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ABSTRACT

A proof-of-concept study was conducted to explore the viability of automated acoustic detection of upcall vocalisations produced by southern right whales (*Eubalaena australis*) on their high-latitude Antarctic feeding grounds. The automated acoustic detector used was that of Shiu et al (2020) which was based on a convolutional neural network and deep learning, and was implemented via the open source Pamguard Deep Learning Classifier software module. Results from the detector are presented after application to a long-term acoustic dataset recorded in the Eastern Indian sector of the Southern Ocean that contained upcalls discovered during manual inspection of recordings for calls from other species. Performance assessments were largely qualitative, but revealed encouraging performance, despite the detector being trained on data recorded decades earlier and in a different hemisphere (with North Atlantic right whale calls). However, uncertainty remains about the capacity to discriminate between southern right whale and humpback whales as the source of at least some of the upcalls detected. Recommendations for future follow-up work are presented, with a key message being that a future, broad-scale, passive acoustic study of the spatial and temporal patterns in detections of SRW upcalls would likely be viable, tractable, and may require only modest additional resources by focusing on the large extant passive acoustic datasets that have already been collected throughout the Southern Ocean.

KEYWORDS: SOUTHERN RIGHT WHALE; PASSIVE ACOUSTIC MONITORING; UPCALLS; SOUTHERN OCEAN; IWC-SORP; ACOUSTIC TRENDS

INTRODUCTION

Motivation

Southern right whales (*Eubalaena australis*; henceforth SRWs) declined from an estimated 120,000 to fewer than 400 due to open-boat whaling in the 19th century (Jackson et al. 2008), and recovery was further setback by industrial whaling in the 20th century. Entering the 21st century, the total SRW abundance remained at 17-20% of their pre-whaling abundance level (International Whaling Commission 2013). More recently their status, abundance and population trends have been described for key wintering grounds in southwest Australia, Aotearoa New Zealand, Argentina and South Africa

(Harcourt et al. 2019, Romero et al. 2022). In addition to understanding trends in population abundance on mid-latitude wintering grounds, there is also a management need to understand SRW distribution, foraging habits and role in the Southern Ocean ecosystem, particularly in the Antarctic and sub-Antarctic where krill and other fisheries follow an ecosystem based approach to management (CCAMLR 1980).

While SRWs are often characterised as a predominantly sub-Antarctic predator (Seyboth et al. 2016, Derville et al. 2023), they are also detected at high latitudes in the Antarctic (Pastene et al. 2018, Jackson et al. 2020, Mackay et al. 2020, Vermeulen et al. 2020). Though these detections are infrequent compared to Antarctic blue, fin, minke, and humpback whales which are traditionally associated with high-latitude Antarctic feeding grounds (Kasamatsu 1995), they do occur over a long time-span and with some spatial fidelity, suggesting that high-latitude detections of SRWs arise from something other than one-off occurrences of vagrant animals (Vermeulen et al. 2020). These regular, but infrequent detections of SRWs during surveys and satellite tracking studies present challenges for understanding the importance of high-latitude habitats for SRWs (Seyboth et al. 2016), particularly in the data-poor Indian sector of the Southern Ocean off East Antarctica (Derville et al. 2023). A recent circumpolar study of SRW foraging grounds using an isoscape approach also showed that foraging ground use has changed over time, but differently in different parts of the Southern Ocean; for example, there has been a decrease in the use of high latitude foraging grounds by whales from South Atlantic but not South Pacific wintering grounds (Derville et al 2023). Another knowledge gap that arises from limited high-latitude empirical data is the prey requirements of SRW, particularly in relation to Antarctic krill. Addressing both of these knowledge gaps may assist with ecosystem based management and ecological risk assessments for regional Antarctic krill-fisheries (Warwick-Evans et al. 2022).

Vocalisations and acoustic detections

Like all cetaceans and their northern hemisphere counterparts, SRWs are known to produce a variety of underwater sounds (Webster et al. 2016). All populations of right whales have been found to produce low-frequency upswept vocalisations around 100-200 Hz and 1-2 s in duration, and these are commonly referred to as upcalls. Because they are relatively stereotyped, fairly easy to identify, and produced by all ages and both sexes as contact calls, upcalls tend to be the call-of-choice for passive acoustic monitoring of right whales (McDonald & Moore 2002, Munger & Mellinger 2005, Parks et al. 2007, 2011, Morano et al. 2012, Davis et al. 2017, Jackson et al. 2020, Kirsebom et al. 2020, Calderan et al. 2021, Johnson et al. 2022). Passive acoustic detections of northern hemisphere right whale upcalls has enabled *inter-alia* real-time detection and localisation of critically endangered North Pacific Right Whales (Wade et al. 2006, Rone et al. 2012), information on trends in distribution and movements of North Atlantic Right Whales (NARW) (Davis et al. 2017), real-time alerting of mariners to the presence of NARWs (Van Parijs et al. 2009), and information on the effects of man-made noise on right whale calling behaviour (Parks et al. 2011). A recent passive acoustic study has used PAM of SRW vocalisations to help increase encounter rate with SRWs for further study (Jackson et al. 2020), and one of the outcomes of this work was a suggestion that upcalls may provide for an complementary means of monitoring for the presence of SRWs on their sub-Antarctic and Antarctic feeding grounds (Calderan et al. 2021).

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Passive acoustic data is a complex mix of biological, anthropogenic and environmental sounds. Automatically extracting target calls from constantly changing spatially and temporally varying soundscapes is not straightforward and so the automated analysis of large PAM datasets is still an active research area. As such, large quantities of raw acoustic data have been archived so that they can re-analysed using more sophisticated automated detection and classification algorithms (or target different species) in the future. As with the study by Davis et al (2017), who collated and analysed 15 years of acoustic recordings from 19 organisations from across the Northwestern Atlantic Ocean for the presence of NARW upcalls, there is similarly an extant network of scientists conducting PAM in the Southern Ocean. This network, the Southern Ocean Hydrophone Network (SOHN; Figure 1) is a sub-project of the IWC-SORP Acoustic Trends Project (Opzeeland et al. 2013). While the Acoustic Trends Working Group (i.e., the scientists who contribute to the SOHN and IWC-SORP Acoustic Trends Project) have previously focused on trends in blue and fin whale sounds, the long-term, raw, acoustic recordings collected for this work should mostly be suitable for also investigating trends in SRW upcalls.

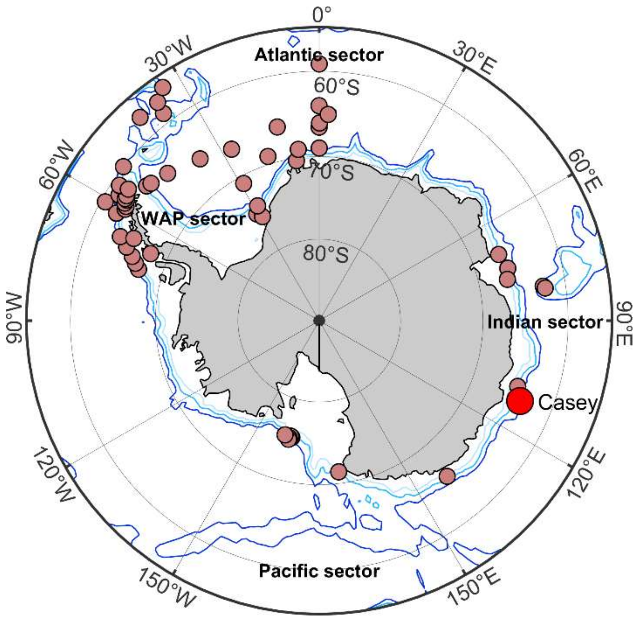

Figure 1 - Map showing long-term recording sites in the Southern Ocean from 2002-2017, including those from the Southern Ocean Hydrophone Network (SOHN). Pink circles indicate sites that contain long-term recordings from moored instruments, while large red circle indicates the recording site for this study, Casey.

Advances in acoustic detection

In addition to the hundreds of thousands of hours of underwater recordings already collected, the prospects for broad-scale PAM of SRW upcalls are further enhanced by two recent factors: 1) the discovery that, despite the presence of confounding species like humpback whales, it may be possible to distinguish SRW upcalls from e.g., humpback whale calls on the feeding grounds (Calderan et al. 2021), and 2) an order-of-magnitude improvement in the performance of recent automated detectors of upcalls that leverage advances in machine learning, namely convolutional neural networks, (e.g., Kirsebom et al., 2020; Shiu et al., 2020).

Here we present a small proof-of-concept analysis that combines the recent advances in automated detection of upcalls with a tiny subset of the long-term recordings from the SOHN. Most of this work was developed opportunistically, so the scope of this work was not suitable for drawing broad ecological conclusions. Rather, the main aims of this work were to investigate the viability and performance of these new acoustic analysis tools. In particular, we wanted to understand the potential for discovering SRW upcalls in extant long-term data, and more importantly to galvanise collaboration and coordination between the IWC-SORP SRW working group and the IWC-SORP Acoustic Trends Working Group.

METHODS

Manual detection of upcalls

The initiation of this work was not planned, and occurred when upcalls were noted by an analyst, (co-author MGA) during inspection of one hour of a 200-hour subset of data from 2019 in order to annotate all occurrences of Antarctic blue and fin whale calls. The subset of data with these upcalls was from the site-year Casey2019, a site off East Antarctica near Australia's Casey station in the Indian sector of the Southern Ocean (circa 63°S , 111°E; Figure 1). The subsequent proof-of-concept analysis all focused exclusively on this site and year.

During initial manual review of the Casey2019 subset, 11 upcalls were annotated by the analyst on 14 Feb 2019 between 0300 and 0400 UTC. The annotation protocol followed by the analyst was developed for low frequency calls of blue and fin whales (Miller et al. 2021a), so it only involved looking at spectrograms with frequencies from 0-125 Hz. This 125 Hz upper limit was potentially below the lowest frequency of some upcalls, so the data in this hour were subsequently re-reviewed by BSM with an upper limit of the spectrogram of 400 Hz. As with the blue and fin whale protocol, manual annotations were saved as a Raven Selection Table, and used as a very small 'ground-truth' dataset for characterising the automated detector.

Automated detection of upcalls

An existing automated detector for North Atlantic Right Whale (NARW) upcalls (Shiu et al. 2020) was then applied to the first quarter (Q1) of the full dataset from Casey2019 (Miller et al. 2021b). The Q1 full dataset included the Q1 annotated subset, as well as the full set of continuously recorded (not duty-cycled) acoustic data starting on 2018-12-23 and ending at midnight on 2019-03-31. Initially, the goal was to process the entire year of recording (from December 2018 through December 2019), but stability issues (i.e. program crashes) in PAMGuard stopped the detector after it had processed only the first few months of data, a process which took only half a dozen hours of computation time on a modern laptop with discrete (NVIDIA) graphics card.

While there are potentially other software algorithms that can detect upcalls, e.g. (Baumgartner & Mussoline 2011), here the NARW was used because Shiu et al (2020) advertised it as having greatly improved performance (e.g. average precision/positive predictive value around 0.9, and average recall also around 0.9 -- with a value of 1 indicating a perfect score for both recall and precision). Importantly this detector was freely available in the open-source software, PAMGuard (http://pamguard.org/), via the recently released Deep Learning Classifier module (https://github.com/PAMGuard/PAMGuard/tree/main/src/rawDeepLearningClassifier). The main aim of applying the automated detector here was to determine whether it could detect the calls that were manually annotated as well as any other upcalls in the dataset. Furthermore, application of the NARW detector helped to serve as a real-world test-bed for this relatively new, PAMGuard-based, open source, software module.

The default parameters from the PAMGuard documentation for the NARW were applied and can be seen in (To qualitatively investigate the automated detector performance, ad-hoc inspections of the detections were conducted. These ad-hoc detections focused on the days that contained the highest number of detections. Spectrograms of these inspected detections are presented in the results section to illustrate the success and limitations of this detector and analytical approach.

Table 1). These parameters and settings included all the pre-processing settings transforms to convert the digitised recordings into spectrograms suitable for input into the convolutional neural network of the NARW detector. As this was just an exploratory study, no attempt was made to tune or optimise the detection threshold (the only parameter for this model that was freely adjustable by the end user).

To qualitatively investigate the automated detector performance, ad-hoc inspections of the detections were conducted. These ad-hoc detections focused on the days that contained the highest number of detections. Spectrograms of these inspected detections are presented in the results section to illustrate the success and limitations of this detector and analytical approach.

Table 1 - PAMGuard parameters used for the deep learning classifier for detection of NARW upcalls.

Parameter	value
Audio sample rate	2000 Hz;
Detection window length	2 s (4000 samples)
Detection window hop	1 s (2000 samples)
Max re-merge	5 segments (seconds)
Input shape	[-1 40 40 1]
Output shape	[1 2];
Resample audio to sample rate	2000 Hz
Spectrogram FFT length	256 samples
Spectrogram FFT hop	100 samples
Interpolate spectrogram	40 bins from 47-357 Hz;
Normalize spectrogram sum	True
Binary classification threshold	0.9

RESULTS

Manual annotation of the ground-truth data from 2019-Feb-14 yielded a total of 21 manually annotated upcalls after re-review of the hour with 11 initial detections. In that same hour, the NARW automated detector also found 21 upcalls.

Over the portion of the full dataset that was analysed (i.e. Q1) the automated detector yielded 6,392 detections with a maximum of 633 daily detections occurring over the 24-hour period starting on 01-Feb-2019 00:00:00 UTC (**Error! Reference source not found.**). Ad-hoc inspection of a few dozen of the 633 calls from 01-Feb indicated that nearly all of the automated detections from this day that were reviewed had certain characteristics of SRW upcalls (e.g. starting frequency, upswept shape in spectrogram), although some were higher frequency (~300Hz) than might be expected, based on recordings from South Georgia (Calderan et al., 2021).

Other days with large number of detections included 02-Jan and 09-Feb. Like 01-Feb, the few dozen automated detections that were inspected on 09-Feb all appeared likely to be SRW detections.

However, nearly all the detections from 02-Jan that were inspected all appear most similar to the calls of Ross seals (e.g. R3 from Van Opzeeland et al., 2010). So, despite the interesting and unexpected revelation of these mysterious and under-studied calls, presumably from Ross seals, the calls from 02-Jan (and likely also those from adjacent days) should in our opinion be considered false-positive SRW detections.

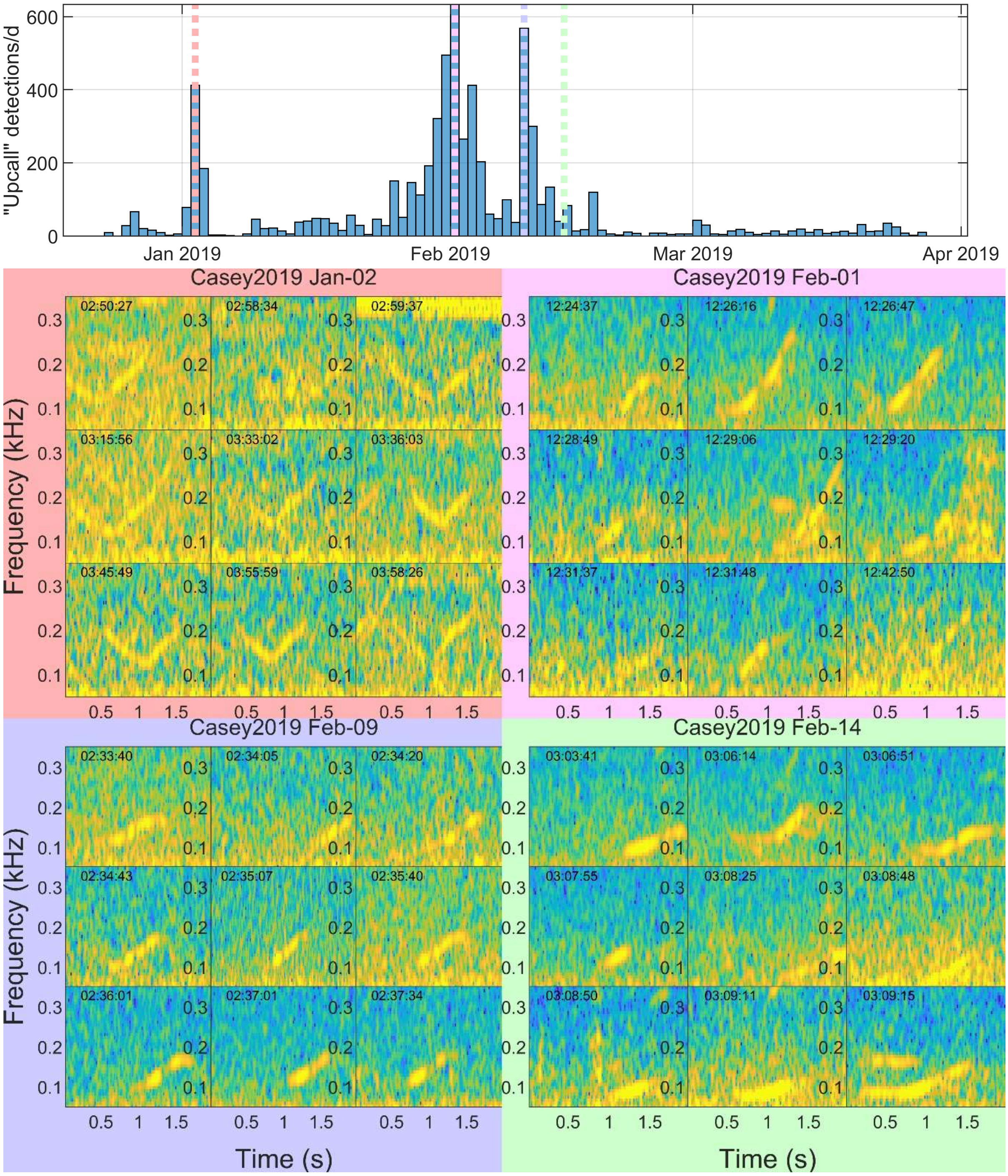

Figure 2 – Histogram of automated detections of upcalls made by the NARW detector (top panel) with remaining panels showing detections from four different days. Bottom four coloured panels show example detections as spectrograms with the background colour of each panel corresponding to the time of dotted lines in the detection histogram. Top-left (red panel): nine example false positive detections of likely Ross seal calls detected by the NARW detector on 02-Jan-2019. Top-right (purple panel): nine example detections of possible SRW upcalls by the NARW detector made on data from 01-Feb-2019. These calls had some

characteristics in common with SRW upcalls, but some characteristics, like upper frequency, that were beyond the range of expected values for SRW calls. Bottom-left (blue panel): nine example true positive detections of SRW upcalls by the NARW made on data from 09-Feb-2019. Bottom right (green panel): nine example true positive detections of SRW calls detected by both the human analyst and NARW detector on data from 14-Feb-2019 03:00.

DISCUSSION

In our exploratory analysis we have demonstrated qualitatively that the freely available, open-source, PAMGuard-integrated, detector for NARW upcalls appears to do a good job at detecting upcalls in our open-access high-latitude Southern Ocean dataset. The evidence of good performance included: 1) the detection of all of the manually annotated upcalls of our 'ground truth' dataset, and 2) the high proportion of detections in the full dataset that, upon inspection by a human expert, were deemed consistent with characteristics of SRW upcalls. The high number of upcalls detected (nearly 6000) from late December to mid-March at our Antarctic site was surprising given that right whales have been characterised as unpredictable and highly variable vocalisers e.g. (Parks et al. 2011, Davis et al. 2017), and that an unknown, but likely small, proportion of individuals are believed to visit the Antarctic in the summer (Mackay et al. 2020). Vocalisation rates of NARW were found to be higher with increasing number of individuals within an aggregation (Matthews et al. 2001). Hence it seems likely that daily detection rates of hundreds of calls a day would suggest aggregations of SRW within detection range. Further studies to improve our understanding of the purpose and context of upcalls, as well as their source level and detection range could help us better understand these intriguing results.

It is unusual that a detector trained on decades old data from another part of the world would perform so well on our Antarctic dataset. Admittedly, our ground-truth dataset was tiny and in no way representative of all of the possible environmental conditions that would be encountered across the data from the SOHN. Yet the vast majority of detections that we inspected also appeared to match the characteristics of SRW upcalls. This is an encouraging result, and suggests that the tools and methods for a broad-scale study of SRW upcalls may already exist. We suggest that such a study would be viable, highly tractable, desktop-based, and potentially require only modest resources. However, prior to conducting such a broadscale study, it would first be prudent to create a larger and more representative ground-truth dataset to confirm the performance characteristics of the detector across the wide variety of long-term Southern Ocean recording sites, environments, and instruments. This could potentially be achieved in the same manner as the IWC-SORP Annotated Library (Miller et al. 2020, 2021a).

One confounding sound source that we discovered in our qualitative study was the low frequency call of Ross Seals (likely call R3 from Van Opzeeland et al 2010). However, we posit that the large number of Ross seal calls detected in early January may not actually be as problematic as it initially appears. First, the detection of Ross seals off East Antarctica occurs over a very narrow time window from late December to early January as reported by (Opzeeland et al. 2010) for west Antarctica, and confirmed by our (unpublished) inspection of many years of long-term Australian Antarctic Division (AAD) recordings off East Antarctica (Miller et al. 2021b). Second, and perhaps more importantly, the Ross seal calls look and sound very different to SRW upcalls, as each upsweep is preceded by a downsweep. Thus, one solution to prevent detection of these false positives would be re-training of the NARW detector to include these non-SRW calls as negative (noise) class examples. Interestingly, that sort of human-review and feedback of new false-positives and detections is almost identical to the process that created such a good training dataset for the NARW detector in the first place (Shiu et al. 2020).

The other uncertainty is the ability to reliably rule out humpback whales as the source of at least some of the upcalls identified by both manual annotation and the detector. Work from South Georgia suggests a separation between southern right and humpback whale calls in terms of call-length and frequency. However, whilst most of the upcalls identified here are consistent with those of known SRWs at South Georgia, there are currently insufficient acoustic data with visual confirmation of species to discount any potential overlap in the upcalls produced by the two species. The upcalls that we inspected from our study did not appear to have a stable repetition rate, and thus would typically be thought of as non-song (AKA social) calls. The repertoire of non-song calls of humpbacks migrating down the East and West coast of Australia have been described from studies conducted over a number of years (Dunlop et al. 2008, Rekdahl et al. 2013, Recalde-Salas et al. 2020). Simple qualitative comparison of spectrograms from these studies to our results yielded no matches in the non-song calls of humpback whales to the calls that we reported here. However, only half of the non-song repertoire appears to be stable over timespans of many years (at least off Eastern Australia where it has been studied), with the remainder being recorded on only one occasion, or matching units from humpback songs for that year and population (Rekdahl et al. 2013). Furthermore, humpback whale songs are complex, include many call units, and can undergo substantial changes annually with frequent introduction of novel sounds and themes (Garland et al. 2011, Darling et al. 2014).

The reported characteristics of the ‘wop’ call reported off Angola (Rekdahl et al. 2016), appeared at similar to the upcalls that we found off Antarctica. However, the signal to noise ratios of the ‘wop’ calls were low, and so the visual appearance of this call was difficult to discern from the sole spectrogram included in the publication. Rekdahl et al. (2016) did indicate that this call matched the ‘wop’ call from eastern Australia (which we discerned in the preceding paragraph was not similar to our upcalls). Furthermore, Rekdahl et al. solely employed passive acoustics for data collection; their results contained no visual confirmation that the source of the calls were humpback whales; and the study was conducted in an area and time of year that overlaps with the historical distribution of SRWs. Thus there is some uncertainty whether the calls they detected were truly those of humpbacks and not SRWs.

In general, the spatial and temporal overlap in occurrence between SRWs and humpback whales along with the wide variety of sounds produced by humpbacks continues to perpetuate potential confusion of SRW upcalls and humpback whale non-song calls. While quantitative analyses of call characteristics might eventually be sufficient to discriminate between these two species, there also remains a need for a larger and more representative collection of acoustic recordings with independent (e.g. visual) confirmation of the species of the source, especially in sympatric areas like high-latitude feeding grounds.

The inclusion of this Deep Learning Classifier in the de-facto standard open source PAM software stack of PAMGuard provided an easy-to-use software environment and graphical user interface for conducting this exploratory analysis. Thus, PAMGuard Deep Learning Classifier may be a better option for students and scientists who are not experienced with and/or do not wish to setup and maintain the relatively complex software stacks (e.g. Python, PyTorch, TensorFlow) typically used to develop, test, and run deep learning algorithms. While we did experience a software crash while analysing our data, the use of discrete binary files for saving results alongside and a detailed PAMGuard log file prevented data loss, and would facilitate restarting subsequent analyses at the point in the dataset where execution unexpectedly ended. Software crashes are not unexpected when testing early versions of software, and secured future funding for the PAMGuard deep learning module will help to improve stability of this software.

The speed at which the automated detector processed data was on the order of 200 times faster than real-time, and as a result, this should enable fast and efficient processing of large datasets like that of the SOHN. Furthermore, the integration of the deep learning classifier in PAMGuard alongside the PAMGuard DIFAR module (Miller et al. 2016) should also enable automated real-time detections of upcalls at-sea during voyages where sonobuoys are deployed –a job that has to date only been done with manual detections by human analysts (McDonald 2004, Wade et al. 2006, Rone et al. 2012, Miller et al. 2015).

We hope that these promising results will serve to galvanise collaboration between the IWC-SORP Acoustic Trends Working Group and the IWC-SORP Southern Right Whale working groups, and we hope that this collaboration will ultimately yield a broad-scale (circumpolar) acoustic study of SRWs from extant recordings in the sub-Antarctic and Antarctic. Additionally, ship time during in-situ studies of SRW behaviour on the feeding grounds, especially for time-depth & acoustic tagging, could help add value to the mountains of passive acoustic data that arise from analysis of long-term datasets work.

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