 2017) and focused on acoustic tracking of critically endangered Antarctic blue whales (*Balaenoptera musculus intermedia*) (Miller et al., 2015). This included a novel experimental design which aimed to compare the number of calls detected with the number of animals seen in a given area.

One element of the survey design for the ENRICH voyage was an adaptive survey with broad-scale, 200 km-long, parallel transects perpendicular to the continental slope. The broad scale transects ran from the continental shelf in the south through the southern boundary of the Antarctic Circumpolar Current in the north. In addition to broad-scale transects, there were multiple smaller-scale structured and unstructured surveys conducted within the study area with transect line lengths ranging from approximately 4 to 80 km. These were conducted chiefly for the purposes of passive and active acoustic surveys.

The passive acoustic research conducted was fundamental to addressing two key science objectives of the voyage. These were:

- Comparison of the krill prey field in the presence and absence of a large predator, Antarctic blue whales, by remotely detecting and tracking the location of Antarctic blue whale aggregations and using active acoustics to map krill swarms.
- Description of the distribution and behaviour of Antarctic blue whales on foraging grounds by investigating the relationships between vocalisations, density, movements and surface behaviour, and comparing the local prey field around whales exhibiting different behaviours.

Analysis to complete these voyage objectives is ongoing, but here we focus on the preliminary results from the passive acoustic survey with emphasis on the distribution of marine mammals throughout the study region.

2 METHODS

We carried out passive acoustic surveys for marine mammals throughout the ENRICH voyage using sonobuoys. Sonobuoy deployments occurred around the clock with listening stations conducted by pairs of acousticians. Passive acoustic research took the form of both broad-scale structured surveys and fine-scale adaptive surveys depending on the operational mode of the ship. Regardless of the mode of operation, listening stations were conducted by deploying SSQ955 sonobuoys (commonly called HIDAR sonobuoys) in Directional and Frequency Analysis and Recording (DIFAR) mode to monitor for and measure bearings to vocalising whales while the ship was underway (Miller et al. 2015).

2.1 Instrumentation, software, and data collection

At each listening station, a HIDAR sonobuoy was deployed with the hydrophone set to a depth of 140 m. Sonobuoys transmitted underwater acoustic signals from the hydrophone and directional sensors back to the ship via a VHF radio transmitter. Radio signals from the sonobuoy were received using one of four VHF antennas (one Yagi and three omnidirectional/collinear) mounted at various locations on the flying bridge or superstructure of the vessel. Radio reception range was typically 10-12 nmi, and was broadly similar to other Antarctic voyages (Miller et al. 2015; Gedamke and Robinson 2010; Širović and Hildebrand 2011). The antennas were each directly connected to a Winradio G39WSBe sonobuoy receiver via low-loss LMR400 coaxial cable.

Received signals were digitised via the instrument inputs of a Fireface UFX sound board (RME Fireface; RME Inc.) with the gain set to 20 dB (maximum undistorted input voltage of 8.396 volts peak-peak). Digitised signals were recorded on a personal computer as 48 kHz 24-bit WAV audio files using the software program PAMGuard (Gillespie et al. 2008). Data from both the Yagi and omnidirectional/collinear antennas were recorded simultaneously as WAV audio channels 0, 1, and 2. Many of the recorded WAV files therefore contain a substantial amount of duplication since multiple antennas and receivers were often receiving the same signals from the same sonobuoy.

2.1.1 Directional calibration

The magnetic compass in each sonobuoy was calibrated and validated upon deployment as described by Miller et al. (2015, 2016). Calibration procedure involved measuring the mean bearing error and standard deviation of errors between the GPS-derived bearing from the sonobuoy to the ship and the magnetic bearing to the ship noise detected by the sonobuoy. As a rule, 10-15 bearings were used for each calibration as the ship steamed directly away from the deployment location. Because the *RV Investigator* is a very quiet ship, calibration using standard ship noise was often challenging or impossible. Whenever possible, acousticians would request that the ship undertake a noisy manoeuvre (i.e. slowing) just after deployment in order to generate sufficient noise to obtain a calibration. When there was insufficient ship noise to provide a calibration, the local magnetic variation was used as the sonobuoy compass correction. The local magnetic variation was obtained from PAMGuard, which supplied magnetic variation using the World Magnetic Model 2015.

Unfortunately, challenges with calibrating the sonobuoy compass extended beyond that of a quiet ship. Specifically, the western portion of the study area was located in close proximity to the magnetic South Pole (135°E). As a result, sonobuoys west of 140°E often could not be calibrated, or seemed to lose their calibration during the period of monitoring such that bearings varied considerably (up to 180°) for successive sounds that were expected to be from the same direction. Eventually it was decided that the passive acoustic study area should be limited to the area east of 140°E. The great majority of sonobuoys east of 140°E yielded good calibrations with plausible, consistent, and reliable bearings.

2.1.2 Intensity calibration

Calibrated acoustic intensity measurements were obtained throughout the voyage. This was achieved via the PAMGuard DIFAR module in conjunction with intensity calibrations from other PAMGuard modules. Two calibrations were entered via the Hydrophone Array Manager in PAMGuard. First, a hydrophone sensitivity of -122 dB re 1 V/μPa was applied, defined in the DIFAR specification as the reference RMS intensity at 100 Hz that will generate a frequency deviation of 25 kHz (Maranda 2001). Second, a 'preamplifier gain' of -9.09 dB was entered, representing the voltage 'gain' of the Winradio receiver (*sensu* Maranda, 2001). In line with manufacturer's specifications, all of the Winradio G39 WSBe had a flat measured voltage response of 1 V peak–peak (approximately -9 dB RMS) at 25 kHz frequency deviation over the audio band of 0.01 -24 kHz (Miller et al. 2014). The combined hydrophone sensitivity and preamplifier gain yielded a system sensitivity of -131 dB re 1 V/μPa. Next, the voltage range of the Sound Acquisition module in PAMGuard was set to match that of the sound board: 8.396 V peak-peak. This voltage was measured directly while the gain of the instrument input on the Fireface UFX was set to 20 dB, so the preamplifier gain in the Sound Acquisition module was set to 0. Lastly, an inverse frequency-response of the sonobuoy shaped-filter (see Greene et al. 2004) was applied by the PAMGuard DIFAR module to obtain calibrated RMS pressure measurements (i.e. in dB re 1 μPa) from the sonobuoy recording chain.

2.1.3 Acoustic monitoring and analysis

Aural and visual monitoring of audio and spectrograms from each sonobuoy was conducted using PAMGuard for at least an hour at each listening station (mean 2.9 hours – excluding failed sonobuoys). Two different spectrograms were typically viewed. For low-frequency sounds we used the following parameters: 250 Hz sample rate; 256 sample FFT; 32 sample advance between time slices, 120 s duration per screen. To view mid-frequency sounds, we used: 8000 Hz sample rate; 1024 sample FFT; 128 sample advance between time slices, 30 s duration per screen. Monitoring was conducted in real-time during data acquisition, and the intensity scale of the spectrogram was adjusted by the operator to suit the ambient noise conditions (with typically 40-50 dB between minimum and maximum intensity).

When signals from marine mammals, ice, or other sources were detected, they were classified manually to species/call-type, and their time and frequency bounds marked on the spectrogram. The PAMGuard DIFAR module (Miller et al. 2016) was then used to measure the direction of arrival and intensity of suitable calls including tonal, frequency-modulated, and pulsed calls of baleen whales, whistles and trills from pinnipeds, and some whistles from toothed whales. Spectrograms of these and other exemplary sounds and call types can be found in the Appendix (Figure A1). Echolocation clicks from sperm whales (*Physeter macrocephalus*) and blackfish were noted in the species summary log, but could not be localised due to limitations inherent in directional sensors in the sonobuoy. Detection, bearing, and intensity measurements were saved both within a PAMGuard binary file and the DIFAR localisation table of the PAMGuard SQLite database. PAMGuard settings and metadata were also saved to the PAMGuard database.

To fulfil voyage objectives, calls from Antarctic blue whales were given priority during periods when multi-species detections were too numerous to measure all sounds in real-time. Four different classifications for Antarctic blue whale sounds were used during the voyage: 'unit a' consisted of the tonal unit of stereotyped blue whale song;

'unit-b' consisted of the tonal and downswept unit together; Z-calls included all three units of Antarctic blue whale song; and D-calls included usual downswept calls as well as other frequency modulated calls produced by blue whales (Miller et al. 2015).

2.2 Survey design and listening regimes

During the voyage, a variety of operational modes were undertaken based on the suite of scientific activities being conducted on the ship at that time (Double 2019). Passive acoustic data collection occurred during all modes of operation, but was fundamental to 'passive acoustic tracking' mode (described in 2.2.2).

2.2.1 Sonobuoy deployments during transit, transects, and CTD stations

During transit and broad-scale transects, listening stations were conducted every 30 nmi in water depths greater than 200 m, and wind speeds less than ~35 knots. The sampling regime during transit & transects was chosen to achieve good spatial resolution, and was comparable to previous studies (Gedamke and Robinson, 2010; Miller et al., 2015, 2017).

When on CTD stations and during fine-scale active acoustic transects, sonobuoys were deployed approximately 1-4 nmi prior to stopping in order to record for the maximal duration of these operations. This distance ensured good radio signal while minimizing potential for interference between the vessel and the sonobuoy.

2.2.2 Passive acoustic tracking

During portions of the voyage dedicated to passive acoustic tracking, multiple sonobuoys were deployed concurrently to precisely locate Antarctic blue whales (Miller et al. 2015, 2016). Bearings from single sonobuoys, pairs, or triplets were also followed in order to track, locate, and sight blue whales to obtain visual observations of group size, behavior, and photographic identifications. Tracking was conducted during 10 days spread throughout the voyage: 30 Jan, and 2, 5, 9, 13, 17, 19, 22-24 Feb 2019 for a total of 124.1 hours. When conducting activities with whales, sonobuoys were deployed adaptively, often in pairs or triplets with 6-9 nmi spacing. When possible during acoustic tracking, the acousticians also continued to monitor other groups of whales that were judged to be nearby (e.g. within a 20-30 nmi radius of the array), as well as more distant animals. Triplets of sonobuoys were also occasionally deployed during small-scale active acoustic surveys even if there was no opportunity to approach whales.

3 PRELIMINARY RESULTS AND DISCUSSION

Passive acoustic monitoring was successfully conducted throughout the voyage. Ten different species of marine mammals were acoustically detected in the study area (Table 1). Antarctic blue whales were detected most often, both during transit and in the survey area. During transit, the calls from southeast Indian Ocean pygmy blue whales and southwest Pacific pygmy blue whales were also detected. Southeast Indian Ocean blue whale song was detected mostly between 47° and 55°S while the southwest Pacific blue whale song was recorded between 44° and 48°S (Figure 1). Calls from southeast Indian and southwest Pacific blue whales were all very faint tonal units, repeated at intervals similar to that reported from previous studies (McCauley et al. 2018; Miller, Collins, et al. 2014). After initial detections of Antarctic blue whale tonal calls at 60°S, aggregations of blue whales were repeatedly located at the southern ends of broad-scale transects within the study area.

Passive acoustic tracking of blue whales greatly assisted in the achievement of key voyage objectives. Identifying locations with high numbers of blue whale calls allowed us to identify the optimal areas to carry out krill survey transects and a biogeochemical 'process station' for the detailed study of phytoplankton and iron in the vicinity of whales.

Other species detected broadly throughout the study area included fin whales (*B. physalus*), humpback (*Megaptera novaeangliae*) and sperm whales, as well as leopard seals (*Hydrurga leptonyx*) and odontocetes (long-finned pilot (*Globicephala mela*) and/or killer whales (*Orcinus orca*) (Figure 2). Minke whales (*B. bonarensis*), (*B. borealis*) crabeater seals (*Lobodon carcinophaga*), and Ross seals (*Ommatophoca rossii*) were detected at only a small number of listening stations (Figure 2).

3.1 Blue whale detection rates and bearings

Whilst Antarctic blue whale calls were heard on most sonobuoys throughout the area (Table 1; Figure 2), the detection rate, bearings, and received level of (Figure 3; Figure 4; and Figure 5 respectively) suggested that they were mainly distributed in the southern part of the study area. They were seen predominantly in deep water near the continental slope, though 15% of encounters occurred on the shelf in water less than 500 m deep.

Table 1 - Summary of listening station effort and number of stations with detections of each sound type.

Type of effort	Total
Sonobuoys deployed (failures)	295 (15)
Acoustic tracking mode hours	124.1
Sonobuoy-hours total	828.8
Hours with only 1 sonobuoy	368.2
Hours with sonobuoy pairs	150.6
Hours with sonobuoy triplets	55.2
Total time recorded	574.0

Species/type of sound	Total stations
Antarctic blue whale unit ‘a’	238
Antarctic blue whale unit ‘b’	154
Antarctic blue whale Z-call	123
Blue whale FM (D-call)	198
Southeast Indian blue whale	15
Southwest Pacific blue whale	9
Fin whale FM (downsweep)	150
Fin whale 20 Hz pulse	111
Humpback whale	105
Minke whale	4
Sei whale	0
Southern right whale	1
Sperm whale	65
Odontocete whistle	82
Crabeater seal	4
Ross seal	1
Weddell seal	0
Leopard seal	37
Seismic airguns	0
Ice	242

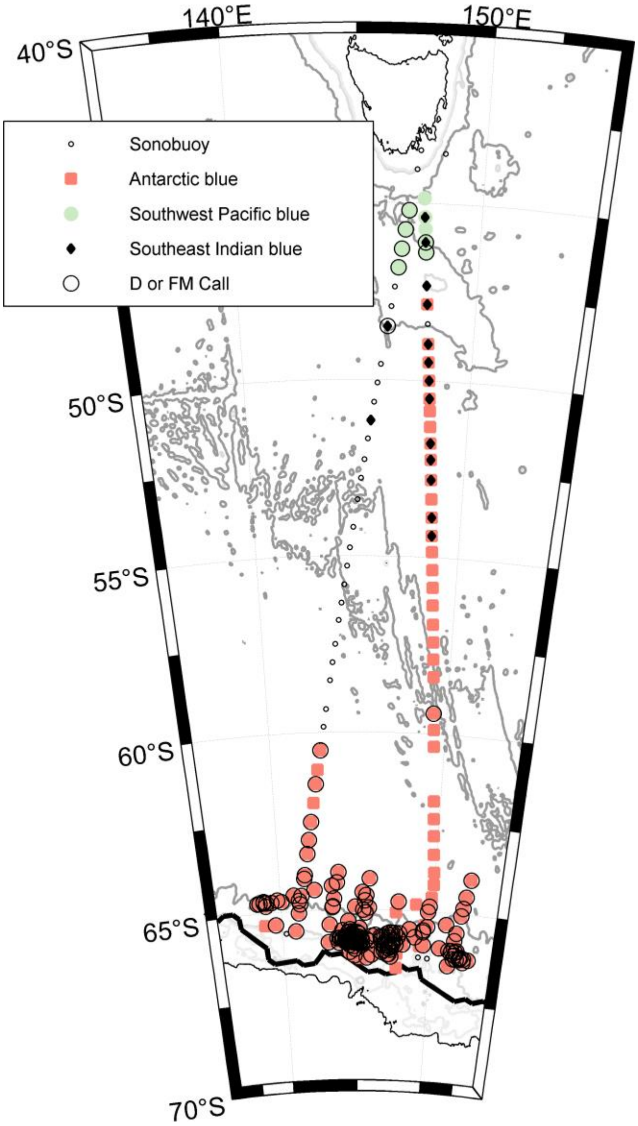

Figure 1 - Blue whale calls by subspecies/population.

As expected, the highest received levels to blue whales occurred in close proximity to sightings. During the voyage an empirically derived threshold of approximately 115 dB re 1 µPa was deemed to be a reasonable indicator that vocal blue whales were within ‘sighting range’ of a sonobuoy (i.e. very likely to be detected by visual observers in suitable weather conditions). The timeline of received levels (Figure 5) indicates when this threshold was exceeded throughout the survey and can be thought of as a simple acoustic proxy for being ‘with Antarctic blue whales’. This figure also illustrates the temporal (and implicitly spatial) variability in received levels due to factors such as background noise from storms, different propagation regimes as well as distance from blue whales. With further work and new statistical methods, it may be possible to account for background noise, propagation regime, and distance and received levels to estimate call density of blue whales (Harris et al. 2018). Additional work beyond that may even allow estimation of the relationship between visually observed density of animals and call density.

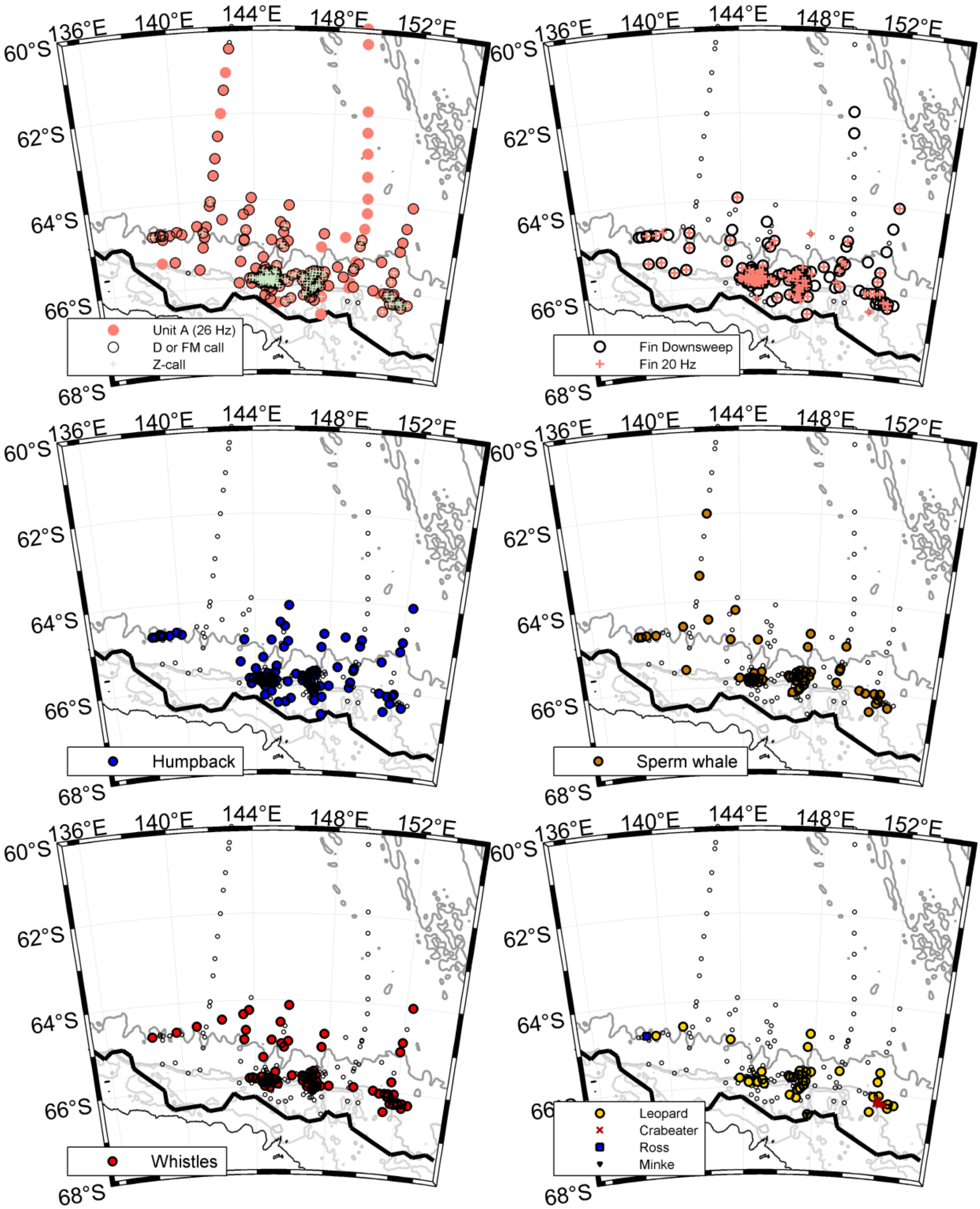

Figure 2 - Sonobuoys (open circles) deployed in the Antarctic study area during 2019 ENRICH voyage with detections of blue whale sounds (top left), fin whale sounds (top right), humpback whale sounds (mid-left), sperm whale sounds (mid-right), odontocete whistles (bottom left), and leopard seal, crabeater seal, Ross seal, and minke whales (bottom right). Thick black line shows the ice edge (10% concentration) on 14 Feb 2019 (AMSR2 ice data; Spreen, Kaleschke, and Heygster 2008). Grey lines from light to dark show the 500, 1000 and 3000 m bathymetry contours.

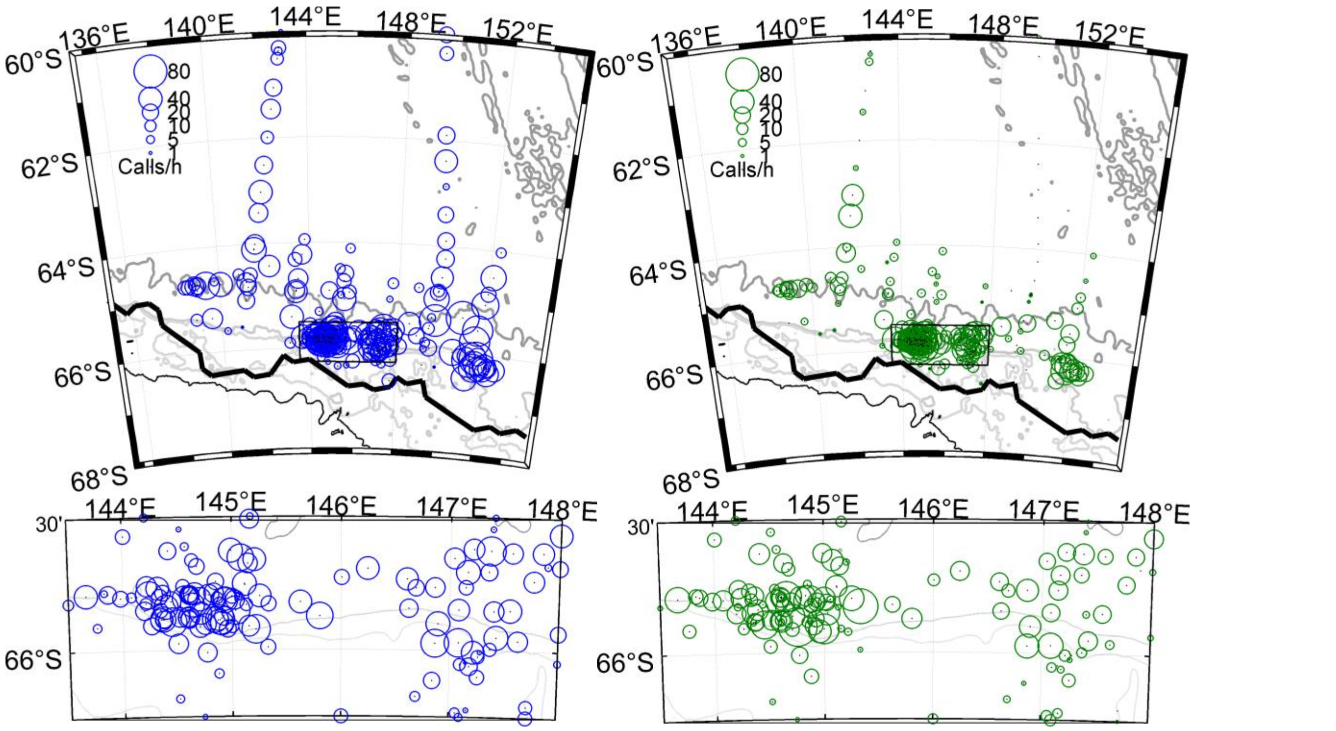

Figure 3 - Detection rates (number of detections per hour of recording effort) of Antarctic blue whale 26 Hz tonals (left) and D-calls (right) recorded on sonobuoys deployed during the 2019 ENRICH voyage. Data from the process station and area where blue whales were encountered are shown in the lower panel. Circle size is proportional to the total number of calls per total hours recorded. Thick black line shows the ice edge (10% concentration) on 14 Feb 2019 (AMSR2 ice data; Spreen, Kaleschke, and Heygster 2008).

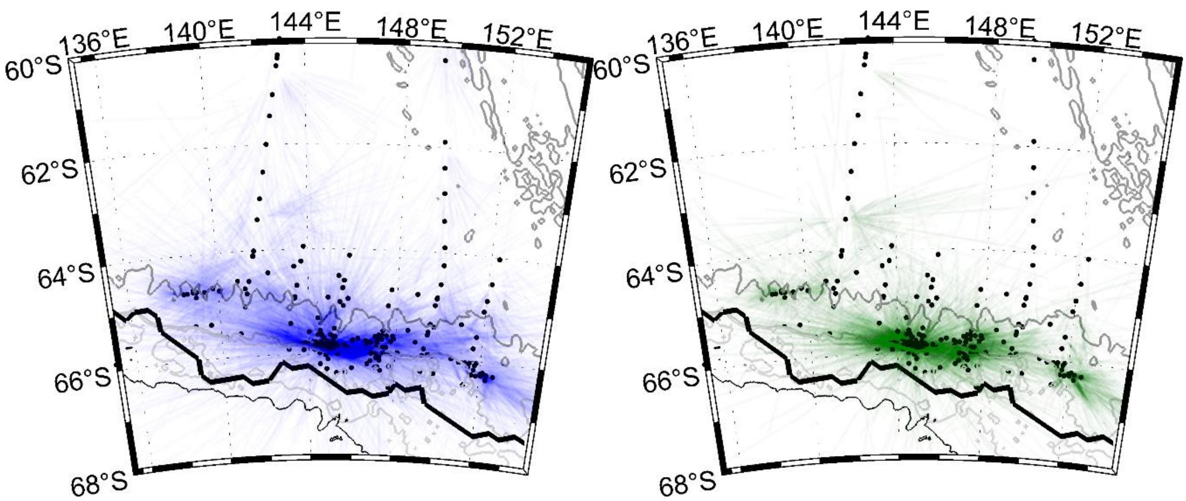

Figure 4 - Bearings to Antarctic blue whale 26 Hz tonals (left) and D-calls (right) during 2019 ENRICH voyage. Bearing lengths are plotted with the assumption of a source level of 182 dB ± 2 dB re 1 μPa, with spherical propagation (20log *r*) out to a transition range of 2000m and cylindrical (10log *r*) beyond 2000 m). Thick black line shows the ice edge (10% concentration) from 14 Feb 2019 (AMSR2 ice data; Spreen, Kaleschke, and Heygster 2008).

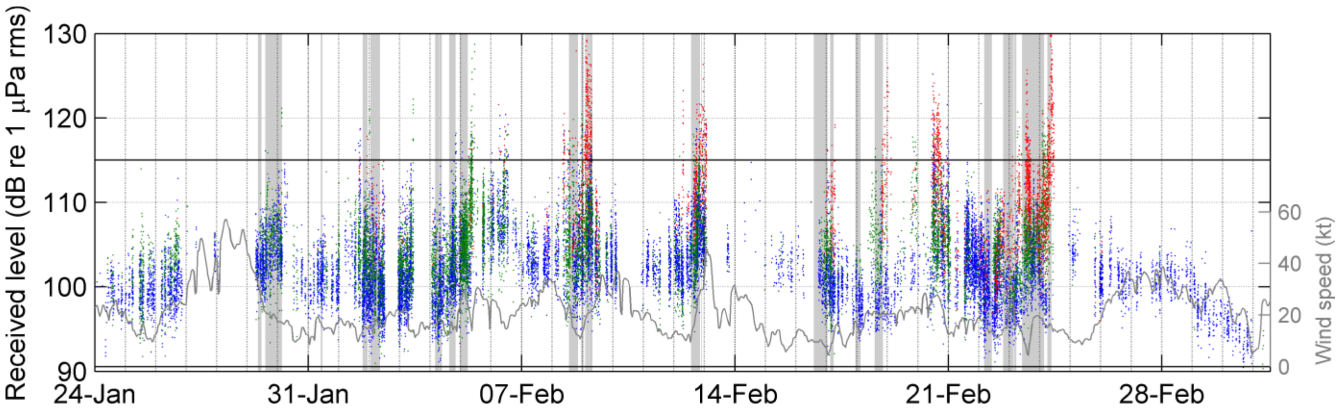

Figure 5 - Timeline and histograms of received levels of calls of Antarctic blue whales during the Enrich 2019 voyage: blue dots are detections of unit A; red dots z-calls; and green dots D-calls. Black line shows a threshold of 115 dB re 1 µPa which preliminary results suggest may be a reasonable indicator of when blue whales were within sighting range of a sonobuoy. Gray line shows a timeline of maximum hourly wind speeds, a major contributor to ambient noise.

4 CONCLUSIONS

Passive acoustic monitoring during the ENRICH voyage yielded acoustic observations of 10 different species of Antarctic marine mammals. Similar to previous studies, acoustic detections of Antarctic blue whales were the most widespread biological sound detected, followed by fin whales, humpback whales, and sperm whales. High densities of most animals were found along the continental shelf break, in sea-ice free waters. Real-time monitoring and directional information collected during the voyage successfully facilitated an adaptive, novel ecological survey design for investigation of krill, phytoplankton, and iron with respect to these species, but particularly blue whales.

DIFAR sonobuoys remain essential for meaningful, dedicated, *in-situ* study of critically endangered Antarctic blue whales. The inclusion of these whales in this ecological study would not have been possible without passive acoustics, and near real-time mapping of their distribution within the survey area would not have been possible without the sufficient quantities of DIFAR sonobuoys.

The consistent and high-quality passive acoustic data collected during the ENRICH voyage will allow future investigation of a number of questions regarding the distribution of Antarctic blue whales and the properties of their acoustic signals. These investigations will focus on the relationship between received level, propagation, and distance to calls and on environmental correlates of blue whale distribution, krill in particular. Visual sightings of marine mammals and focal follows of blue whales were also conducted by a dedicated team of observers during the ENRICH voyage (Double 2019), and future work will compare these visual and acoustic observations.

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APPENDIX – SPECTROGRAMS OF EXEMPLARY CALLS

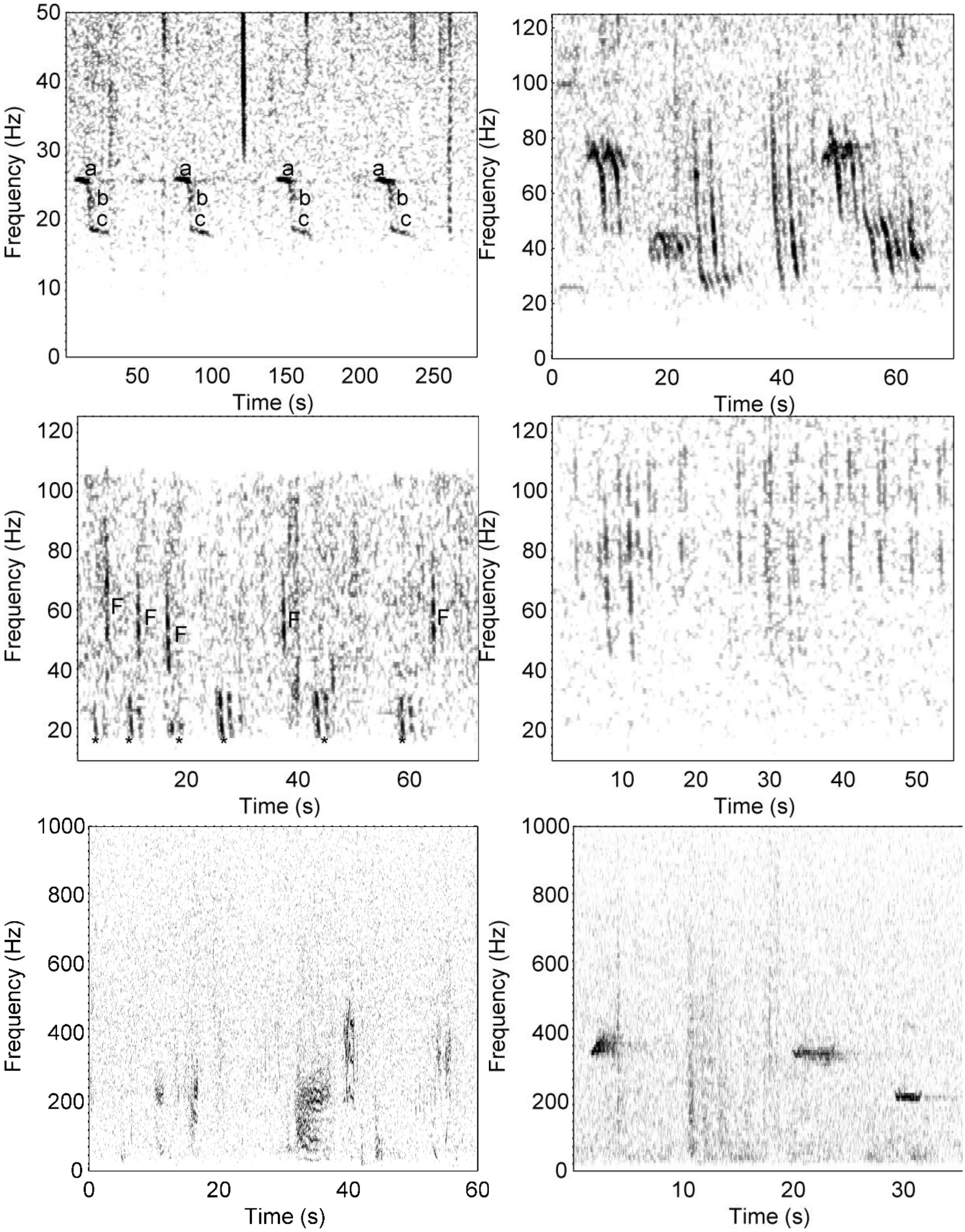

Figure A1 – Examples of sound types recorded during ENRICH. Top left: Blue whale Z-calls with labels for units a, b, & c. Top right: blue whale D and FM calls with reverberation. Middle left: Fin whale downsweeps (F) and 20 Hz pulses (*). Middle right: minke whale downsweeps. Bottom left: humpback whale sounds. Bottom right: leopard seal trills and whistles. Note that time and frequency axes differ among panels.