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TEMPORAL CHANGES IN MARINE ENVIRONMENTS IN THE ANTARCTIC PENINSULA AREA DURING THE 1994/95 AUSTRAL SUMMER

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Abstract: To reveal the temporal changes in Antarctic marine environments during the 1994/95 austral summer, oceanographic surveys were carried out in the Antarctic Peninsula area by Germany, Japan, Korea, and the USA. Five oceanographic stations at 15 nautical mile intervals were selected north of Elephant Island along 55°W; water temperature, salinity, nutrients, phytoplankton, krill and other zooplankton, and acoustic backscatter were sampled by similar sampling protocols. The transect was surveyed six times during the austral summer, from early December 1994 to late February 1995. The major findings from this time-series were:

1) The north/south position of the oceanic frontal zone north of Elephant Island along 55°W varied by 15 nautical miles; the northeasterly current associated with this front, determined by geostrophy, varied in strength depending on position of the front;

2) Most chl-*a* was concentrated in the upper 50 m above or near the pycnocline. Surface chl-*a* concentrations ranged from 0.5 mg/m^3 to >3.5 mg/m^3. Peak chl-*a* (3.62 mg/m^3) was found in the surface water during 18 February 1995.

3) Krill spawning during the 1994/95 season was early, extensive and apparently successful compared to previous years; and

4) Taxa other than krill may have contributed substantially to the observed acoustic backscattering.

Footnote: The first four authors were organizers of the Hamburg Workshop (CCAMLR, 1995) wherein this manuscript originated. The next five authors were participants at the workshop, and the remaining six contributors of data and/or analyses who did not attend the workshop, respectively. The contributions from these groups are in the same weight, and in alphabetic order.

1. Introduction

Although the Southern Ocean has many interesting ecological aspects to study, the area to be covered is too large to be surveyed by any one nation or one research group. Hence, our knowledge of the Antarctic marine ecosystem is still limited. Therefore multinational cooperation is essential to improve our understanding of the Antarctic marine ecosystem. However, since the completion of Biological Investigations of Marine Antarctic System and Stocks (BIOMASS) program in the mid 1980s, no intensive multinational oceanographic cooperation has been conducted in the Southern Ocean due to different research interests and funding limitations.

A group of scientists from the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has jointly researched in the Antarctic Peninsula area to find relationships among Antarctic krill, *Euphausia superba*, recruitment and environmental factors. An area of major ecological interest to the north of Elephant Island near the Antarctic Peninsula is very fertile, and a large portion of the commercial krill catch is taken from this area. High krill abundances to the north of the South Shetland Islands were associated with abundance of phytoplankton in frontal systems over the continental slope and shelf-break areas (HEWITT and DEMER, 1993; LOBE *et al.*, 1993). With high primary production as well as an abundant krill population, this area supports many predatory species such as seals and penguins. Furthermore, krill swarms pass through from one to another fishing areas, *i.e.*, they are thought to move from the South Shetland Islands to South Orkney, and to South Georgia along the Weddell-Scotia Confluence (BRINTON, 1991; HUNTLEY and BRINTON, 1991; ICHII and NAGANOBU, 1996). Therefore many nations have conducted scientific surveys near the Antarctic Peninsula area.

Though the proper management of krill resources is an urgent requirement, organizing a big research program such as BIOMASS is not easy. One possible way to solve this difficulty, in the beginning stage, is to keep national programs in the area, while cooperating internationally for the common interests in ecosystem changes. Based on this philosophy, a multi-national oceanographic survey in the Antarctic Peninsula area was suggested and planned at the 1993 CCAMLR meeting. During the 1994/95 austral summer, four countries (Germany, Japan, Rep. of Korea, and USA) conducted surveys in the Antarctic Peninsula region with similar sampling methods. The main purposes of this international cooperative research were: 1) to realize changes in ecosystem structure near the Antarctic Peninsula during the austral summer inter-seasonally as well as interannually; 2) to investigate the processes by which environmental factors influence life forms; 3) to compare this ecosystem with those in other subantarctic island areas such as the South Georgia and Kerguelen Islands; and 4) to accumulate experience in international joint activities in the Southern Ocean. Data from the cruises were analyzed at a workshop in Hamburg, Germany, in July 1995 (CCAMLR, 1995). This manuscript is a summary of the Workshop findings.

2. Methods

Water properties, nutrients, phytoplankton, krill and other zooplankton, and acoustic data were collected by each research team using standardized or similar sampling protocols. Five sampling stations (60°S, 55°W to 61°S, 55°W) at 15 nautical mile intervals were selected based on ecological significance and accessibility of area (Fig. 1). Samples were collected six times from early December 1994 to late February 1995 (Table 1). In addition, Germany and the USA conducted multi-purpose oceanographic surveys around Elephant Island during the early and mid-late austral summer of 1994/95, respectively. Below are the details of sampling procedures.

CTD casts were carried out for temperature and salinity profiles at each station. CTDs used by Germany, Japan, Korea and the USA were ME CTD, BP-702 (Falmouth Scientific) and Mark IIIb (Neil Brown Instruments), Mark V (General Oceanics), and SBE-9 (Sea Bird), respectively, and each country covered the vertical range from the surface to at least 750 m at deep water stations or close to the bottom at shallower stations. Seawater temperature, salinity, and water density were available for each cruise, and geostrophic velocity and transport between stations were calculated from Japanese and Korean data assuming the level of no motion to be at 750 m.

A Rosette water sampler was used in order to see the temporal variability of vertical and horizontal distribution patterns and standing stocks of chlorophyll-*a* (chl-*a*) and nutrient concentrations at each station. Chl-*a* and nutrients (silicate, nitrate, nitrite, and phosphate) were measured at each station from water samples (200–500 m*l*) collected from the similar sampling depth layers: *e.g.*, Korea and Japan sampled from 0, 10, 20, 30, 50, 75, 100, 150, and 200 m, and the USA from 5, 10, 15, 20, 30, 40, 50, 75, 100, and 200 m depths. Chl-*a* concentration was determined using a spectrophotometer or fluorometer after filtration by glass fiber filters, and nutrients were measured by autoanalyzer aboard research vessels or in the laboratory after cruises.

Oblique net tows with 0.505 and/or 0.333 mm mesh sizes were carried out for

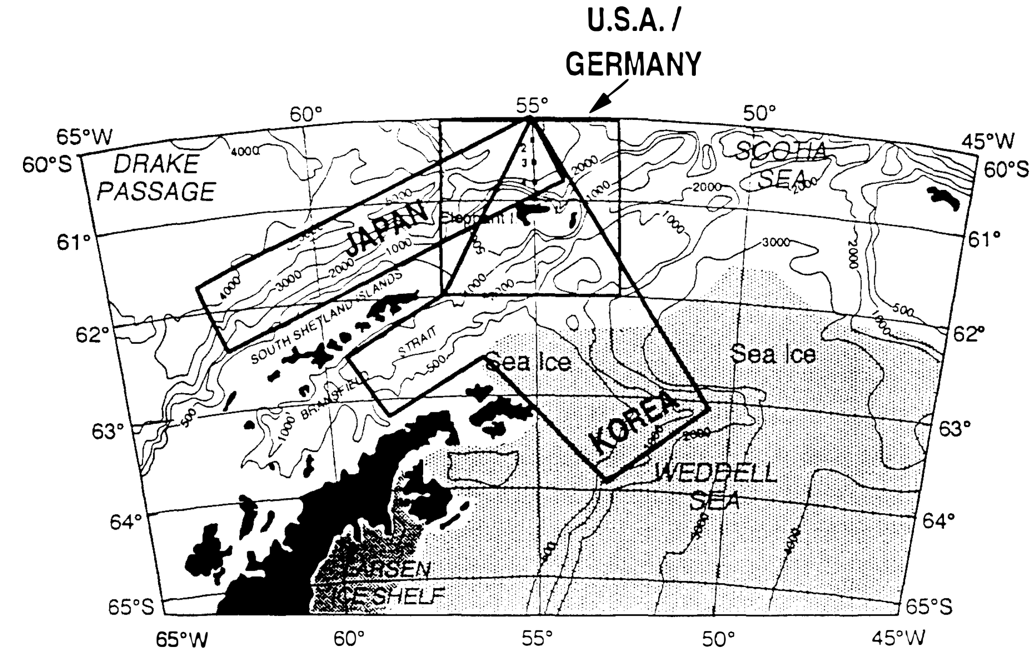

Fig. 1. Survey areas covered by different nations during late November 1994 to late February 1995.

Table 1. Antarctic 1994/95 cruises conducted by participating countries.

Dates Entire cruise (55° W transect)	Country	Observations
Nov. 26–Dec. 5, 1995 (Dec. 2, 1995)	Germany	north and south of Elephant Island; water properties, krill/zooplankton; CTD, RMT 8 (4 mm) net
Nov. 30–Dec. 30, 1994 (Dec. 15–16, 1994)	Japan (Leg I)	north and South Shetland Islands; krill/zooplankton, phytoplankton, water properties, nutrients, acoustics; CTD, rosette, WP-2 (0.350 mm), KYMT, (3×3 m with 3.4 mm mesh), MOCNESS at 3 stations (0.335 mm mesh), Furuno FQ-72 echosounder
Jan. 4–17, 1995 (Jan. 7–8, 1995)	Korea	Bransfield Strait and northwestern Weddell Sea; krill/zooplankton, phytoplankton, water properties, nutrients; CTD, rosette, Bongo (0.333 mm mesh and 0.505 mm mesh), MOCNESS (0.505 mm mesh)
Jan. 15–Feb. 12, 1995 (Jan. 18–19, 1995)	Japan (Leg II)	north of South Shetland Islands; krill/zooplankton, phytoplankton, water properties, nutrients, acoustics; CTD, rosette, WP-2 (0.350 mm), MOCNESS (0.335 mm mesh) at 6 stations
Jan. 11–Feb. 4, 1995 (Jan. 24–25, 1995)	U.S.A (Leg I)	north and south Elephant Island; krill/zooplankton, phytoplankton, water properties, acoustics; CTD, IKMT (1.8×1.8 m with 0.505 mm mesh), rosette, Simrad EK-500 echo sounder
Feb. 8–Mar. 5, 1995 (Feb. 18–19, 1995)	U.S.A (Leg II)	north and south Elephant Island; krill/zooplankton, phytoplankton, water properties, acoustics; CTD, IKMT (1.8×1.8 m with 0.505 mm mesh), rosette, Simrad EK-500 echo sounder

zooplankton collected from depth 0 to 200 m or close to the bottom at shallower stations. Plankton nets used for German, Japanese, Korean, and USA cruises were RMT8 and RMT1, WP-2 and MOCNESS, Bongo and MOCNESS, and IKMT, respectively. Filtered water volume was recorded for each tow. Samples from targeted tows were not considered in the analysis. Major components of the zooplankton, if possible all other zooplankton components, were determined to the species level and recorded total counts of specimens per species as well as density to allow analysis of diversity.

Krill length was measured as total length (marginal tip of the eye to tip of the telson) in 1 mm size classes (MAKAROV and DENYS, 1981). Krill length frequency was constructed from the samples at 5 stations along 55° W as well as all stations around Elephant Island conducted by Germany and the USA, even if the total number of krill in the sample was very low. Maturity stages were determined following the classification of MAKAROV and DENYS (1981). The total number of krill in the catch was recorded, even if only a subsample was measured and staged. Krill density was expressed as number per 1000 m^3. Measurements from subsamples must contain at least 100 krill for reliable length frequency distributions. Before pooling length frequency distributions from different stations, numbers of krill per length class were standardized to 1000/m^3. Groups of stations with similar krill length frequency distribution were separated by Cluster analysis as described by SIEGEL (1988).

Hydroacoustic surveys for krill abundance/biomass at 55° W longitude were taken four times from December to February by Japan and the USA. The methods and formulas used in this study have been adopted by CCAMLR, and results were expressed as density and Target Strength (TS) values. The Japanese data were collected from R/V KAIYO MARU during two periods, mid December 1994 and mid January 1995, using a Furuno FQ-72 echosounder, configured with a 120 kHz hull-mounted transducer. Pulses (1.2 ms) were transmitted every second during surveying at speeds of 6–8 knots. The system was calibrated using a 38.1 mm diameter tungsten carbide sphere at Admiralty Bay, King George Island. The USA data were collected from the R/V SURVEYOR in late January and mid February 1995. USA acoustic surveys were conducted with a Simrad EK-500 echosounder, configured with 120 and 200 kHz hull mounted transducers (Simrad ES 120-7 and 200-28). Surveys were conducted at speeds between 5–10 knots. Pulses of length 0.3 and 0.2 ms were transmitted every second at 120 and 200 kHz, respectively. The system was calibrated in Admiralty Bay, King George Island, using copper spheres, both before and after the surveys. Mean volume backscattering strength (S_v) data from Japan were calculated for 10 m depth ranges from 10 to 150 m and 50 m ranges from 150 to 250 m. Japanese data were averaged over distance intervals corresponding to 100 pulses or approximately 370.4 m. Mean S_v data from the USA were averaged over 5 m depth ranges from 10 m to 250 m and averaged over 185.2 m distance intervals. Assuming that the acoustic backscattering in the area is dominated by *Euphausia superba*, the resulting maps using block Krigging methods for the integrated data can describe the general distribution patterns of krill.

Because several species reside in the epi-pelagic zone of the Elephant Island area, it is generally necessary to apportion the backscattered energy to krill and the other scatterers. Zooplankton data in this area indicated a diverse species composition along the 55° W transect. Additionally, there is some indication that myctophids may be contributing to appreciable scatter at times. Using the 120 and 200 kHz data along the 55° W transect, two methods were explored to delineate the species dominating the acoustic scatterers. For each 5 m depth by 185.2 m distance bin, the average sound pressure level at 120 kHz (p120) was subtracted from the average sound pressure level at 200 kHz (p200). Similarly, the mean S_v values were subtracted (delta $S_v = S_v200 - S_v120$).

3. Results

3.1. Hydrography

The research area is located between Elephant Island in the south and the Antarctic Convergence in the north, covering from the continental slope near the island (Stns. 4–5) to sea floor areas offshore (Stns. 1–3). At most stations, the bottom depths exceed 3000 m except for the coastal area (*i.e.*, about 600 m at Stn. 5). Temperature profiles revealed the existence of at least, three categories of water type: surface water, cold winter water, and Circumpolar Deep Water (CDW) masses from top to bottom. The CDW mass showed a temperature maximum of 1.8°C at around 400 m, but temperature did not vary much below 200 m. On the other hand, due to the intensification of solar insolation through summer, seawater temperature in the surface layer increased rapidly during the study period. In early December, the water temperature of the surface layer was about 0.6°C. As the season progressed, however, sea surface temperature (SST) increased up to 3.5°C during late January, and the temperature increase was more conspicuous in the offshore area than the coastal area. The rate of increase at 10 m depth offshore (Stn. 1) and inshore (Stn. 5) stations from December 2 to January 18 was approximately 0.077°C/day and 0.037°C/day, respectively (Table 2). After January, the temperature decreased slightly. Salinity values were stable at around 34.0–34.2 psu over the whole period.

One of the persistent phenomena is the existence of a cold water mass between 50–100 m. The center of this cold water mass (called the Winter Water) was located in the middle of the transect (*i.e.*, Stns. 2 and 3), but this cold water did not intrude to the coastal area. The vertical temperature gradient in the upper 100 m was consequently higher in the middle of the transect. The vertical profiles of salinity and density indicated that there was upward water mass movement from the middle layer in the coastal areas. Saline and dense waters occupied inshore areas, and salinity values at 10 m at Stn. 5 were always higher than those found at Stn. 1 (Table 2), which resulted in a strong density frontal zone between the offshore and inshore areas (Fig. 2). The location of the front moved back and forth with time. In early December, the front existed onshore between Stns. 4 and 5 (Fig. 2a), and moved offshore between Stns. 3 and 4 in mid-December (Fig. 2b). It moved toward the coast and was located between Stns. 4 and 5 in January (Fig. 2c, d and e), and again moved offshore in February (Fig. 2f).

The location of the front, which marked the boundary of coastal water mass, influences on the current speed and volume transport in the coastal areas. When the coastal area is broad, the current strength becomes weak, and *vice versa*. Calculations of the geostrophic current speed in the coastal area resulted in a very low value (1–3 cm/s) during mid-December when the front was located offshore. However, the geostrophic speeds between Stns. 4 and 5 during mid-January (*i.e.*, the front formed close to the coast) were much stronger (>10 cm/s) than those in December (Fig. 3).

Table 2. Time series changes in water temperature and salinity at 10 m depth of offshore (Stn. 1) and onshore (Stn. 5) areas. Locations of Winter Water minimum were always found in the middle of the Transect 55° W.

	Dec. 2, 94	Dec. 15	Jan. 7, 95	Jan. 18	Jan. 24	Feb. 18
T_{10} at Stn. 1	−0.65	0.47	1.10	2.57	3.42	2.17
T_{10} at Stn. 5	−0.59	0.20	0.69	1.10	1.35	1.74
S_{10} at Stn. 1	33.84	33.77	33.83	33.72	33.80	33.67
S_{10} at Stn. 5	34.18	34.08	34.14	34.09	34.09	34.00
Lowest temp. & location	−1.18°C at 82 m of Stn. 3	−1.22°C at 50 m of Stn. 3	−0.77°C at 55 m of Stn. 3	−0.89°C at 100 m of Stn. 2	−0.83°C at 82 m of Stn. 3	−0.84°C at 76 m of Stn. 3

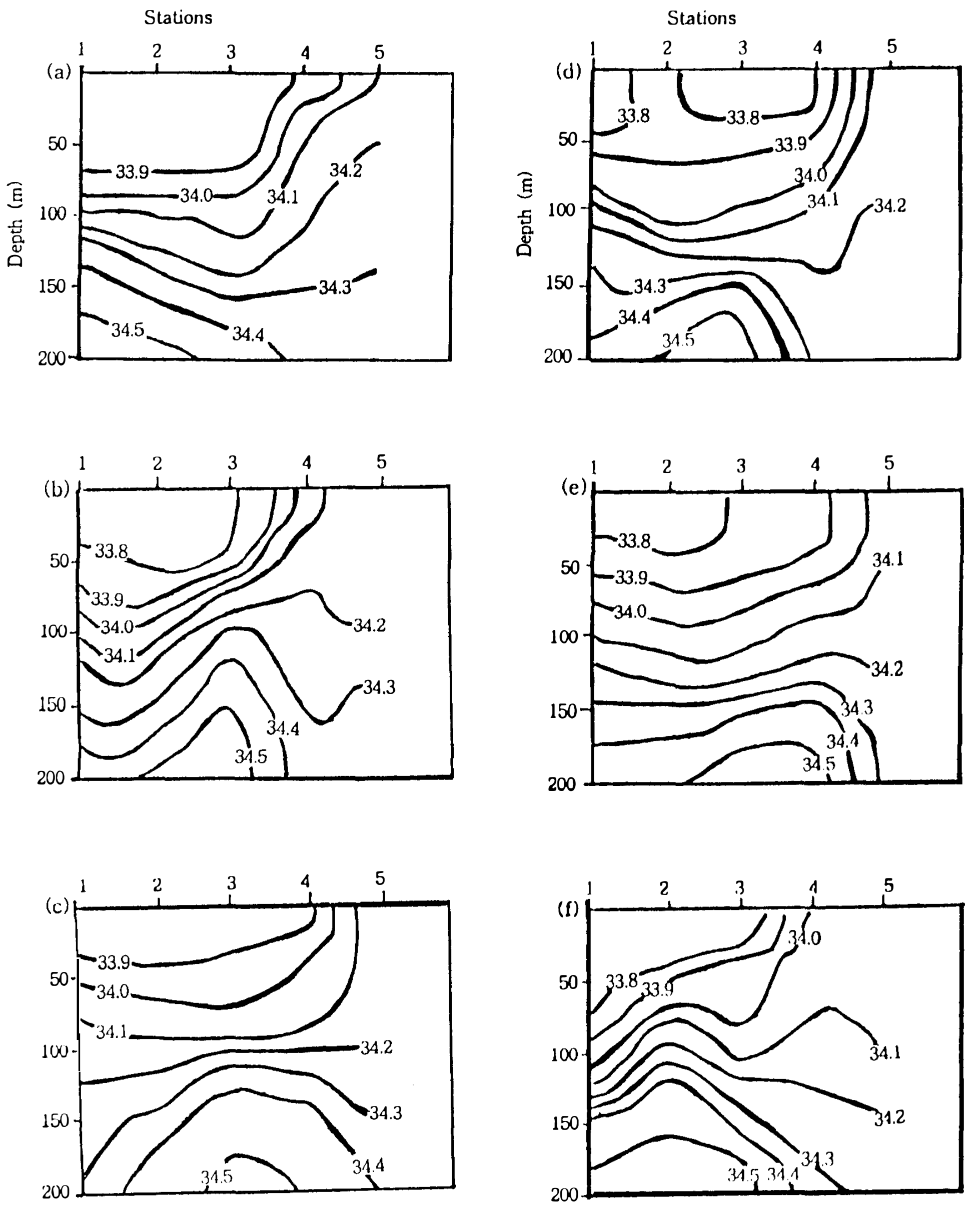

Fig. 2. Salinity (psu) profiles of the upper 200 m at 55° W on (a) 2 December 1994, (b) 15–16 December 1994, (c) 7–8 January 1995, (d) 18–19 January 1995, (e) 24–25 January 1995, and (f) 18–19 February 1995.

3.2. Chlorophyll-a and nutrients

During mid-December 1994, two chl-*a* maxima ($>2.0\,mg/m^3$) were found at Stns. 1 and 4 in the upper 20 m (Fig. 4). About 20 days later (7/8 January 1995), overall surface concentrations were decreased. Most chl-*a* ($>1.0\,mg/m^3$) was distributed throughout the transect. During mid-January 1995, a slight increase of chl-*a* concentration was observed in the southern stations with peak ($2.1\,mg/m^3$) at Stn. 5 near Elephant Island. In late January 1995, increased chl-*a* concentrations ($>1.0\,mg/m^3$) were observed in the southern stations, similar to those in mid-January. In February, about 23 days later, highly increased chl-*a* concentrations ($>2.5\,mg/m^3$) were observed

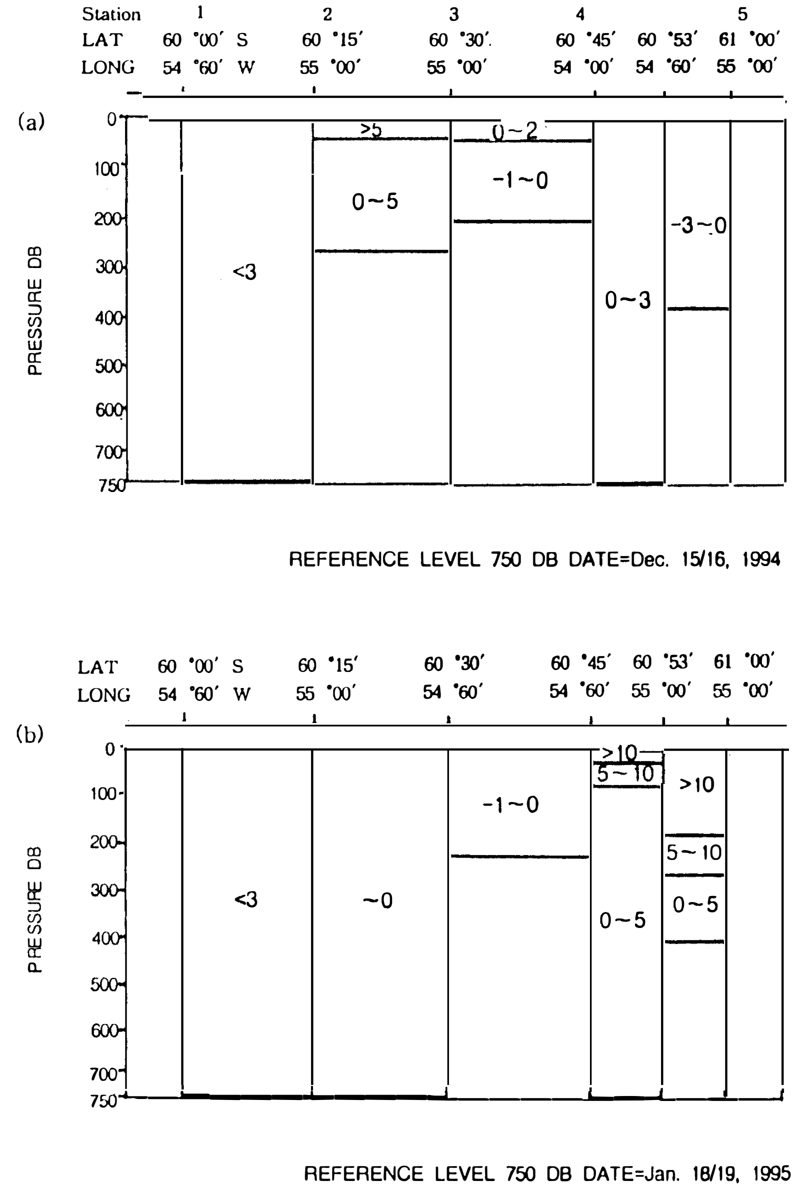

Fig. 3. Geostrophic flow (cm/s) relative to the 750 decibar (DB) surface through 55° W (a) 15–16 December 1994, and (b) 18–19 January 1995.

in Stn. 4 near the frontal zone.

In order to see the temporal differences of chl-*a* concentrations, we integrated the discrete chl-*a* values at all stations along the transect between the surface and 50 m depth (Table 3). Mean integrated chl-*a* (0–50 m) was 60.9 mg/m^2 for the five cruises over two months. Integrated chl-*a* values with standard variation in the upper layer (0–50 m) ranged from 46.6$\pm$17.2 mg/m^2 in late January to 76.4$\pm$25.4 mg/m^2 in mid-February. Mean values of the integrated chl-*a* in January (46.6–55.4 mg/m^2) were lower than in December (74.9 mg/m^2) and February (76.4 mg/m^2).

In contrast to the relatively low chl-*a* levels, overall nutrient concentration was high in the surface 100 m. Nitrate, phosphate, and silicate concentrations during the study

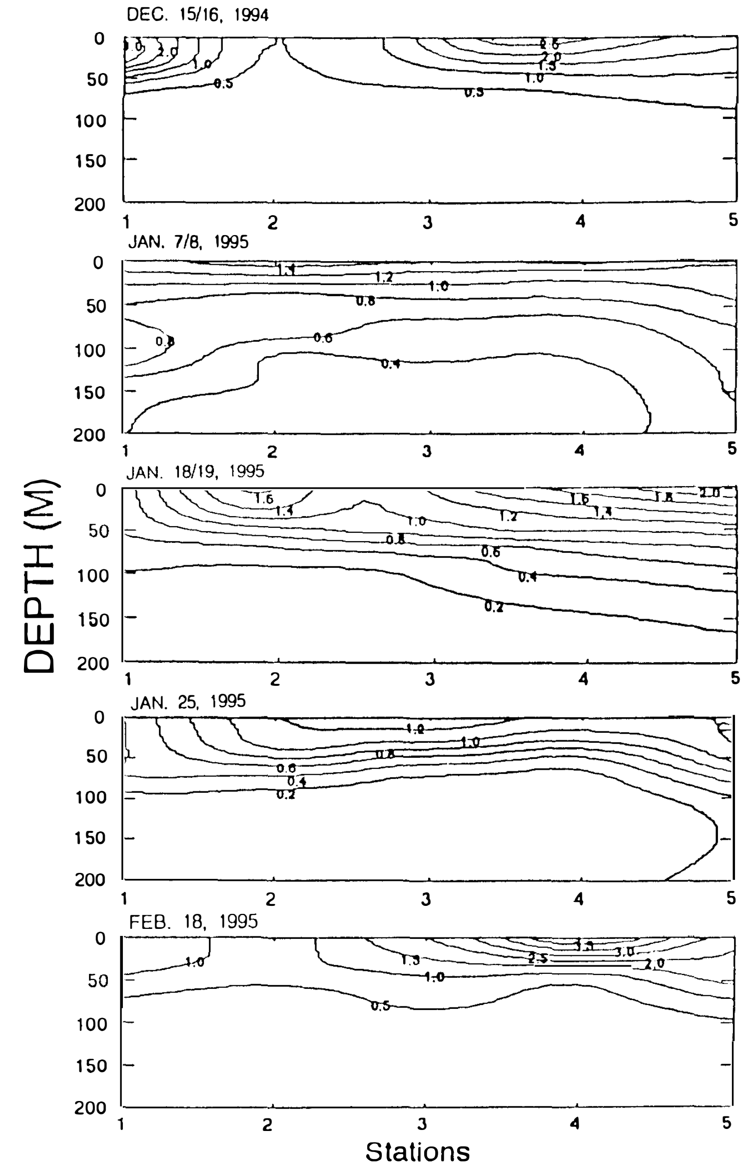

Fig. 4. Contour map of chlorophyll-a concentrations (mg/m³) in the 55° W line spanning from 60° S to 61° S at 15 nautical mile intervals for two month period from 15 December 1994 to 18 February 1995.

periods ranged from 26.9 μM on 7 January to 29.5 μM on 15 December (mean of 28.1 μM), 1.8 μM on 19 January to 3.1 μM on 7 January (mean of 2.4 μM), and 62.9 μM on 19 January to 67.9 μM on 7 January (mean of 64.7 μM), respectively (Table 3).

3.3. Krill and zooplankton

Table 4a gives the seasonal changes in zooplankton composition and densities at 5 or 6 stations along the 55° W transect from early December to late February. These values indicate extreme patchiness of all categories. Further, zooplankton density data from the larger areas around Elephant Island are tabulated in Table 4b. Comparison of these two datasets indicates that the 5 or 6 samples along 55° W are inadequate to

Table 3. Mean values of integrated chl-a between 0 and 200 m and 0 and 50 m (mg/m^2), nitrate, phosphate, and silicate concentration (μM) near Elephant Island during the 1994/95 austral summer.

	Dec. 15	Jan. 7	Jan. 19	Jan. 24	Feb. 18
INTEGRATED chl-*a* (0–200) mg/m^2					
Minimum	34.7	110.3	47.0	34.3	44.6
Maximum	179.8	158.4	149.9	87.9	130.0
Mean	104.5	130.7	94.0	55.9	91.0
Median	115.9	118.4	87.0	52.4	94.3
Std Deviation	55.8	23.4	38.6	21.3	32.6
INTEGRATED chl-*a* (0–50) mg/m^2					
Minimum	20.3	49.7	24.3	19.5	43.7
Maximum	156.4	55.3	79.7	62.2	106.4
Mean	74.8	51.5	55.4	46.6	76.4
Median	66.5	50.9	62.0	53.0	70.4
Std Deviation	53.0	2.3	20.6	17.2	25.4
NITRATE + NITRITE					
Minimum	21.6	18.3	23.0		
Maximum	36.7	37.1	35.8		
Mean	29.5	26.9	27.9		
Median	28.8	25.6	27.7		
Std Deviation	4.1	4.4	4.1		
PHOSPHATE					
Minimum	1.8	1.0	1.4		
Maximum	2.8	4.5	2.3		
Mean	2.2	3.1	1.8		
Median	2.2	3.2	1.7		
Std Deviation	0.28	0.8	0.3		
SILICATE					
Minimum	48.1	46.0	39.6		
Maximum	77.0	105.8	84.6		
Mean	63.2	67.9	62.9		
Median	65.8	66.0	63.9		
Std Deviation	8.9	13.6	12.7		

Remarks: Only chl-*a* were measured for U.S. cruises during late January–late February.

represent seasonal change in this area. Given this uncertainty we cannot expect these results from the transect to be representative of the larger Elephant Island area, so that we included results from Germany and USA surveys around Elephant Island.

Temporal variability in the krill length-frequency distributions was shown from the different surveys along the 55°W transect (Fig. 5). Adult krill were dominant through the entire summer season. Adult size in December was relatively small (<50 mm), while larger individuals (>50 mm) appeared from mid-January through late February 1995. Small size (20–35 mm) krill appeared from mid-January, and the proportion was comparatively lower than that of the large one. The increase of mean krill size during the survey period indicates the growth of krill during summer; however, the size

Table 4. Zooplankton density (no. per 1000 m^3) from December 1994 to February 1995. One extremely large krill catch during the Dec. 15–16 survey was omitted from calculations. (a) Along 55° W north of Elephant Island, (b) around the Elephant Island area.

(a) Date of survey / No. Tows	Germany Dec. 2 (5)	Japan Dec. 15–16 (5/6)	Korea Jan. 7–8 (5)	Japan Jan. 18–19 (5)	US Jan. 24–25 (5)	US Feb. 18–19 (5)
E. superba (post larvae)						
Mean	95.0	11.1	7.8	44.2	2.8	3.9
S.D.	196.4	16.5	4.1	30.6	2.0	2.4
Median	8.7	3.0	10.0	31.6	2.6	4.6
E. superba (larvae)						
Mean	0.0	—	—	—	1620.5	6198.1
S.D.	0.0	—	—	—	3227.8	11356.8
Median	0.0	—	—	—	0.0	435.4
T. macrura						
Mean	2.3	—	53.0	—	90.0	276.3
S.D.	2.6	—	93.0	—	72.3	251.4
Median	1.0	—	2.0	—	65.1	140.2
E. frigida						
Mean	0.0	—	0.0	—	48.4	21.4
S.D.	0.0	—	0.0	—	58.5	10.9
Median	0.0	—	0.0	—	2.6	21.0
E. tricantha						
Mean	0.0	—	0.0	—	6.1	3.4
S.D.	0.0	—	0.0	—	7.2	1.8
Median	0.0	—	0.0	—	0.8	2.7
S. thompsoni						
Mean	1.5	123.8	0.4	32.8	7.4	12.4
S.D.	2.2	215.6	0.8	43.8	6.4	11.3
Median	0.0	7.0	0.0	10.2	9.3	5.2

(b) Survey period / No. Tows	Nov. 26–Dec. 5 (75)	Jan. 18–29 (71)	Feb. 15–24 (71)
E. superba (post larvae)			
Mean	29.6	9.5	5.2
S.D.	84.3	20.6	12.0
Median	1.3	3.6	1.2
E. superba (larvae)			
Mean	0.0	172.1	4478.6
S.D.	0.0	969.4	20239.8
Median	0.0	0.0	253.2
T. macrura			
Mean	13.8	124.3	426.4
S.D.	21.1	235.7	584.1
Median	5.4	53.0	212.2
E. frigida			
Mean	0.3	12.1	19.3
S.D.	1.1	32.1	36.8
Median	0.0	0.0	2.1
E. tricantha			
Mean	0.3	1.7	2.0
S.D.	0.9	0.4	4.6
Median	0.0	0.0	0.0
S. thompsoni			
Mean	3.9	20.2	20.6
S.D.	8.7	46.5	66.5
Median	0.6	1.6	0.7

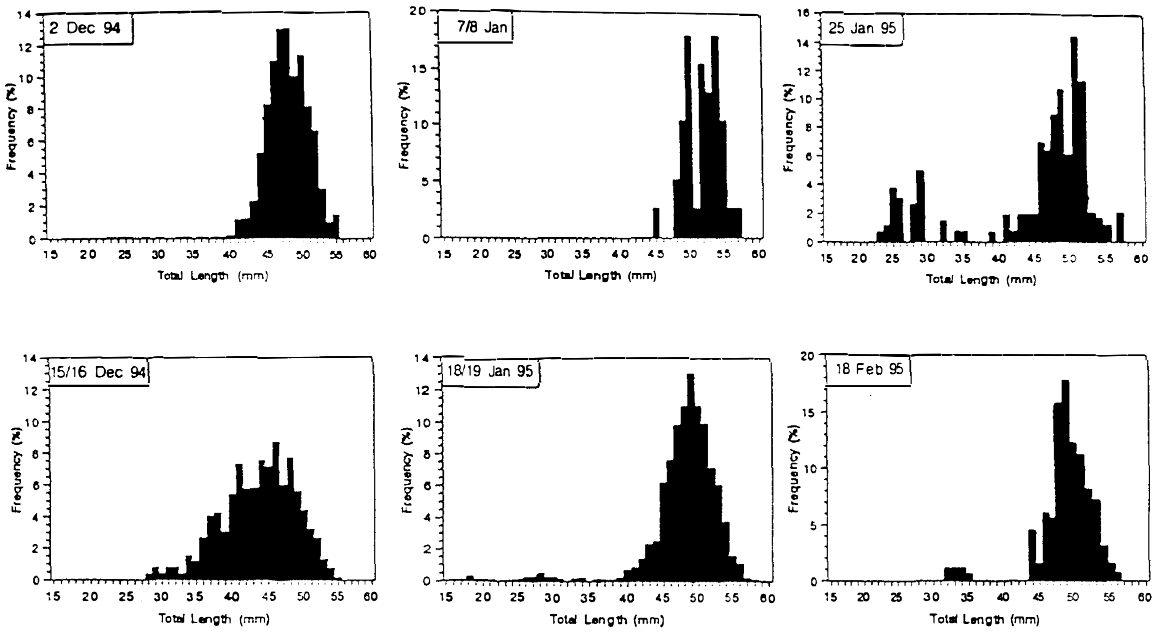

Fig. 5. Overall length-frequency distributions of postlarval krill collected at 55° W transect stations north of Elephant Island, December 1994–February 1995.

difference could have resulted from sampling gear differences between cruises. Japanese catch data indicated that only large and matured krill were caught in the offshore areas, while a mixture of several sizes and maturity stages of krill were caught in slope and inshore areas (Ichii *et al.*, 1996).

Cluster analysis of krill lengths yielded three clusters during November/December (Fig. 6). Cluster 1 was primarily comprised of small (15–25 mm) individuals, Cluster 2 included primarily large krill (35–55 mm), and Cluster 3 was a mixture of intermediate and large sized krill. Only two clusters resulted from analysis of the January and February data; the mixed intermediate and large size Cluster 3 from the preceding month was not present. During both months low proportions of small krill and larger sizes co-occurred in Cluster 1 while Cluster 2 was almost completely large krill. These changes apparently result from disappearance of Cluster 3 krill (probably of Weddell Sea origin as observed in previous years) along with the receding ice edge and dispersal of the small November/December Cluster 1 krill across the southern portion of the Elephant Island area. Figure 7 shows the association between Cluster 3 and the ice edge and restriction of small Cluster 1 krill in the southwest survey area during the November/December Survey. In subsequent months the combined small and large krill of Cluster 1 were distributed across the southern survey area, while the large sized krill of Cluster 2 were distributed in the northern area. These distribution patterns of small and large sized krill during January/February are similar to those reported in the past from the Elephant Island area.

The maturity stage composition of krill in the Elephant Island area is related to the size distribution (Fig. 8). Juvenile (1+ year class) and immature (2+) stages were rare and sexually mature forms dominated during all three surveys. Female maturity stages show a seasonal progression in the proportions of mating (3B), developing (3C), gravid (3D) and spent (3E) forms from November/December through February (Fig. 8). The appearance of significant numbers of krill larvae in net samples after 23 January suggests initiation of spawning activity at the end of December/beginning of

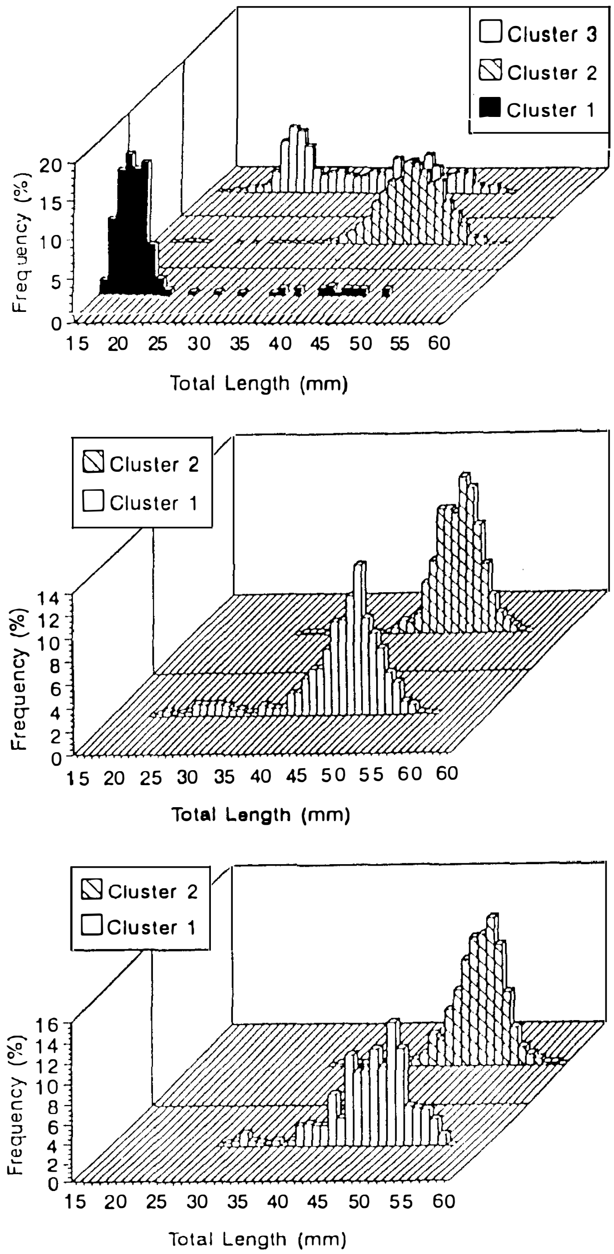

Fig. 6. Krill length frequency in clusters in the Elephant Island area during (a) November/December 1994, (b) January 1995, and (c) February 1995.

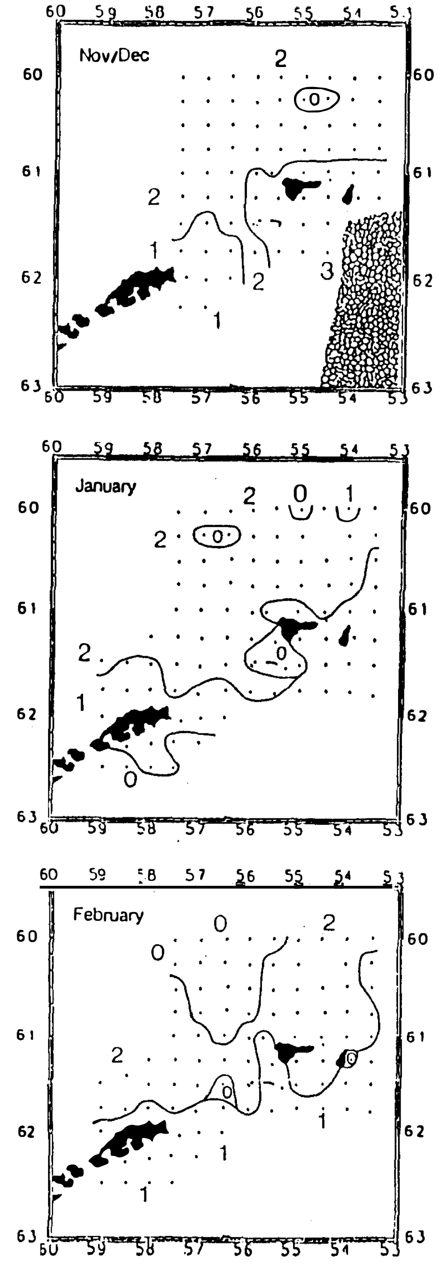

Fig. 7. Spatial distribution patterns of krill belonging to different clusters based on similarity of length-frequency distribution characteristics, (a) November/ December 1994, (b) January 1995, and (c) February 1995 cruises.

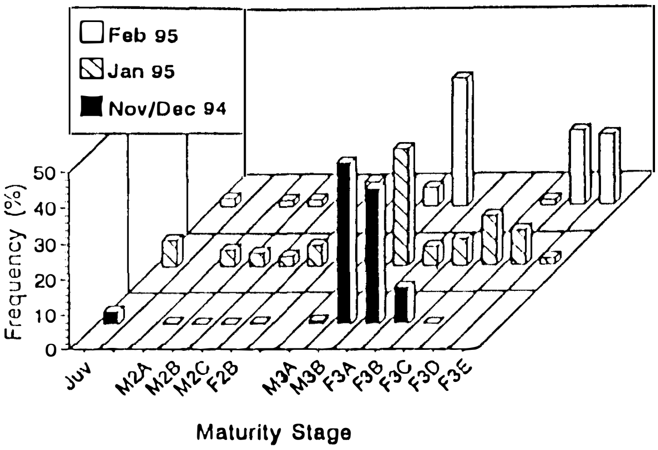

Fig. 8. Maturity stage composition of krill collected in the Elephant Island areas during November/December 1994, January 1995, and February 1995.

January. This coincides with the appearance of spent individuals in January. Female krill maturity stages indicate an early spawning season, with spawning initiating in late December and almost all of the females in gravid or spent condition by mid-February.

Table 4b presents the density (numbers per $1000\,m^3$) of euphausiids collected in the Elephant Island area during the November/December German cruise and January/February USA cruises. Densities of krill postlarvae demonstrated a seasonal decrease from December to February. This decrease was also indicated by the acoustics krill biomass estimates for the survey area during January and February. Krill larvae were not caught in November/December, but were present in January, sometimes in relatively high densities; their overall abundance increased dramatically in February when they numerically dominated the zooplankton collections. The time of appearance and extreme abundance of these larvae indicate an early and apparently successful krill spawning season.

Increased densities of the smaller euphausiid species, *Thysanoessa macrura* and *E. frigida*, appeared in January and February rather than November/December. However, the increased January/February densities of *E. triacantha*, a relatively large species (to 42 mm) with a more northern distribution, suggests a possible influence by northern water masses at that time. Such an influence may also contribute to the elevated abundances of *E. frigida* in January and February. Salp densities were higher in January/February, possibly resulting from seasonal population growth. However, the salp abundance in the Elephant Island area during January/February 1996 was over two orders of magnitude lower than those during the previous two years.

3.4. Acoustics

All four repeats of the 55°W transect indicated the presence of a discontinuous scattering layer (Fig. 9). In the surface layer (0–50 m) this scattering layer was most strongly developed during January (Fig. 9b and c) and was only present as sparse patches in December and February (Fig. 9a and d, respectively). Below the thermocline, an additional scattering layer extending from 50 to 225 m was also observed during

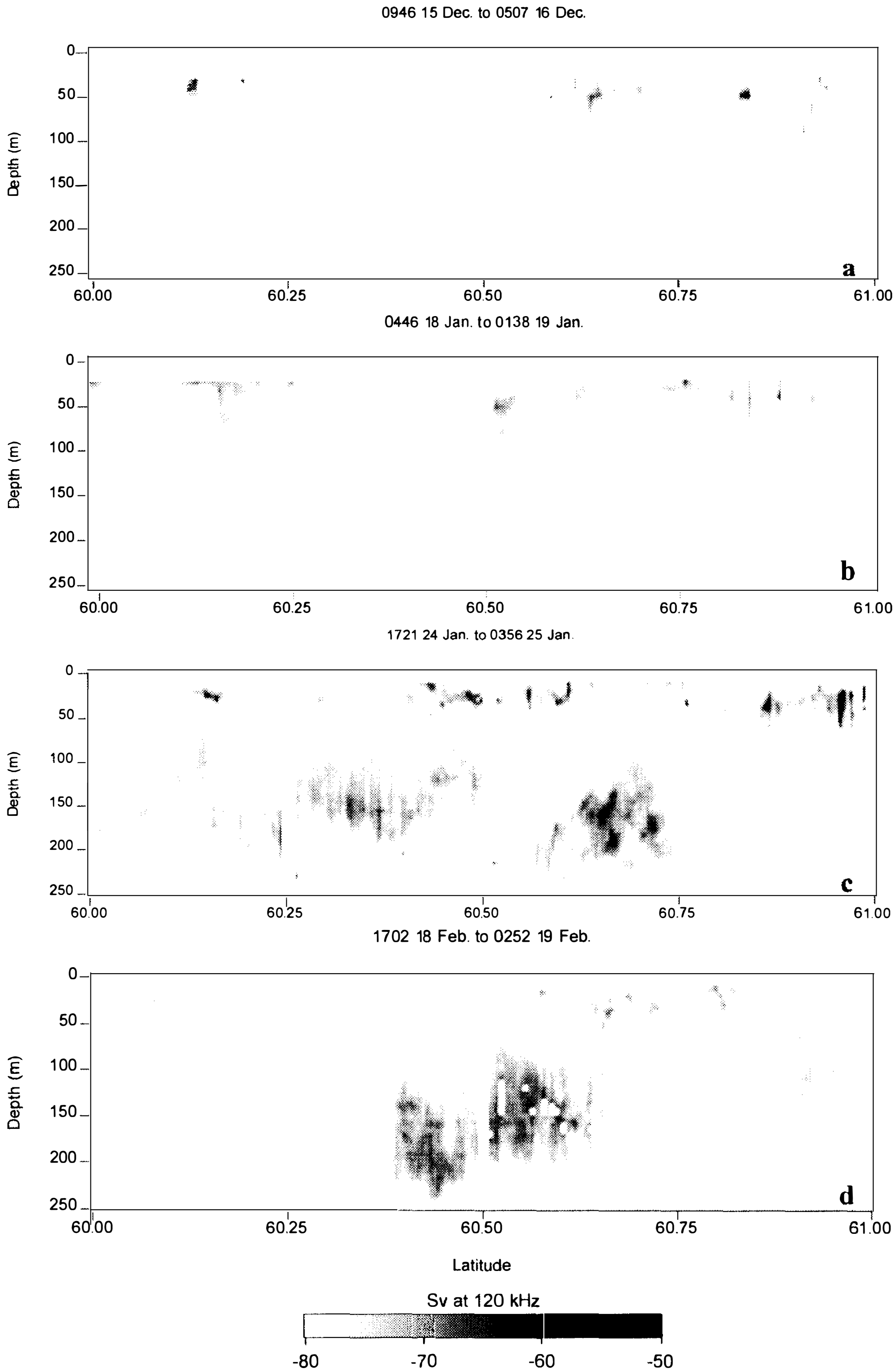

Fig. 9. Vertical distribution of volume backscattering strength along 55° W from surveys conducted on (a) 15–16 December, (b) 18–19 January, (c) 24–25 January, and (d) 18–19 February.

the USA survey. In late January, this layer was roughly continuous from 60°S to 60.75°S latitude (Fig. 9c); it was strongest between 60.35°S and 60.65°S in late February (Fig. 9d).

Differences in the two scattering layer morphologies, which might be caused by the pycnocline around 50 m depth, prompted an investigation of species composition using differences between backscattering data at the two frequencies. Delta S_v was plotted versus depth and latitude (Fig. 10a). Noteworthy is the identification of a third

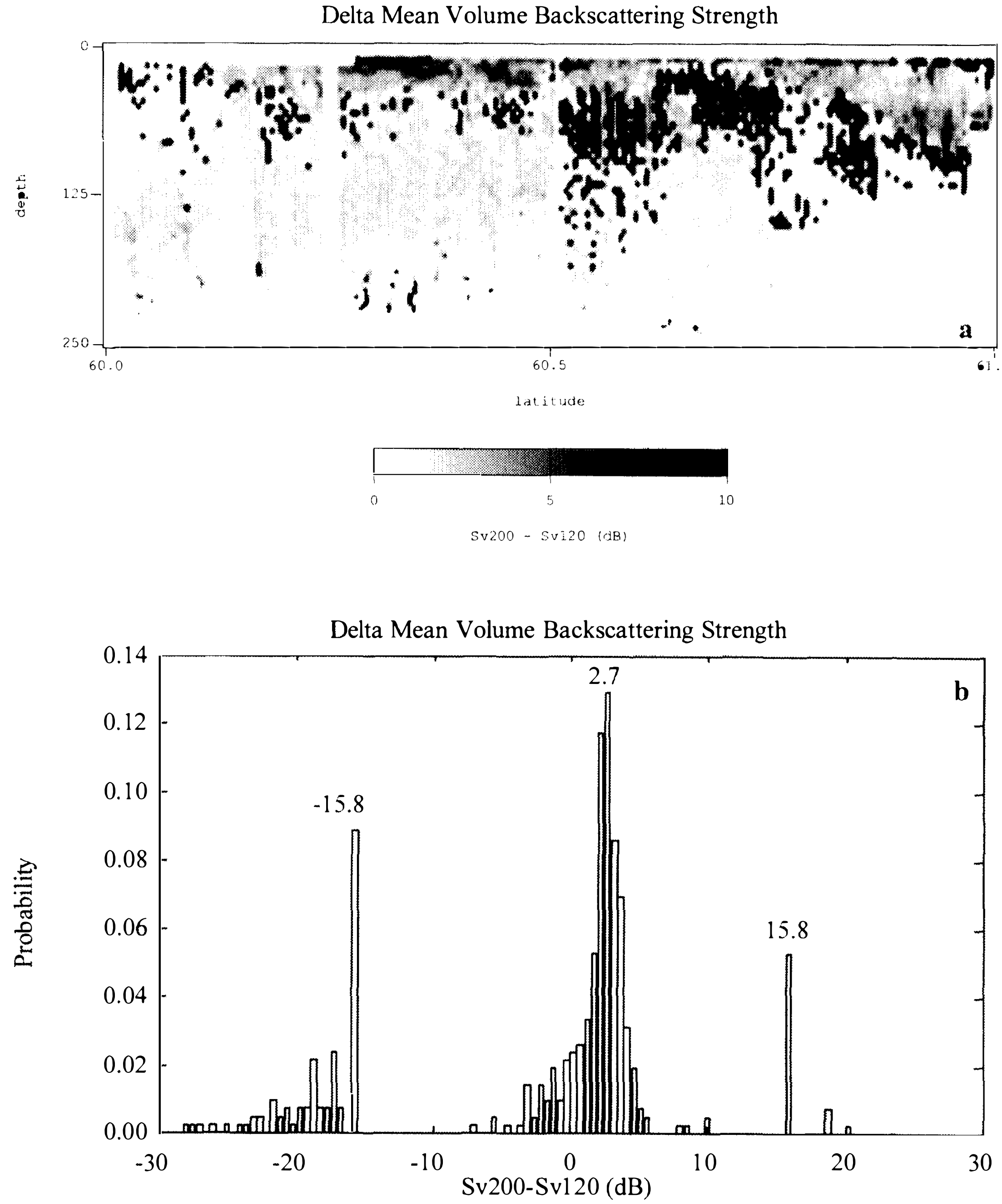

Fig. 10. (a) Vertical distribution and (b) probability distribution (frequency histogram) of the volume backscattering strengths along 55° W on 24–25 January.

scattering layer at approximately 25–75 m depth, which was not evident from the plots of $-80\,dB < S_v < -50\,dB$. The S_v200 and S_v120 values are both well above the threshold noise level. Therefore, the third layer was likely the result of scattering by small zooplankton. Identified from the net samples, abundant species in the area were copepods (<5 mm), *T. macrura* (about 17–22 mm), *E. superba* (42–52 mm), and *E. superba* larvae (about 2–3 mm). However, the larvae were collected at only one of the five stations. Therefore, the upper layer is likely the result of scattering from *E. superba*, and the intermediate layer is possibly *T. macrura*. A histogram of delta S_v indicated a large peak at 2.7 dB, which is consistent with theory for scattering from krill. Additionally, there was a peak at +15.8 dB which indicates scattering from one or more additional species (Fig. 10b).

4. Discussion and Suggestions

Although repeated surveys of a single transect can provide some evidence of environmental associations, a large-scale survey may be more instructive in determining the interactions between organisms and their environment. The spatial distribution of water density from the Germany and USA surveys shows a meandering current around Elephant Island. Figure 11 illustrates the changes in water density (or salinity) in surface layer through the season. The density gradient was higher near the coast of Elephant Island in January, but a higher gradient was found further north in February depending on the location of fronts. In general, the water properties and current patterns in 1994/95 were consistent with previous years. USA surveys conducted near Elephant Island for several years showed northeastward flow and changes in location of the oceanic front. Also the existence of subsurface cold water (Winter Water Temperature Minimum) was previously reported (Anonymous, 1994) as we found in the 1994/95 cruise. This feature could affect the diel vertical migration of zooplankton including krill. However, comparing with USA historical data, January SST and Winter Water Temperature Minimum found along the transect appeared to be higher in 1995 relative to 1992–1994.

The two USA hydroacoustic surveys from the Elephant Island area, where historically there is considerable variability of both biotic and abiotic features of the ecosystem indicated broadly similar distributions of krill over the two month duration. The spatial distribution pattern of krill size/maturity categories observed in the Elephant Island area during 1994/95 is similar to those previously described for this area during the austral summer. The distributions of krill were patchy with concentrations along the shelf break to the northwest of the island, in water of 1000 to 3000 m depth, and patches close inshore (Fig. 12). High concentrations of krill were consistently evident in the usual fishing areas to the north and northwest of Elephant Island. Additional areas of high krill concentration were located near the large chinstrap penguin colonies on Clarence Island. The krill density peak in the Elephant Island area during 1994/95 occurred earlier than in previous years (December *vs.* January/February). This early seasonal abundance peak has been observed in other years (*e.g.*, 1980/81). This observation may be an artifact of the assumption that all backscatter is the result of krill. The distribution maps and abundance estimates should be recreated

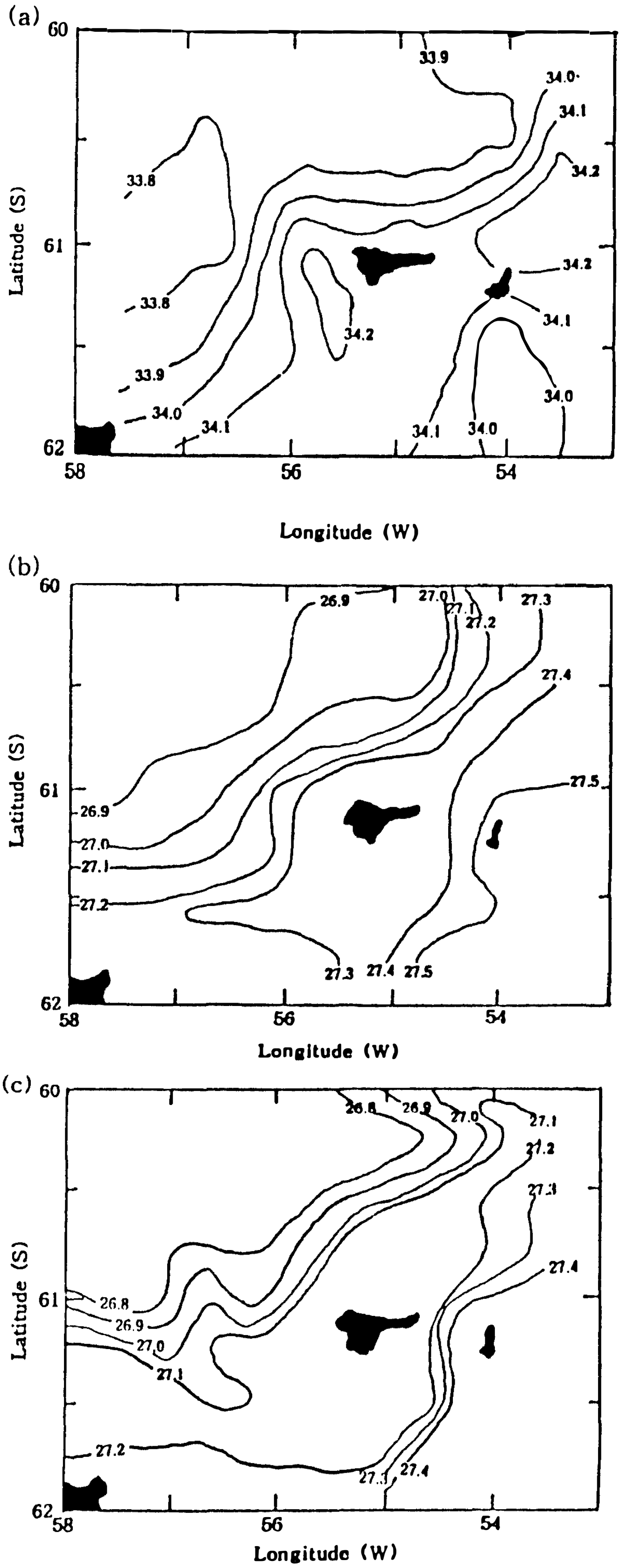

Fig. 11. Horizontal distribution of (a) salinity (psu) at 4 m and dynamic topography (0/500 dyn m) on 26 November-5 December 1994, (b) density at 10 m and dynamic topography (0/500 dyn m) on 16-29 January 1995, and (c) density at 10 m and dynamic topography (0/500 dyn m) on 15-16 February 1995.

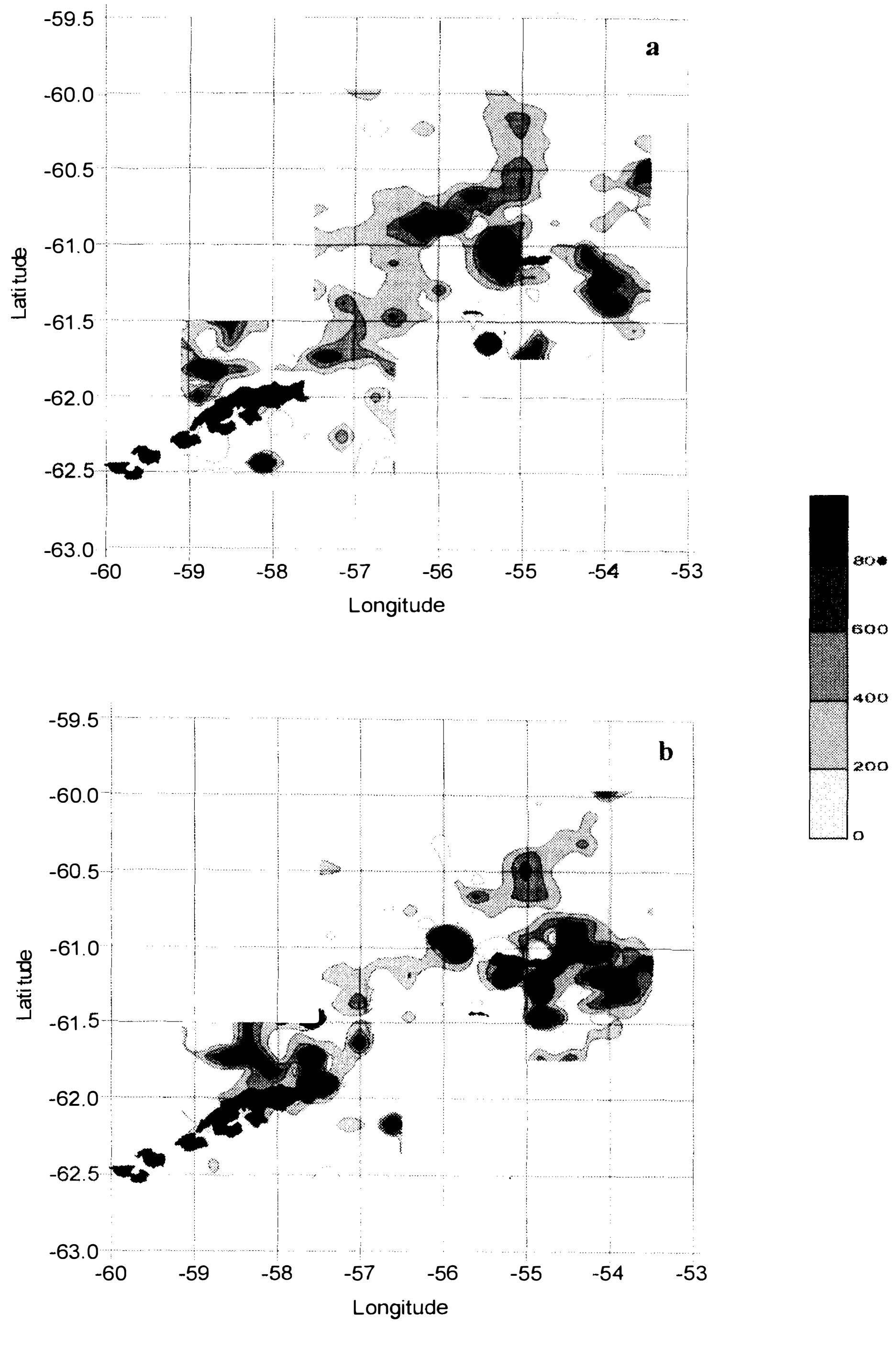

Fig. 12. Areal distribution of volume backscattering strength during (a) 16–29 January and (b) 15–27 February.

after the integration of S_v is apportioned to the various scatterers in the survey area. There are some noticable differences in the densities of the various taxa which can be related to both sampling gear differences and seasonal change. Increased density of the smaller euphausiid species may result from net-catch differences; the RMT8 net does not effectively sample individuals smaller than 20 mm due to mesh size selection.

Species composition of phytoplankton seems to indicate a succession in size. Pico- and nano-sized phytoplankton ($<20\mu m$) was a dominant component during December but one month later nano- ($2-20\mu m$) and micro-sized ($>20\mu m$) phytoplankton dominated the population. This result suggests that phytoplankton assemblages changed from pico- or nano-sized phytoplankton such as phytoflagellates including prymnesiophytes (*Phaeocystis antarctica* in motile stage), cryptomonads (*Cryptomonas* sp.) and dinoflagellates (*Gymnodinium* spp.), to microplanktontic phytoplankton such as diatoms. KANG and LEE (1995) found that micro-sized diatoms such as *Chaetoceros criophilum, Corethron criophilum,* and *Rhizosolenia antennata f. semispina* were important carbon contributors in the western Bransfield Strait region in February.

VILLAFAÑE *et al.* (1993) reported that species succession, from nanoplanktonic phytoflagellates (January–February) to microplanktonic diatoms (February–March), occurred in the vicinity of Elephant Island during the USA Program in 1991. It can be speculated that the same kind of species succession may have happened during the present study period.

In winter, annual sea-ice usually covered the southern part of the survey area, providing good shelter for overwintering krill. The sea-ice cover seems to be related to the year-class strength of krill (SIEGEL and LOEB, 1995). Krill length-frequency distributions in the Elephant Island area in the 1994/95 field season showed very little seasonal change, though the proportion of large (>50 mm) krill became bigger as the season progressed (Fig. 5). Large krill dominated the catches during all three cruises. The contribution of small forms <30 mm is hardly apparent during November/December and January and is virtually nonexistant in February. These size distributions result from three years of poor krill recruitment. The krill recruitment index values calculated for November/December, January, and February in the 1993/94 season ranged from 0.000 to 0.060; Krill length-frequency distribution and recruitment index values (see DE LA MARE, 1994) in the Elephant Island area reflect 3 years of poor year class success (Table 5), and are quite low relative to years of good krill recruitment (*e.g.*, 1980/81, 0.677; 1985/86, 0.448; and 1987/88, 0.673). Larval krill densities

Table 5. Mean krill recruitment index, results of surveys to Elephant Island during summer seasons (after SIEGEL and LOEB, 1995).

Year Class	Mean RI	Year Class	Mean RI	
75/76	0.132	86/87	0.224	
76/77	0.058	87/88	0.673	
77/78		88/89	0.000	
78/79	—	89/90	0.115	
79/80	0.037	90/91	0.351	
80/81	0.677	91/92	0.000	
81/82	0.329	92/93	0.064	
82/83	0.028	93/94 Nov./Dec.	0.020	SE=0.0014
83/84	0.031	93/94 January	0.060	SE=0.0025
84/85	0.132	93/94 February	0.000	SE=0.0000
85/86	0.448			

observed in 1994/95 were comparable to those in 1981, 1986, and 1988. This signifies a successful spawning season and probably good recruitment success for the 1994/95 year class.

As the season progresses, the sea-ice edge retreats toward the south in spring. Usually the cold and diluted water from melting ice remains in the surface layer for a while and produces a stratified water column. Since water stability is thought to be one of the most important factors controlling the growth of phytoplankton in Antarctic waters (MITCHELL and HOLM-HANSEN, 1991), the relationship between water stability and chl-*a* was examined. Integrated chl-*a* values from 0 to 50 m (around the depth of the pycnocline) favorable for feeding krill were plotted against density. Solid symbols show the northern 3 stations and open symbols show the southern 2 stations (Fig. 13). Among the offshore stations, density differences between 0–50 m were highly variable with relatively constant low chl-*a* values. On the other hand, relatively low density differences with high chl-*a* values compared to offshore stations were observed at the near shore stations. Note that fronts are located around Stns. 4 and 5 where water stabilities are low. Therefore, in the area north of Elephant Island, the high abundance of phytoplankton possibly depends on the local front location instead of water stability.

Krill size, maturity, and feeding behavior of animals were investigated north of Elephant Island (ICHII *et al.*, 1996). In general, krill tend to be larger and more mature in continental slope/offshore than those in the inshore regions. Also, the foraging areas of penguins and seals were further north in mid-December than in mid-January. Considering the location of the front during these two periods, predators may prefer foraging in locations with more nutritionally valuable foods. When the front moves offshore, the foraging distance becomes longer, and vice versa.

There was indication of scatter from zooplankton species other than krill. The middle scattering layer shown in Fig. 10a is likely indicative of an assemblage of small zooplankton. Currently unexplained, however, is the case in which scattering at 120 kHz is greater than that at 200 kHz (Fig. 10b). The acoustic backscatter data is the re-radiation of sound energy caused by a gradient in the acoustic impedance (ρc) across a boundary. If the wavelength is very large compared with the target size, the Rayleigh

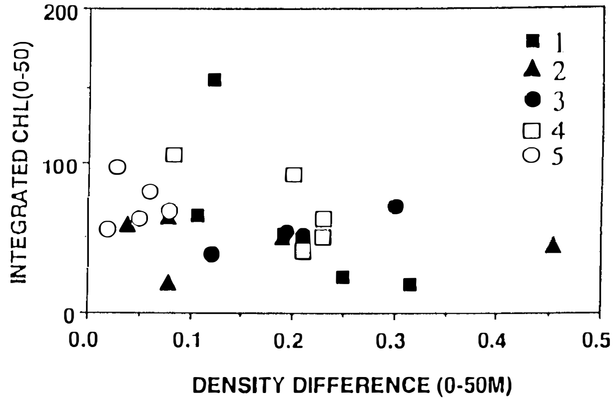

Fig. 13. Relationship between water stability and integrated chlorophyll-a between 0–50 m. Solid symbols indicate the northern 3 stations and open symbols the southern 2 stations.

scattering law predicts point scattering with a backscatter intensity proportional to the fourth power of the animal's characteristic size. When the target is similar in size to or larger than the wavelength, the scattering intensity is a complex function of the animal's morphology. The negative differences between scattering at 200 and 120 kHz is possibly the result of destructive interference, or a null, at the transition between Rayleigh and geometric scattering regimes.

The TS of an elongated crustacean zooplankton depends primarily upon the size, shape, density, and orientation within the acoustic beam. Therefore, to convert integrated echo energy into animal density, integrated data must be apportioned between scatterers, and the average TS value must reflect the distributions of these parameters for the animals in the area, at the time of the survey. Although some models of sound scattering by krill have incorporated various aspects of animal size and physiological condition, they have been verified only to a limited degree. Additional TS studies and models are warranted.

Based on the scientific results derived from this first joint multinational oceanographic research, the following suggestions are recommended for future study.

a) Based on earlier studies (Amos and Lavender, 1991; Helbling *et al.*, 1993, 1995; Villafañe *et al.*, 1993), the causes of the frontal zone movement north of Elephant Island and its influence on the behavior of organisms should be investigated thoroughly. The persistent feature of Winter Water between 75 and 100 m north of Elephant Island should be investigated in relation to zooplankton distribution and primary productivity.

b) In conjunction with currently on-going research programs, measurements of the size distribution of phytoplankton, carbon biomass, and species composition of phytoplankton should be added, in addition to measurements of chl-*a* concentrations.

c) The factors that control krill recruitment have been described in a conceptual model by Siegel and Loeb (1995). The 1994/95 field season data analyzed were consistent with the first half of the model (early krill spawning, high larval production, low salp density). The second half of the model (recruitment) can be tested during the coming austral summer season. A new survey for testing the prediction of krill recruitment is required. Collection of additional krill length frequency data from commercial fishing operations in the area is highly recommended.

d) A two-frequency approach was shown to be useful in delineating size classes and in identifying a previously undescribed acoustic scattering layer. In the future, multiple frequency echo sounders and species delineation techniques should be used to apportion the total integrated echo energy to the various scatterers. Frequency combinations which include both the Rayleigh and geometric scattering regimes are most powerful when using inversion techniques.

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