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ABSTRACT

Antarctic blue whale (*Balaenoptera musculus intermedia*) foraging grounds were characterised during a recent joint New Zealand-Australia Antarctic Ecosystems Voyage. A combination of passive acoustics to locate Antarctic blue whales, and active acoustics to map krill, were used. This study demonstrates that using these two complementary technologies provides insights into sub meso-scale Antarctic blue whale foraging behaviour. Preliminary results from a single survey suggest that krill swarms are smaller and denser inside vocal aggregations of Antarctic blue whales, but have a similar encounter rate outside vocal aggregations. Further work is planned to analyse the data from additional surveys and to model Antarctic blue whale densities from passive acoustics.

Introduction

Prey availability is assumed to be a key driver of the habitat selection and fine-scale distribution of baleen whales (e.g. Croll et al., 2005; Friedlaender et al., 2015; Redfern et al., 2006). Few studies have focused on the relationship between baleen whales and krill in the Antarctic and most to date have focused on humpback whales, minke whales, and fin whales over a variety of spatial scales (Friedlaender et al., 2014; Friedlaender et al., 2015; Nowacek et al., 2011; Santora et al., 2010; Santora et al., 2014). Only a single recent study, near the Western Antarctic Peninsula, focused on the relationship between Antarctic blue whales and krill (Širović & Hildebrand, 2011). Though no blue whales were visually encountered, this study found a negative relationship between the detection of blue whale song calls and the mean krill biomass from 0-100 m depth. Despite the lack of empirical data, there have been several studies that have attempted to model the relationship between blue whales and krill, and it is believed that this relationship plays an important role in the Southern Ocean Ecosystem (e.g. Roman et al., 2014; Wiedenmann et al., 2011; Willis, 2014).

In addition to the selection of appropriate conceptual and quantitative models, the successful study of predator-prey interactions between whales and krill is contingent on the selection of an appropriate scale for observation and analysis (Fauchald, 1999; Kotliar & Wiens, 1990). The scale-dependency of predator-prey relationships varies with prey patchiness and predictability (Fauchald et al., 2000; Heithaus & Dill, 2006; Redfern et al., 2006). At larger scales, it is reasonable to expect that Antarctic blue whales may travel to regions where krill are known to be found and within this range the whales may travel to regions where there are high densities of krill, (e.g. the ice edge, Brierley et al., 2002) that are close to the surface (Goldbogen et al., 2011; Goldbogen et al., 2012). At these smaller scales much remains unknown about interactions between Antarctic blue whales and krill and it is difficult to precisely measure the position and density of both predator and prey at fine spatial scales; the dynamics of predator-prey behaviour complicate this relationship further.

The swarming behaviour of krill in response to a predator threat is well documented (for review see Hamner & Hamner, 2000). Multi-beam acoustic instruments have shown changes in swarm shape in response to predation (Cox et al., 2009) and in aquaria, krill exhibit extremely short-range rapid swimming (e.g. Kawaguchi et al., 2010; Letessier et al., 2013). Such small-scale anti-predation behaviour may weaken any predator-prey correlative patterns. This behavioural response and the perennial problem of being unable to determine why krill are absent (i.e. is the krill evading the whales or have the whales eaten the krill) make it unlikely that a monotonic relationship between krill and whale density would be observed.

Antarctic blue whales currently have a low population size and are spread out over a wide region. While it is unlikely that large-scale (1,000 km) krill surveys will greatly inform the relationship between krill distribution and these whales, localised krill surveys requires the ability to reliably locate these rare whales. By employing recent advances in passive acoustic technology including DIFAR sonobuoys it is now possible to locate Antarctic blue whales reliably (Miller et al., 2015; Miller et al., 2014) and thus facilitate small-scale studies of their feeding ecology.

An objective of the recent multidisciplinary New Zealand-Australia Antarctic Ecosystems Voyage (January 29th and March 11th 2015) of the IWC-Southern Ocean Research Partnership was to use passive acoustics to locate groups of Antarctic blue whales, and then use active acoustics - scientific echosounders - to map the distribution of krill swarms in their vicinity (Double et al., 2015). Active acoustics is a proven, mature technology and is capable of observing krill in an undisturbed form (Brierley et al., 2003). For our purposes, active acoustics enabled us to observe krill en route to blue whale feeding grounds and well as conduct local krill mapping in the vicinity of blue whales. Our motivation for conducting this research was two-fold, first to determine the utility of combining passive and active acoustics for sub meso-scale (< 100 km) prey-field mapping around Antarctic blue whales. Second, data from this voyage will be used to refine observation methods and survey design for use in future field campaigns. This paper presents preliminary results from the voyage and plans for future analyses.

Methods

Active acoustic data were obtained using a calibrated EK60 scientific echosounder (Horten, Norway) with transducers mounted on the hull of the *RV Tangaroa*. Two echosounder frequencies, 38 and 120 kHz, were used in this analysis. Aggregations were isolated from a 7 x 7 convolution (moving average) applied to the 120 kHz acoustic data using the ‘schools detection module’, an implementation of the SHAPES algorithm (Barange, 1994) in Echoview v6.1 (Myriax, Hobart, Australia). Aggregations were identified as krill using dual frequency ‘dB-difference’ approach, 120-38 kHz, which has been used in the study of krill swarms (e.g. Cox et al., 2011; Tarling et al., 2009).

Target fishing was conducted using a trawl the NIWA fine-mesh midwater trawl. This trawl has a circular mouth opening of about 12 m diameter, and a codend mesh of 10 mm. During tows for acoustic identification, the midwater trawl was targeted at the aggregation of interest and towed for 20–30 minutes at 3–4 knots. The profile and performance of each tow was monitored from net depth data obtained from a Furuno CN22 net monitor.

Krill length frequency distribution obtained by target fishing, along with the Calise & Skaret (2011) krill target strength model, was used to calculate a krill identification 120-38 kHz dB difference range of 2.2 to 10 dB. Aggregations falling within this range were identified as krill volumetric density was estimated again using the Calise & Skaret (2011) krill target strength model and the Morris et al. (1988) krill length to wetmass relationship.

Passive acoustics tracking of Antarctic blue whales was conducted following methods described by Miller et al.(2015; 2014). In short, DIFAR sonobuoys were deployed adaptively in order to track down vocalising groups of Antarctic blue whales. Throughout the voyage sonobuoys were deployed at intervals no greater than 30 nmi, but more frequently in the vicinity of Antarctic blue whales. During time dedicated to blue whale research bearings from a single sonobuoy were used to guide the ship directly towards the vocalising whales. During approach, proximity to vocalising Antarctic blue whales was estimated via rate of change of bearings and intensity to whale calls. When whales were estimated to be within 30 nm of the ship, two sonobuoys were deployed simultaneously to acoustically triangulate the location of calling whales. When deploying a second sonobuoy for the purposes of triangulation, a course of 30° to 60° relative to the bearing from the first sonobuoy to the target was often selected to facilitate accurate triangulation (i.e. Nardone & Aidala, 1981) while continuing to reduce the distance between the vessel and the target.

When weather permitted, acoustically located whales were approached to obtain visual confirmation of the species, estimate group size, obtain photographic identification, and conduct focal (i.e. behavioural) follows. In addition to locating whales for further study acoustic triangulations were also considered when planning the locations of line-transect surveys. The ability to track the location of whales in real-time facilitated the collection of active acoustic data in the vicinity of Antarctic blue whales.

While passive and active acoustic data were collected throughout the voyage, in this preliminary analysis we focus on a single active acoustic survey that included similar amounts of track line outside and within the vicinity of Antarctic blue whales. The boundary of the blue whale aggregation was determined by smoothing blue whale triangulations using the kde2d function in the R (R Core Team, 2015) MASS package (Venables & Ripley, 2002). The 99% contour of the surface's density is used to the boundary of the Antarctic blue whale aggregation.

Krill swarms were then split into two groups: inside and outside of the boundary. Differences in swarm corrected length (the correction pertains to transducer beam geometry, for defintion see Diner, 2001) and volumetric density were examined using Kolmogorov–Smirnov tests.

Results

Double et al. (2015) provides general information on the voyage and describes the strong aggregation of calling blue whales in this region between early February and March 2015.

Within the survey considered here 90 krill swarms were detected along the 1,063 km of transect line, giving an average encounter rate of one swarm per 11.8 km of transect. There were 562 km of line transect outside of the blue whale aggregation boundary and 501 km of transects with the aggregation boundary (Fig. 1). Krill swarms roughly split evenly outside and within the boundary: 46 swarms outside the boundary and 44 inside giving broadly similar encounter rates of one swarm per 12.2 km of transect outside and one swarm per 11.4 km inside the blue whale aggregation boundary.

The lengths of krill swarms outside the boundary were longer than swarms within the boundary (KS-test, D=0.64, p-value=3.5e-9; Fig. 2A) and swarms outside the boundary had lower volumetric density (KS-test, D =0.36, p-value=0.003; Fig. 2B).

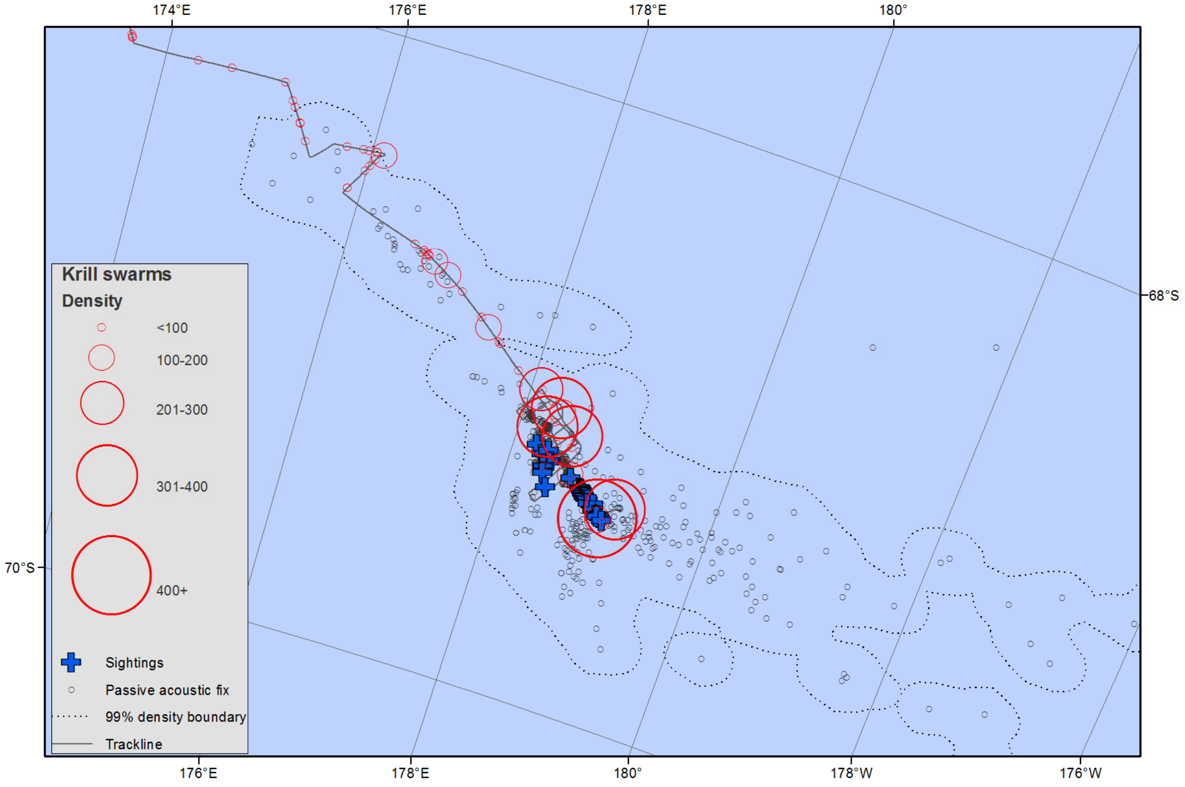

***Figure 1:** Krill swarms in the vicinity of the Antarctic blue whale aggregation (boundary black dotted line). The area of a red circle is proportional to swarm volumetric density, passive acoustic cross bearing locations are shown as only black circles, and visual sightings as blue crosses. The vessel track is a solid grey line.*

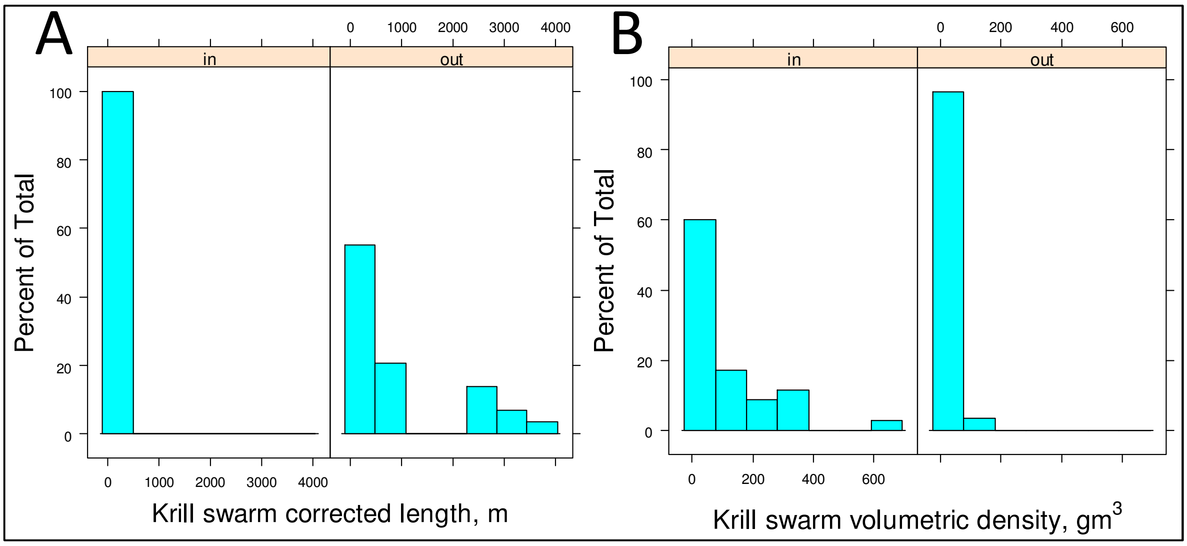

***Figure 2**: Krill swarm descriptors, A) corrected length, m, and B) volumetric density, gm^{-3}, in and outside the Antarctic blue whale aggregation.*

Discussion

Our preliminary results demonstrate that the combination of passive and active acoustics enabled Antarctic blue whales to be located reliably and tracked in real-time, and to measure simultaneously the characteristics of individual krill swarms in their vicinity. Analyses of 36 hr of active and passive acoustic data presented here show that krill swarms were smaller and have higher internal densities in the vicinity of Antarctic blue whales. This is consistent with the hypothesis of Goldbogen et al. (2012), that blue whales prefer to feed on shallow, high density krill swarms in order to maximise their energy intake per unit effort, and that diffuse krill layers are unlikely to contain sufficient krill to sustain an Antarctic blue whale.

We reiterate that the results presented here are preliminary and only the results of a short period of sampling (a single krill survey) are presented here; there were ten more surveys conducted during the 2015 NZ-Aus Antarctic Ecosystems Voyage which are still to be analysed.

We will continue by applying the methods presented here to analyse data collected during this voyage to describe other krill distributions in the vicinity of Antarctic blue whales. Our next step will be to process the active acoustic data from each of these surveys and extract descriptions of krill swarms in order to look at daily variability in krill. Additionally, there are two key developments we intend to implement to support further analyses.

First, in addition to the swarm-by-swarm descriptions, e.g. volumetric density, we will investigate descriptors of the overall krill prey field such as the clumping of multiple swarms, e.g. Petitgas (2003). Second, we will move away from discrete analysis used here, where krill swarms were classed as either inside or outside of the blue whale aggregation, and use continuous spatial analysis supported by density surface modelling. Marques et al.(2013) successfully implemented density estimates using passive acoustics but further development is required. Spatial density surface modelling approaches that account for imperfect detectability are available, for review see Miller at al. (2013), and could be applied here, perhaps using krill swarm descriptors as covariates.

Multi-disciplinary voyages are complex to plan and execute; juggling competing sampling methods often necessitates using multiple survey designs. For example, conventional active acoustic surveys of krill typically use some kind of line transect pattern, which is clearly at odds with a research vessel operating in close approach mode when obtaining identification photographs or biopsy samples of whales. During the 2015 Antarctic Ecosystems Voyage such limitations were overcome by providing dedicated ship time for active acoustic surveys, and the simultaneous use of passive acoustics to locate blue whales.

Important features of predator-prey interactions of highly mobile predators occur at small spatial scales. Conducting separate predator and prey surveys will very likely miss these local features particularly at sub meso-scales (<100 km). A key strength of combining active and passive acoustic data is that time and space mismatches are reduced by sampling krill within the vicinity of Antarctic blue whales at the same time as the whales are feeding. Simultaneous local surveys of predators and prey are essential for describing the foraging ecology of whales and eventually, their distribution and habitat selection.

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