Deep-Sea Research II 57 (2010) 508–518

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Three-dimensional observations of swarms of Antarctic krill (*Euphausia superba*) made using a multi-beam echosounder

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ARTICLE INFO

Article history:
Accepted 30 October 2009
Available online 11 November 2009

Topical issue on "Krill Biology and Ecology." The issue is compiled and guest-edited by the North Pacific Marine Science Organization (PICES), International Council for the Exploration of the Sea (ICES), and Global Ocean Ecosystem Dynamics (GLOBEC) project.

Keywords:
Antarctic krill
Euphausia superba
Pelagic
Multibeam echosounder
Swarm morphology
Three dimensions
Livingston Island
South Shetland Islands

ABSTRACT

Antarctic krill (*Euphausia superba*) aggregate in dense swarms. Previous investigations of krill swarms have used conventional single- or split-beam echosounders that, with post-processing, provide a two-dimensional (2-D) view of the water column, leaving the third dimension to be inferred. We used a multi-beam echosounder system (SM20, 200 kHz, Kongsberg Mesotech Ltd, Canada) from an inflatable boat (length = 5.5 m) to sample water-column backscatter, particularly krill swarms, directly in 2-D and, with post-processing, to provide a three dimensional (3-D) view of entire krill swarms. The study took place over six days (2–8 February 2006) in the vicinity of Livingston Island, South Shetland Islands, Antarctica (62.4°S, 60.7°W). An automatic 3-D aggregation detection algorithm resolved 1006 krill swarms from the survey data. Principal component analyses indicated that swarm morphology metrics such as length, surface area and volume accounted for the largest between swarm variance, followed by echo energy, and finally swarm geographic location. Swarms did not form basic cylindrical or spherical shapes, but had quite consistent surface area to volume ratios of 3.3 m^{-1}. Swarms were spatially segregated, with larger sizes (mean north-south length = 276 m, at least double that of two other swarm classifications), found to the northwest of the survey area. The apparent clustering of swarm types suggests that krill biomass surveys and ecosystem investigations may require stratified survey design, in response to varying 3-D swarm morphology, variation that may be driven in turn by environmental characteristics such as bathymetry.

1. Introduction

Many pelagic marine organisms exhibit patchy spatial distributions that are driven by a variety of biotic and abiotic factors (Genin, 2004). Aggregation appears to be a fundamental component of the behaviour of Antarctic krill (*Euphausia superba*), and indeed the swarm has been referred to as the "fundamental unit of krill ecology" (Murphy et al., 1988; Hofmann et al., 2004). Aggregations of Antarctic krill may form as a consequence of individuals seeking to reduce the chance of predation (O'Brien, 1987; Hamner and Hamner, 2000; Szulkin and Dawidowicz, 2006), to facilitate mating and/or feeding (Watkins et al., 1992; Miller et al., 1993; Hofmann et al., 2004), or to convey locomotive energetic advantage (Ritz, 1994, 2000).

Previous investigations suggest there are large variations in krill swarm shape (Miller et al., 1993; Woodd-Walker et al., 2003) and packing density (Barange et al., 1993). Swarm dimensions and density have been used to classify swarms into types, and previous studies have implied spatial clustering of swarms by type (Miller and Hampton, 1989; Watkins and Murray, 1998). For example, Mauchline (1980) classified three types of aggregation based on numerical density: the densest swarm type contained from 1000 to 100,000 krill m^{-3}; and was followed by logarithmically decreasing class densities of 1 to 100 and 0.1 to 1 krill m^{-3}.

It is believed that some of the observed variation in swarm density and shape occurs in response to environmental conditions (Barange et al., 1993; Alonzo and Mangel, 2001; Hofmann et al., 2004), such as upwelling or localised water currents that occur in the vicinity of rapid changes in bathymetry (Trathan et al., 2003). It will be important to understand how krill aggregate to elucidate possible relationships between various potential physical or biological forcing mechanisms and swarm shape. This in turn would enable the extent to which krill demographics (e.g., age, sex, and maturity) are important to swarm formation (Watkins et al., 1986, 1992; Tarling et al., 2007). Understanding the mechanisms of krill swarm formation, and potential spatial variation in these mechanisms, may also be vital for unbiased

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doi:10.1016/j.dsr2.2009.10.003

estimates of biomass (Gerlotto et al., 1999), and for addressing ecological issues such as predator–prey interactions (Zamon et al., 1996) and responses by krill to variation in their abiotic environment such as water depth (Hewitt and Demer, 2000; Trathan et al., 2003).

Most observations of krill swarms have been made acoustically with scientific echosounders, as per biomass surveys (e.g., Everson and Miller, 1994). Acoustic observations of krill swarms made using conventional vertically-downward looking single- or split-beam echosounders (SBE) are limited by the small conical sampling volumes (typically 7°) inherent with these instruments. Following each SBE acoustic transmission (ping), samples of volume backscattering strength (S_v) are recorded versus sound-propagation time, or water depth. Sequential recordings combine to build up a two-dimensional (2-D) matrix of water-column observations (Reid and Simmonds, 1993). The narrow acoustic beam effectively samples only a 2-D slice through the water column and any krill swarm in it. The three-dimensional (3-D) krill swarm shape cannot be estimated directly from 2-D observations without making assumptions about the swarm shape (e.g., it is cylindrical or spherical; Simmonds and MacLennan, 2005). Consequently, the volume of a krill swarm that falls outside of the narrow SBE beam cannot be determined. Krill biomass estimation techniques and investigations into krill ecology would both benefit from improved 3-D observations of individual krill swarms.

In this investigation, we used a multi-beam echosounder system (MBE) to observe Antarctic krill swarms in 2-D in the field, and extended these 2-D MBE observations into 3-D visualisations of swarms during post-processing. The purpose of this investigation was three fold. Firstly we sought to determine if krill could be observed in the nearshore environment using an MBE deployed from a small boat. Secondly, we wanted to investigate if the 3-D acoustic reconstruction of krill swarms could be used to improve understanding of the variability of swarm shape and density. Thirdly, we sought, using multivariate analyses, to examine the scale of variation of various swarm metrics. We hoped that, if successful, combining these elements could lead to future incorporation of MBEs into studies to improve understanding of krill biology and ecology.

2. Materials and methods

Two inflatable boats (Mark V Zodiacs, length=5.5 m) were deployed in the vicinity of Cape Sheriff, from 2 to 9 February, 2006. Operational constraints meant that a different number of transects was sampled each day (Fig. 1). The survey-site seabed depth ranged from 20 to 140 m. Seabed depth is an important consideration because it influences the MBE sampling volume and, due to side-lobe interference, the maximum observable across-track swarm width.

One inflatable boat, R/V *Roald*, was equipped with an MBE (200 kHz SM20, Kongsberg Mesotech Ltd, Canada) and conducted a high-resolution seabed-bathymetry survey (100% seabed coverage, resolution=1 m) with simultaneous water-column sampling to observe krill swarms acoustically. The second inflatable boat, R/V *Ernest*, was equipped with 38 and 200 kHz SBEs (calibrated single-beam Simrad ES60s). The MBE survey comprised 35 2.5-km transects and four 3.5-km transects, each with a 120 m inter-transect spacing (Fig. 1). On the final day of surveying, two 'tie lines' of length=5.2 km with spacing=1.2 km were run perpendicular to the main transects, the purpose of which was to assess any day affect (i.e. possible day-to-day variation) in the MBE krill swarm data. In addition to acoustic observations, visual observations of air-breathing krill predators were collected from both Zodiacs (Cox et al., 2009).

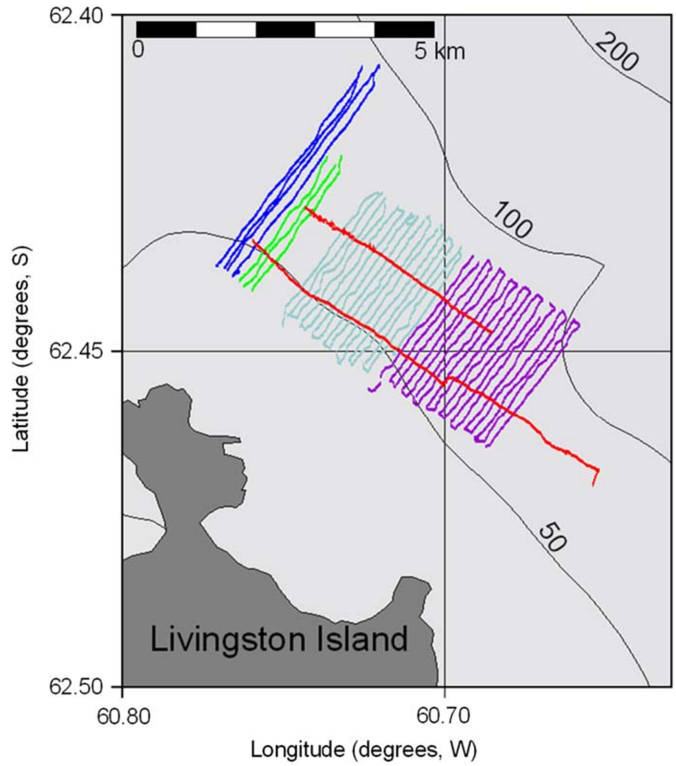

Fig. 1. The Cape Sheriff study site, Livingston Island, South Shetlands, Antarctica. Multi-beam survey transects are shown, colour coded by day. Bathymetric contours are shown as black lines. Note the two tie-lines which were surveyed perpendicular to the main survey.

2.1. Multibeam equipment and data description

The MBE had a total swath width of 120°, made up of 128 receive beams each with a 1.5° across-track and 20° along-track beam width. The MBE head was mounted facing vertically downwards, along the centreline of the boat, so ensonified a 60° swath either side of the track line. An orthogonally-mounted (with respect to the MBE head) external profiling transmitter was used and reduced the along-track beam width from 20° to 1.5°. This improved the precision of water-column target sampling and reduced between-ping along-track sampling volume overlap. Acoustic pulses were transmitted every 1.5 to 3 s (this varied because of computer processing limitations). Time varied gain was *20 log_{10}(range)*, pulse length was 825 μs, and the transmission power was set to 'medium'. MBE detections throughout the fixed 200-m observation range had 0.5 m resolution to standardise sampling and were logged continuously to the control computer. Recorded MBE data were converted to the SM2000 data format using Kongsberg Mesotech MsToSm (v1.0), and resulting S_v data were processed using Echoview v3.5 (Myriax, Hobart, Australia).

2.2. Scaling uncalibrated MBE S_v observations

The MBE cannot be calibrated easily in the field using the conventional standard reference sphere techniques (Foote et al., 1987) that would typically be applied to SBEs. Consequently, the uncalibrated data from the MBE were calibrated by comparison to the S_v observations calibrated by the standard sphere method and collected by the ES60 along the tie lines (two lines run