Deep-Sea Research II 51 (2004) 1205–1213

DEEP-SEA RESEARCH
PART II

www.elsevier.com/locate/dsr2

Editorial

The CCAMLR 2000 Survey: a multinational, multi-ship biological oceanography survey of the Atlantic sector of the Southern Ocean

Accepted 18 June 2004

Abstract

The CCAMLR 2000 Survey is the first large-scale multinational, multi-ship survey in the Southern Ocean since 1979/80. Conducted using strict method protocols and within a 32-day time frame it provides a truly synoptic view of the oceanography, zooplankton, krill, and higher predator biomass and distribution for the Scotia Sea and Antarctic Peninsula region. The innovative design of interleaved transects surveyed only during the hours of daylight has provided a comprehensive and robust estimate of krill biomass.

1. Introduction

Antarctic krill (*Euphausia superba*) is a key species in the Southern Ocean ecosystem and is an important component of the diet of many predators, such as seals, penguins, flying birds, whales, fish, and squids (Laws, 1985). Over the last 30 years it has also been the target of a large multinational fishery (see review by Ichii, 2001), with up to 0.5 million tonnes of krill caught annually. Over much of the 20th century the relationship between krill and some form of commercial exploitation has been a powerful force in promoting the scientific study of this large and abundant euphausiid. Some of the earliest studies on Antarctic krill resulted from its importance as the staple food for the commercially exploited species of whales. The resulting Discovery Reports (numbering 34 volumes as of 1967; Hardy, 1967) describe the work carried out by R.R.S. *Discovery*, R.R.S. *William Scoresby*, and R.R.S. *Discovery II* in a set of cruises carried out between 1925 and 1951. Ten years later, the 431 page publication by Marr (1962) brought together all the work on Antarctic krill from over 12,000 plankton samples from these voyages.

Commercial whaling in the Antarctic had ceased by the mid-1960s and it was not until the 1970s, when interest in directly exploiting krill as a protein source arose, that significant pressure to further investigate krill ecology was generated. At this time, a series of multinational scientific investigations were coordinated by the Scientific Committee on Antarctic Research (SCAR) and the Biological Investigation of Marine Antarctic Stocks and Systems (BIOMASS) program was initiated (El-Sayed, 1994). Through this program, two ground-breaking multi-ship surveys were undertaken. The first, First International Biomass Experiment (FIBEX), took place in 1979/80.

0967-0645/$ - see front matter
doi:10.1016/j.dsr2.2004.06.010

A total of 11 ships undertook coordinated acoustic surveys to map the large-scale distribution of Antarctic krill in the Atlantic and Indian Ocean sectors of the Southern Ocean. The second, Second International BIOMASS Experiment (SIBEX), investigated temporal changes in krill distribution and abundance focusing on the Antarctic Peninsula region in 1985/86 (El-Sayed, 1994).

The severe over-exploitation of fish stocks in the Southern Ocean led to the development of the Convention for the Conservation of Antarctic Marine Living Resources, which came into force in 1982 (Miller and Agnew, 2000). The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) now manages the stocks of fish and krill in an ecosystem context. The total allowable catch of krill is estimated through the use of a generalized yield model (GYM; see Hewitt et al., 2004). One of the key parameters in this model is an estimate of pre-exploitation biomass (B_0). Concerns over the degree of independence between krill populations and the effect of potential large-scale transport of krill between regions of the Southern Ocean meant that determining the area over which to estimate B_0 was not trivial (Trathan et al., 1995). To minimize the effects of krill transport, surveys covering large areas are most acceptable. However, while many nations have conducted krill surveys in specific small-scale areas of the Southern Ocean (see for example Brierley et al., 1999; Hewitt and Demer, 1995), there are very few large-scale surveys of krill abundance. To date, the multi-ship FIBEX survey is the only acoustic survey to have covered the entire Scotia Sea region; comprising FAO statistical areas 48.1, 48.2, and 48.3 (see Fig. 1). As a result, the GYM has used the value of biomass derived from FIBEX. While this estimate was based on the most up-to-date technology available at the time, it is now over 20 years old and within CCAMLR the appropriateness of the estimate for current management of the fishery has been questioned (CCAMLR, 1996).

As a result, the CCAMLR 2000 Survey was commissioned. The priority for this survey was to estimate krill biomass within Area 48; the key fishery and management area that extends through the Scotia Sea and Antarctic Peninsula region of the Southern Ocean (Fig. 1). From the outset it was recognized that the survey was also a unique opportunity to undertake a large-scale synoptic sampling of many elements of the krill-based pelagic ecosystem and the following survey aims were developed.

- To generate an up-to-date estimate of B_0 and the associated estimate of error for the major area where commercial fishing takes place.
- To collect data on krill demography to help interpret population connections within the Scotia Sea area.
- To collect data to further insights into the ecology of the krill-based ecosystem, in particular to describe physical and biological processes influencing the distribution, growth, and predation of krill.

To adequately survey Areas 48.1, 48.2, and 48.3 it was estimated that a minimum of three ships would each need to provide around 3–4 weeks of survey time (Watters and Hewitt, 1995). Experience derived from the FIBEX cruises had shown that planning, execution, and analysis of the CCAMLR 2000 Survey would have to be meticulously undertaken to achieve the aims of the project. This paper describes the planning process, looking particularly at the innovative elements that set this survey apart from previous large-scale cruises. It then describes the general conduct of the cruise and provides an overview of the outcome.

2. Cruise planning

From the outset the cruise was planned as a multinational and multi-ship operation. The opportunity for meetings was limited and so a primary means of communication was through a dedicated website available to all participants. Planning meetings were held during the annual meetings of the CCAMLR Working Group on Ecosystem Monitoring and Management and at a meeting in Cambridge (UK) in March 1999. Full details of the sampling design and rationale developed at the Cambridge meeting are given by

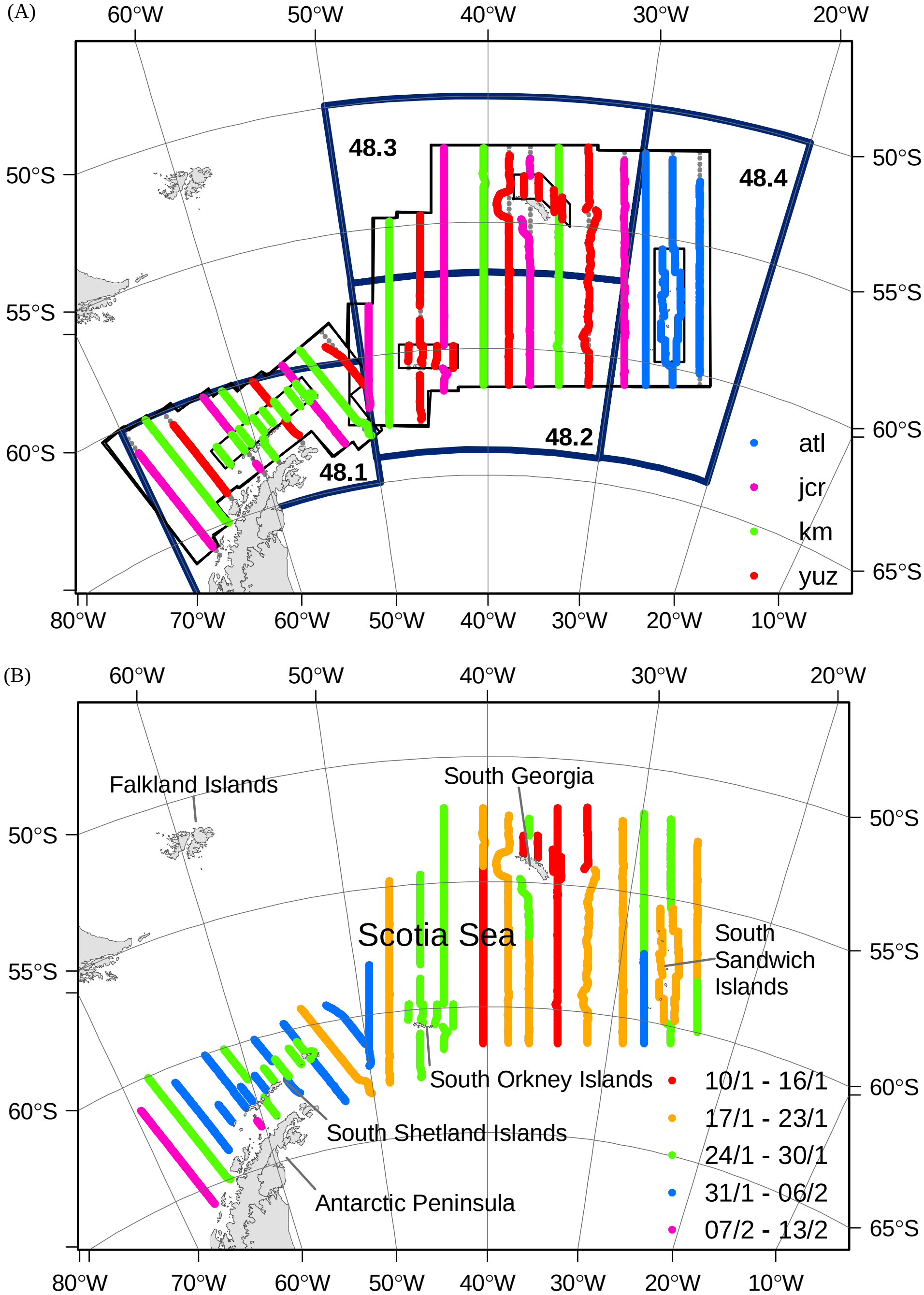

Fig. 1. Map of CCAMLR 2000 Survey. (A) Acoustic transect lines conducted by R.V. *Atlantida* (atl), R.R.S. *James Clark Ross* (jcr), R.V. *Kaiyo Maru* (km) and R.V. *Yuzhmorgeologiya* (yuz) with boundaries of sampling strata marked with black lines and FAO statistical areas bounded by dark blue lines, (B) date of sampling for acoustic transects lines.

Trathan et al. (2001). This paper summarizes key aspects of the design and rationale relevant to the overall planning process.

2.1. Sampling strategy

The survey was designed to achieve the following design criteria:

- To cater for the probable behavior of krill in terms of diurnal availability to acoustic sampling.
- To allow analyses that would be statistically robust and valid.
- To be relatively insensitive to reduction in effort due to equipment failure or bad weather.
- To operate on a set of common protocols to produce a single combined data set from all ships.
- To cover all regions where krill are likely to occur in Areas 48.1, 48.2, and 48.3.
- To cater for additional survey effort without having to re-design the entire survey.

To fulfill these design criteria the survey was laid out as a series of pre-planned, randomly placed parallel transects (Fig. 1). The randomization was carried out in two stages (Brierley et al., 1997; Trathan et al., 2001) to not only ensure that there would be a minimum separation (62.5 km) between adjacent transects but also to ensure that every point within the survey area had an equal chance of being sampled. The survey was stratified into two types of regions; oceanic and mesoscale. The mesoscale strata were areas of expected high krill biomass (Fig. 1) where the krill fishery tended to concentrate and had twice the sampling effort of the oceanic strata. The survey boundaries were initially set to contain all regions where the krill were expected to occur within Areas 48.1, 48.2, and 48.3, however, the survey was extended just prior to execution to include Area 48.4.

To ensure that the survey was relatively insensitive to gear failure or loss of data during bad weather, within Areas 48.1, 48.2, and 48.3 alternate transects were surveyed by the ships from Japan, UK, and USA (Fig. 1). The staggered start times for each ship meant that adjacent tracks were surveyed at different times, further reducing the probability of losing adjacent tracks due to bad weather (Fig. 1).

During FIBEX and in many national krill surveys, acoustic transects interspersed with a series of net sampling stations have been carried out irrespective of the time of day. However, Antarctic krill often migrate vertically to within a few meters of the sea surface at night (Godlewska, 1996; Morris and Ricketts, 1984; Watkins, 2000) and such krill are not detected acoustically (Hewitt and Demer, 1996; Watkins, 2000). The CCAMLR 2000 Survey took account of vertical migration by only carrying out acoustic transects during daylight, when there was a high probability that the krill would be located below the depth of the transducers. No acoustic transects were run during the night-time period. This period was used for station-based sampling.

As the survey was planned it became apparent that sampling at stations during the night-time period only would result in a relatively sparse net sample grid and would not facilitate acoustic target identification. Provision was thus made to sample stations either during the middle of the day or to undertake a target identification tow during the day. A hierarchical set of options was agreed to ensure that all ships operated according to a common sampling strategy (Trathan et al., 2001).

2.2. Protocols

Previous experience (from surveys conducted during FIBEX and SIBEX and from mesoscale surveys undertaken by CCAMLR participants) indicated that rigorous comparison of acoustic data from different ships was only feasible if each ship used equipment of the same specification and operated to a common set of data collection protocols. Considerable effort was expended prior to the cruise to ensure that the protocols for the primary datasets (acoustic, net, and CTD sampling) were fully defined and accepted by all participants. These protocols are published on the CCAMLR website (www.ccamlr.org) and their key features are discussed below.

2.2.1. Acoustics

Unlike the 11 ships of the FIBEX survey, each ship participating in the CCAMLR 2000 Survey used the same make and model of echo sounder (Simrad EK500). SonarData Echoview software was chosen as the standard data logging and analysis software package. To further standardize data collection, every setting for the echo sounder was given either a mandatory value or if a single value was not appropriate then a limited set of options was specified. Every menu setting for the Simrad EK500 echo sounder was detailed on the survey website (accessible via the CCAMLR website; www.ccamlr.org).

Calibration of the echo sounders was equally important and tightly controlled in terms of methodology, location, and timing. Each ship calibrated the echo sounder immediately before and after the survey. Calibrations were carried out within the survey area at South Georgia and King George Island (Fig. 2). Calibration used the standard sphere technique (Foote et al., 1987). Each ship used tungsten carbide spheres provided by a single manufacturer especially for the survey. Further details of acoustic sampling are to be found in Hewitt et al. (2004) and Demer (2004).

2.2.2. Netting

There were two primary objectives for the net sampling program. The first, to validate and identify acoustic targets, confirming which targets could be considered as krill and obtaining krill length frequency data for target strength estimation, and the second, to describe krill demography and large-scale distribution patterns of size classes and maturity stages as well as regional recruitment indices. Comparing samples collected by different nets is problematic (see Anon., 1991, for FIBEX analyses of krill collected with nets that ranged from Bongo nets to commercial krill trawls). Differences in net selectivity have a profound effect on the analysis of krill length for both target strength estimation and demographic studies. For the CCAMLR 2000 Survey a standard net type was specified, the RMT8 + 1 (Rectangular Midwater Trawl; Roe and Shale, 1979), as the most appropriate type of net presently available. Prior to the survey, only one of the four participating ships used this particular net. However, suitable nets were contributed by other CCAMLR nations (Australia, South Africa, and the UK). Differences in availability of ancillary equipment meant that two of the ships (UK and USA) were able to deploy the RMT8 + 1 as a multiple opening and closing net while the other two ships had to deploy the net in a permanently open state. This resulted in some slight differences in the way the nets were sampled.

The two primary net sampling objectives required different sampling strategies. To validate acoustic targets, the UK and USA varied the depth, trajectory, and opening/closing of the net so that only targets of interest were sampled. In contrast, samples to describe krill demography and large-scale distribution patterns were usually taken over the complete depth range of occurrence of krill at a series of predetermined stations. This sampling strategy was possible with all the RMT8 + 1 nets used during the survey. Further details of the net sampling are given in Siegel et al. (2004).

2.2.3. CTD sampling

The main objective of CTD sampling was to identify environmental characteristics of the survey area, in particular the water masses that influence krill distribution and transport. A further objective was to identify the approximate location of important fronts and to estimate geostrophic currents. The protocols were based on World Ocean Circulation Experiment (WOCE) standards (http://whpo.ucsd.edu/manuals.htm) and further details of the CTD sampling are given in Brandon et al. (2004).

2.2.4. Other sampling protocols

Table 1 shows the full list of activities undertaken on the participating ships, including sampling protocols for data sets additional to the primary data sets described in Sections 2.2.1 to 2.2.3. These additional activities were not carried out according to a set of centrally defined protocols; individuals responsible for such measurements on each ship were left to coordinate methodology at an appropriate level.

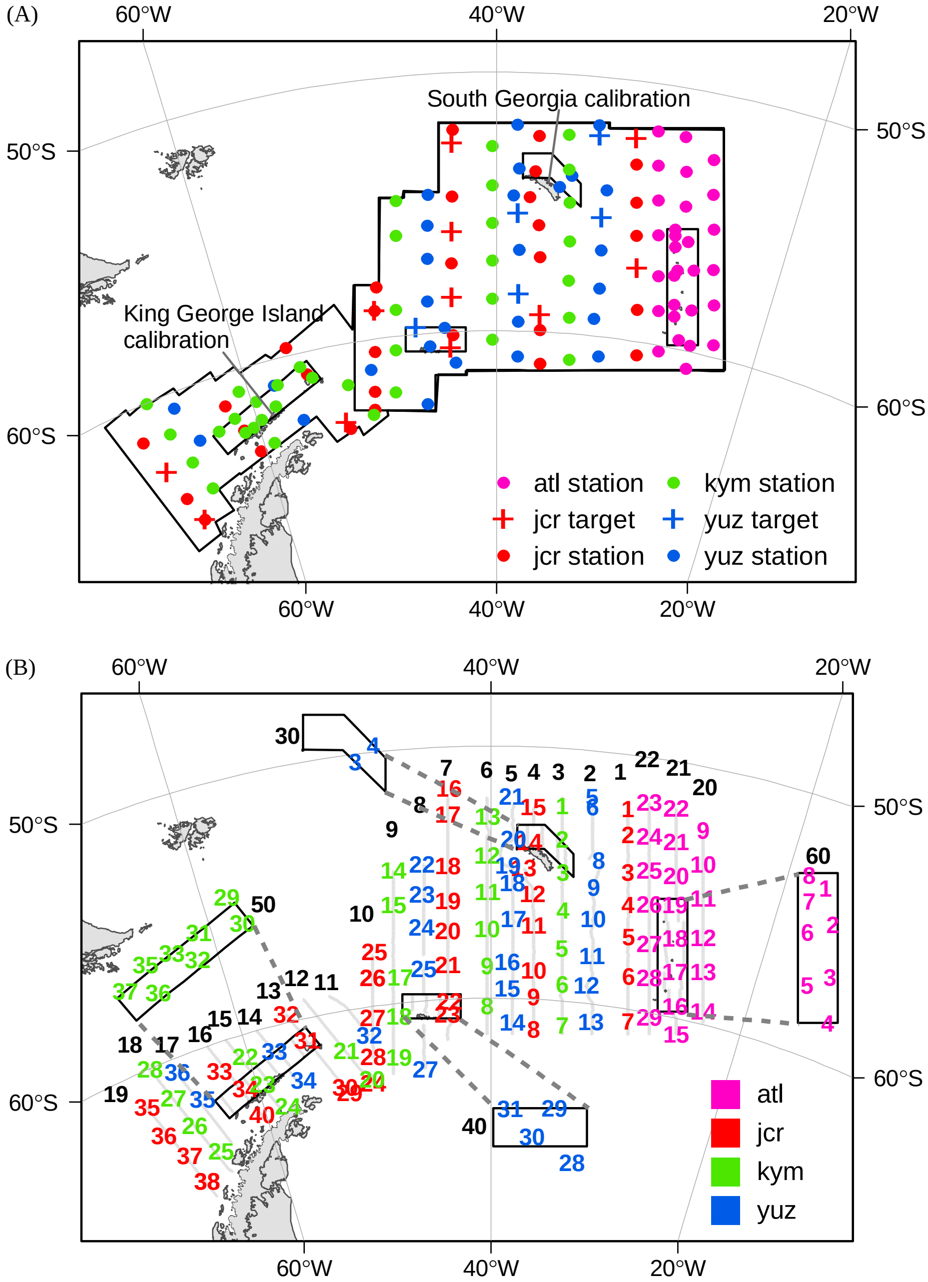

Fig. 2. CCAMLR 2000 Survey net sampling grid. (A) Showing net sample stations identified by ship and type of haul, (B) showing station numbering where each station descriptor comprises two figures for transect number (shown in black) followed by two figures for net haul number, e.g., station 2010 is Atlantida net haul 10 carried out on transect 20. Net hauls carried out during mesoscale surveys are identified by two figure transect numbers as follows: South Georgia—30, South Orkney Islands—40, South Shetland Islands—50, South Sandwich Islands—60. Sample numbers relating to these mesoscale boxes are shown for clarity around the edge of the main survey region.

Table 1
Summary of data collected.

	Atlantida	*James Clark Ross*	*Kaiyo Maru*	*Yuzhmorgeologiya*
Underway observations				
Acoustic survey				
Water column acoustic profiles	EK500	EK500	EK500	EK500
Bathymetry	—	EA500 (12 kHz)	—	—
Physical oceanography				
Meteorological data	Instruments	Instruments	Instruments, MAPT	Instruments
Satellite images	—	—	NOAA	SeaWiFS
Current velocity and direction	ADCP	ADCP		
Water temperature and salinity	—	Thermosalinograph	EPCS, XBT, XCTD	Thermosalinograph
Biological sampling				
Chlorophyll	—	Fluorometer	EPCS	Fluorometer
Chlorophyll calibration	Water samples	Water samples	Water samples	Water samples
Zooplankton sampling	—	OPC	EPCS, CPR	—
Seabird and marine mammal observations	National observers	JNCC, IWC	IWC	IWC
On-station sampling				
Physical oceanography				
Temperature and conductivity	CTD	CTD	CTD	CTD
Dissolved oxygen	CTD		CTD	CTD
Current velocity and direction	—	ADCP	LADCP	—
Water samples	To 1000 m	To 1000 m	To 1000 m	To 1000 m
Biological sampling				
Krill and other micronekton	RMT8 (O)	RMT8 (O/C)	RMT8 (O)	RMT8 (O/C)
Mesozooplankton	RMT1	RMT1, Bongo	RMT1, NORPAC	RMT1
Chlorophyll-*a*	—	Y	Y	Y
Nutrients			Y	

ADCP: acoustic Doppler current profiler; CPR: continuous plankton recorder; CTD: conductivity temperature depth probe; EK500: Simrad EK-500 echo sounder (38, 120, 200 kHz) with SonarData Echoview software; EPCS: electronic plankton counting system; IWC: International Whaling Commission observers; JNCC: Joint Nature Conservancy Council Seabirds-at-Sea; LADCP: lowered ADCP; MAPT: meteorological automatic picture transmission; NORPAC: North Pacific standard net; O/C: opening/closing mechanism available; RMT1: rectangular midwater trawl 1 m^2; RMT8: rectangular midwater trawl 8 m^2; SeaWiFS: sea-viewing wide field-of-view sensor; XBT: expendable bathythermograph; XCTD: expendable CTD.

2.2.5. Monitoring progress

The survey tracks for the ships were geographically fixed (as shown in Fig. 1); however, the time available for surveying was limited to daylight hours as defined by the time of nautical twilight. As a result, start and end times and positions for each daily segment of transect depended on both location and date. Any changes to planned itinerary could change both the distance surveyed and the station positions as these were determined by the position of the ship at midday and midnight. To ensure a balanced survey plan, it was essential that the effect of any changes to the itinerary was assessed regularly. A spreadsheet was therefore created to predict arrival times at waypoints, daily start and end times, and station positions for the remainder of the cruise. Progress was monitored daily and it was possible to make revisions to the program based on a hierarchy of agreed procedures to be implemented if ships fell behind schedule (Trathan et al., 2001).

3. Cruise conduct

The survey started with transect SS03 on 11 January 2000 and was completed with transect AP19 on 11 February 2000. For logistic reasons, the start and end times for each ship were slightly different (Table 2). However, all survey tracks

Table 2
Start and end dates of transects.

	Start date	Stop date
R.V. *Atlantida*	17 January 2000	01 February 2000
R.R.S. *James Clark Ross*	18 January 2000	11 February 2000
R.V. *Kaiyo Maru*	11 January 2000	02 February 2000
R.V. *Yuzhmorgeologiya*	13 January 2000	04 February 2000

were completed within a 32-day period, thus achieving the synoptic objectives of the cruise. A total of 17,424 km of transect were surveyed from an original planned distance of 18,025 km (Fig. 1). One consequence of the ships starting at slightly different times is that ships were sampling all across the survey area in the middle of the survey. A number of deviations from the planned transects occurred due to the presence of ice. This was particularly noticeable on transects around South Georgia where significant ice fields were found to the south and the west of the island.

A total of 136 net hauls were undertaken; of these, 16 were targeted net hauls and 122 oblique net hauls (Fig. 2). On R.R.S. *James Clark Ross* (UK) the use of an RMT8 + 1 with two independently controlled nets allowed target and oblique station hauls to be carried out during the same haul, such hauls were carried out on two occasions. In these cases, the first net was target fished and then once this net was closed the nets were lowered to 200 m before the second net was opened and then hauled obliquely to the surface. The naming convention for the net hauls is also shown in Fig. 2.

4. Post-cruise analysis

The primary focus of the CCAMLR 2000 survey was the estimation of B_0. These analyses were carried out jointly at a workshop held at the Southwest Fisheries Center (La Jolla, USA, May/June 2000) and results were submitted to the CCAMLR Working Group on Ecosystem Monitoring and Management in August 2000. The report of the working group went to the CCAMLR Scientific Committee in November 2000. The results of the analyses are presented by Hewitt et al. (2004).

While the derivation of a precautionary catch limit was the main aim of the survey, it is obvious from Table 1 that many other measurements and observations on the krill-based ecosystem were made. The intensity and areal coverage of transects and stations combined with the synoptic time scale were recognized as an international resource that deserved detailed and careful analysis. A second workshop was held in Cambridge in May 2001 and the outcome of the coordinated analyses are presented in this volume.

Core data from the CCAMLR 2000 Survey have been deposited at the CCAMLR data center in Hobart, Australia. Zooplankton samples (RMT8 + 1) from all participating countries are presently held at the British Antarctic Survey, UK. In addition, samples of krill preserved in 95% ethanol have been retained for future genetic studies on population structure. Any future analyses of samples or data will be coordinated through the scientific steering committee (the authors of this paper) to whom all correspondence or queries should be addressed.

Acknowledgments

The planning, execution, and analysis of the CCAMLR 2000 Survey has involved many people in addition to those whose names appear on papers within this volume, and many are acknowledged for their help in the appropriate papers. Here we would like to record our thanks to Dr. Stephen Nicol and the Australian Antarctic Division for providing one RMT8 + 1 system and to Dr. Denzil Miller and the Sea Fisheries Institute, Cape Town for providing the other. We also thank the Polish Antarctic Base at Arctowski for providing temporary storage of plankton samples collected during the survey. The publication of this volume would not have been possible without considerable help. In particular, we thank all the reviewers for their hard work. Finally, we thank Dr. Carolyn Symon who acted as technical editor.

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