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# Distribution, density and relative abundance of Antarctic krill estimated by maximum likelihood geostatistics on acoustic data collected during commercial fishing operations

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ABSTRACT

There is a substantial harvest for Antarctic krill in the Southern Ocean, but little regular scientific monitoring of the resource. Recently, however, the Commission for the Conservation of Marine Living Resources (CCAMLR) has initialised a process to make use of acoustic data from commercial fisheries to increase the amount of relevant information available for making management decisions. We here provide an example where 34 days of acoustic data, collected during commercial krill fishing operations on the vessel 'Saga Sea' were processed to produce probability of presence, conditional density and relative abundance estimates on monthly, weekly and daily basis. Data were analyzed using a maximum likelihood time-series and geostatistical approaches, selected to account for the lack of sampling design, and likely correlation in space and time. The applied method showed low sensitivity of monthly estimates to different repeated measure criteria and location sub-settings. Most weekly estimates, but the last one, were also consistent with the full data (monthly) estimate. Highly variable and lower estimates were obtained, however, from daily data sets. Although our results suggest the method had provided an adequate treatment for time and space correlation, we were not able to evaluate potential bias due to preferential sampling of high density krill aggregations and/or limited area coverage within short time periods. The results suggest that this method, combined with some additional design based coverage by the fishing vessels, can be useful to obtain quantitative evaluations of krill density and distribution for management purposes.



## 1. Introduction

Proper evaluations of distribution, abundance and/or biomass of exploited marine organisms are often keys to a successful resource management. Typically, such evaluations are based on scientific surveys characterized by the use of full-time dedicated vessels and pre-planned sampling designs (Gunderson, 1993). In some areas, however, routine scientific monitoring is limited by factors such as high costs, low accessibility and the mere size of the monitoring area of interest. The Southern Ocean is an example of such an area.

The Southern Ocean is one of the remotest fishing areas, but contains one of the most abundant marine resources on earth, namely the Antarctic krill (*Euphausia superba*), hereafter krill. The krill is exploited commercially, and at present the total annual krill catch is in the range of 300,000 t per year. Even though the krill has a circumpolar distribution, the fishery is concentrated to the Scotia Sea, and above all to small regions at the shelf breaks of the South Georgia Islands, the South Orkney Islands and the west coast of the Antarctic peninsula (Atkinson et al., 2008; Everson, 2008). The harvesting is managed by The Commission for the Conservation of Marine Living Resources (CCAMLR) which regulates all exploitation of marine resources in the Antarctic waters. The precautionary catch level for krill based on a synoptic acoustic survey estimate from 2000 is at 5.61 million t (CCAMLR, 2010). Although the regulation of the krill harvest is carried out according to the explicit aim that the harvest shall not negatively impact krill-dependent predators (Hewitt et al., 2002), there is presently not enough information available to properly evaluate the effect of the fisheries on the predators, at the scale the fishery occurs. As a consequence, the trigger level that instigates management actions, which presently sits at 620,000 is static and based on historical catches. For several years, however, CCAMLR has been working towards a feedback management system, aiming for a more flexible resource management, where up-to-date information about the state of the krill and

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krill dependent predators can be used as a basis for management decisions (Constable, 2011; Constable et al., 2000).

As part of the feedback management approach, alternative cost-effective methods to obtain information on krill are being evaluated. One approach is to obtain information directly from the fishing vessels, which operate in the Southern Ocean waters through most of the year. As part of this approach, the CCAMLR Subgroup on Acoustic Survey and Analysis Methods (SG-ASAM) has been working with a proof of concept for using acoustic data from krill fishing vessels to inform managers (Watkins et al., 2016). Such data are typically of a poorer quality than data from scientific vessels, and even though commercial vessels may be required to carry out systematic surveys, most of the data collection will not follow any sampling design. Moreover, data tends to be clustered (Menezes et al., 2008) and preferentially collected (Diggle et al., 2010) as commercial vessels use historical records, personal knowledge and technological means to find, follow and fish the densest krill aggregations, producing observations that are very intense and repetitive in time, but highly irregular and limited in spatial coverage. Thus, underlying assumptions implicit in design-based estimation methods, such as those used by Jolly and Hampton (1990) or Bez (2002) are not valid. Even more liberal assumptions, such as the existence of random searching patterns (Aubry and Debouzie, 2000) are most probably violated.

A possible approach, suitable to face time and spatial correlation, and lack of sampling design problems, is the utilization of model-based time-series and geostatistical methods, which do not require of probabilistic sampling designs (Aubry and Debouzie, 2000; Diggle and Ribeiro, 2007). Several of these model-based methods exist, including a number of non-parametric and parametric ones, whose application may present relative advantages or disadvantages, depending on the data (Cressie, 1993; Henley, 2012). Within parametric methods, likelihood-based geostatistics (Diggle and Ribeiro, 2007; Roa-Ureta and Niklitschek, 2007) present several properties that are highly relevant for the analysis of acoustic data collected from commercial fishing operations: (i) flexibility to accommodate additional sources of sampling correlation, e.g. repeated acoustic surveys carried out over the same stock and/or data collected from several vessels operating simultaneously; (ii) flexibility to accommodate non-Gaussian distribution functions for the regionalized variable; and (iii) straightforward methods to calculate measures of precision (for geostatistical parameters) and model selection criteria, such as Akaike's (1973) Information Criterion, from likelihood profiles.

Within the likelihood-based geostatistical framework, Roa-Ureta & Niklitschek (2007) presented a method designed explicitly for fishery resource surveys. It uses a delta approach to analyse zero-inflated data (Aitchison and Brown, 1957; Lambert, 1992; Lo et al., 1992; Pennington, 1983), where distribution (presence/absence) and conditional density are treated as two independent (and multiplicative) responses. Presence/absence is modelled as a binomial process, while conditional density (i.e. positive values, NASC > 0) is treated as a realization of a Gaussian, gamma, poisson or any other process belonging to the exponential family. This delta likelihood-based geostatistical method has been used to evaluate distribution and abundance of several fish and shellfish stocks, using data collected through repeated surveys and/or by multiple scientific or commercial vessels operating simultaneously (Arkhipkin et al., 2013; Molinet et al., 2010, 2015; Niklitschek and Roa, 2006; Roa-Ureta and Niklitschek, 2007).

A practical issue, that may affect the magnitude of preferential sampling effects upon abundance estimates based on data from sonar-assisted commercial operations, is the time interval chosen to discretise the total period of observation. As the length of this interval increases, locations tend to be sampled only when the stock is present, but avoided otherwise, leading to overestimating the mean and to underestimating the variance of the binomial process. As the length of sampling time-interval decreases, a larger proportion of locations will not be sampled, but extrapolated using mean values from observed locations

In the present paper, we apply a delta likelihood geostatistical method to an existing data set containing 34 days of acoustic data collected by a krill fishing vessel around the South Orkney's Islands, and use it to investigate the sensitivity and precision of abundance estimates under different sub-sampling strategies and inference time intervals.

## 2. Material and methods

### 2.1. Vessel and area of operation

The F/V 'Saga Sea' is one out of typically 10–12 vessels fishing krill in Antarctic waters. It is owned by the Norwegian company Aker ASA and operates in the CCAMLR statistical areas 48.1, 48.2 and 48.3, usually from December to August. The vessel is equipped with a continuous trawling system by which the krill is continuously pumped on board from the cod end through rigid hoses. During operation, a trawl haul at ca. 2 knots speed can last for days or even weeks in a stretch within limited areas.

### 2.2. Acquisition of acoustic data

The possibilities, utilities and limitations of collecting acoustic data from krill fishing vessels have been investigated in CCAMLR through a proof of concept process, which is described in detail in Watkins et al. (2016), SC-CCAMLR (2012) and SC-CCAMLR (2014). In the specific case of the 'Saga Sea', the vessel was equipped with a Simrad ES60 echo sounder system running the two frequencies 38 and 120 kHz. As part of an agreement between Aker ASA and scientists at the Institute of Marine Research, Norway, the data from the vessel's echosounder system have periodically been logged while the vessel has been carrying out regular fishing operations. The data presented here were collected from 28 January to 2 March 2009 when scientists were on board while the vessel was conducting regular fishing operations, and krill from the catch were sampled regularly. Fishing occurred along the northern shelf edge off the South Orkney Islands. The echosounder system was not calibrated so the logged data represent relative levels of acoustic backscatter. However, a post-calibration of the system was carried out off Brindisi, Italy later that year using standard sphere calibration with a 38.1 mm tungsten carbide sphere (Foote et al., 1987), and showed that the transducers worked according to specifications, with no malfunctions.

### 2.3. Processing of the acoustic data

The acoustic raw data collected are typically flawed by noise from interference with other acoustic instruments, false bottom detection and surface bubbles. Regions with bad data were removed partly manually, and partly using noise removal algorithms incorporated in the software Large Scale Survey System (LSSS) (Korneliussen et al., 2006). The noise filtered data were then stored in sample bins of 50 pings horizontal × 5 m vertical resolution, and the dB-difference method for target discrimination following the CCAMLR protocol with modifications was applied. This method takes advantage of the predictable frequency dependent volume backscattering strength ($S_v$; dB re m$^{-1}$) for krill within a specified range of body lengths. The range of $\Delta S_v$-values ($S_{v,120}$–$S_{v,38}$) is used to discriminate krill from other targets. We used the krill length distribution based on the collated trawl samples to calculate the values of $\Delta S_v$ (Reiss et al., 2008). The dB-difference method was applied to the sample bins of 50 pings