

DISTRIBUTION OF ANTARCTIC KRILL CONCENTRATIONS EXPLOITED BY JAPANESE KRILL TRAWLERS AND MINKE WHALES

Taro ICHII

National Research Institute of Far Seas Fisheries, 7-1, Orido 5-chome, Shimizu 424

Abstract: Based on Japanese krill fishing and minke whaling data, the distribution of Antarctic krill (*Euphausia superba*) concentrations was investigated in relation to bottom topography, sea-ice and hydrographic features. Data were from the Indian, Pacific and western Atlantic sectors. In early summer (December) high density concentrations of krill frequently occurred in the vicinity of southerly positioned pack-ice edges and in the embayments surrounded by the pack-ice edge. In mid and late summer (January-March) when the ice-edge was at its southernmost limit, krill fishing data indicated that harvestable areas were associated with the continental and insular shelf breaks, not with the pack-ice edge. Minke whaling data also suggested that not only sea-ice but also topographical features such as the continental shelf breaks and banks may be important factors affecting minke whale (*Balaenoptera acutorostrata*) distribution. Krill harvesting areas in the vicinity of the shelf breaks were often coincident with hydrographic fronts. These results suggested that hydrographic features caused by uneven bottom topography (e.g. shelf breaks or banks) may induce the formation of krill concentrations in mid and late summer.

The extremely high concentration of minke whales and their food composition suggested the high abundance of *E. superba* around a bank on the Ross Sea shelf.

1. Introduction

Antarctic krill, *Euphausia superba*, are distributed in a wide circumpolar belt between the Antarctic Continent and the Polar Front (MARR, 1962). They characteristically aggregate into concentrations which consist of many swarms and are so targeted by both fishing trawlers and predators (BUTTERWORTH and MILLER, 1987). Concentrations are defined as extending over distances of 1 to 100 km with the mean surface density of at least 10 g/m² based on the acoustic work (KALINOWSKI and WITEK, 1985).

Krill trawlers target only fishable concentrations which exceed a few tens of kilometers in horizontal extent (ICHII, 1987) and consist of swarms denser than 100 g/m² (BUTTERWORTH, 1988). In order to facilitate the detection of harvestable concentrations, krill trawlers have to synthesize various information. Such information includes the past locations of concentrations, the pack-ice edge, sea-surface temperature, icebergs on which sea birds are resting and the appearance of baleen whales.

After fifteen years of operation, the area covered by the Japanese krill fishery extended to approximately two-thirds of the Antarctic continental periphery including the East Wind Drift where knowledge concerning the distribution of krill concentrations is

currently limited. For the period of 1973/74 to 1976/77, the main fishing grounds were located in the waters off Kemp and MacRobertson Lands. Later, they extended toward the waters off Adelie Land (1977/78–1982/83) and in recent years the southwestern Scotia Sea has become the main area of operation.

Currently the minke whale (*Balaenoptera acutorostrata*) constitutes the largest biomass of all baleen whales in the Antarctic, primarily as a consequence of the depletion of other baleen whales by commercial whaling (F. KASAMATSU, pers. commun.). Japan conducted commercial exploitation for this species over 16 seasons in the Antarctic. Minke whales are most often observed near the ice-edge and feed almost exclusively on *E. superba* (BUSHUEV, 1986). Thus, the areas of minke whaling is expected to reveal, to some extent, areas of higher krill abundance in the ice-edge zone where krill distribution patterns are much less clear. SHIMADZU and KASAMATSU (1981) have pointed out that the distribution of the minke whaling grounds was not only governed by the distribution of minke whales *per se* but also by economic factors. SHIMADZU and KASAMATSU (1984) and KASAMATSU and SHIMADZU (1985) have shown, however, that in mid-summer minke whale concentrations tend to occur regularly in relatively restricted areas, suggesting that such areas may regularly be of high krill abundance.

The Ross Sea region, which had not been covered by the conventional exploitations of minke whales and krill, was also examined in this paper since extremely high concentrations of minke whales have recently been discovered by the systematic sighting survey of minke whales conducted under the International Whaling Commission's International Decade of Cetacean Research program (KASAMATSU, 1988). Because of the enormous biomass of minke whales, this region drew the attention and was covered by the last minke whaling conducted in 1986/87 and also by the latest Japanese feasibility study on southern minke whales in 1988/89.

The accumulated data on both Japanese krill fishing and minke whaling operations were examined in order to reveal the distribution of krill concentrations in relation to available data on bottom topography, sea-ice, and hydrographic fronts.

2. Materials and Methods

Krill fishing is mainly carried out during December to March using mid-water trawling techniques. Information on fishing operations is recorded in a prescribed format for each tow (SHIMADZU, 1985), and data on the position of catches greater than two tonnes of krill for the period 1973/74 to 1987/88 seasons have been utilized to delimit fishing areas.

In order to locate minke whaling ground, the noon positions of the factory ship, the number of minke whales caught each day and their stomach contents for the period 1971/72 to 1986/87 were analyzed. Distribution of minke whales and their food composition in the Ross Sea were also available from the Japanese feasibility study on southern minke whales in 1988/89 (KATO *et al.*, 1989). Information on the pack-ice edge and icebergs in whaling grounds was obtained from both catcher boats and satellite information.

Bathymetry information was obtained from General Bathymetric Chart of the Oceans (GEBCO) and Defense Mapping Hydrographic/Topographic Center (DMA).

The mean extent of sea-ice was derived from the sea-ice maps of the U.S. Navy-NOAA Joint Ice Center for the period 1973/74 to 1983/84 and from ZWALLY *et al.* (1983). Occasional and limited oceanographic information in the fishing areas was obtained by krill trawlers chartered by Japan Marine Fishery Resource Research Center (JAMARC, semi-governmental organization), or by research vessels.

3. Results

3.1. Distribution of operated areas, December

The ice-edge retreats rapidly in this month. Nonetheless, the major zones of krill distribution are not completely free of ice and krill trawlers have to spend a considerable time searching for concentrations in the vicinity of the retreating ice-edge. Figure 1a shows that in the Indian sector krill trawling was most frequent between 120°–140°E and around 60°E, where the retreat of ice-edge is most rapid.

Minke whaling was also frequent around the southerly positioned ice-edge (Fig. 1b,

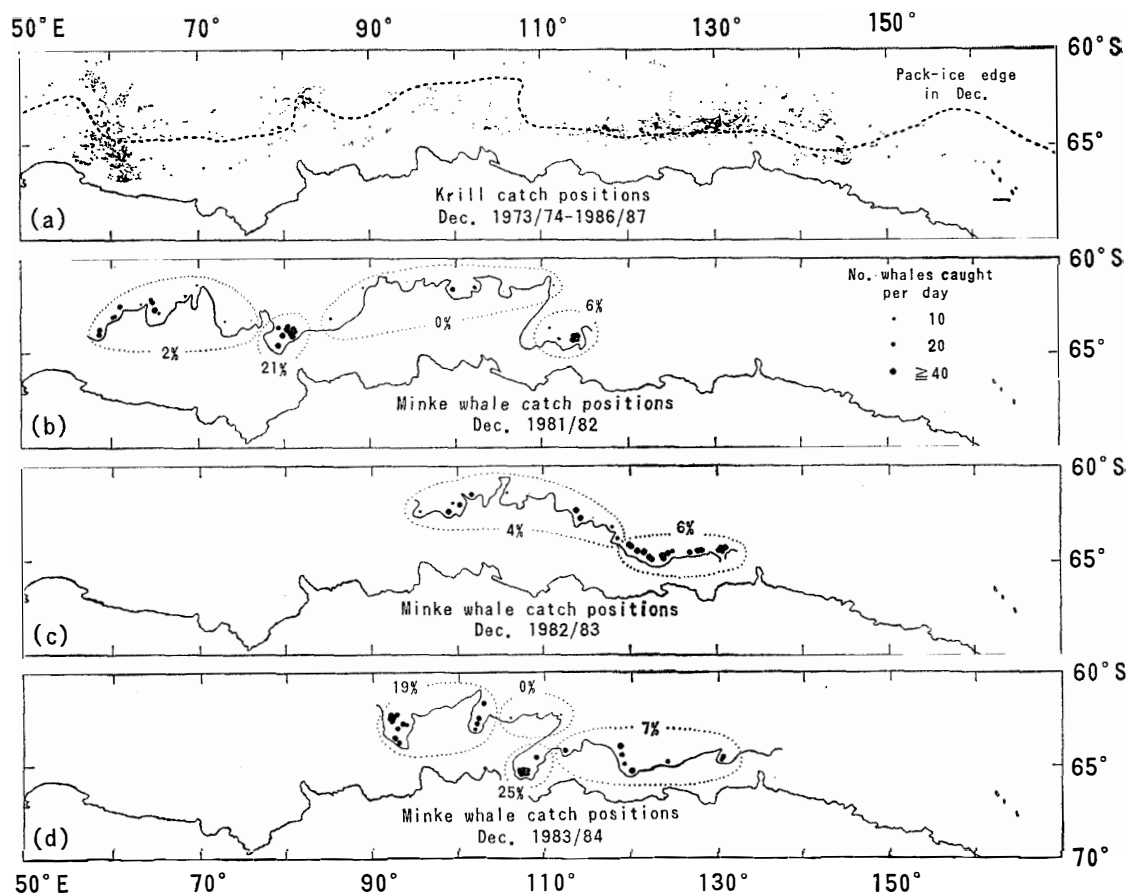


Fig. 1. Distribution of krill fishing and minke whaling areas in December between 50°–170°E. (a) Krill trawling positions from 1973/74 to 1986/87 together with the mean position of the pack-ice edge in December (broken line). (b)–(d) Minke whale catch positions (noon positions of factory ship) together with the pack-ice edge in 1981/82, 1982/83 and 1983/84. The percentage of minke whales with 75–100% full stomachs to total whales caught per morning is shown for each area enclosed by dotted line.

c). When the pack-ice edge was composed of marked/prominent topographic features (e.g. large embayments or polynyas), large numbers of minke whales were often observed in embayments irrespective of their latitudinal positions and hence good whaling grounds were formed there (Fig. 1b, d). The percentages of minke whales whose stomach is 75–100% full to total whales caught in the morning (the main feeding time according to H. KATO and Y. SHIMADZU (unpublished)) are shown in Fig. 1b–d. There is a tendency that the relative quantity of stomach contents was larger in good whaling grounds, *i.e.* near the southerly positioned ice-edge or in embayments in each season.

3.2. Distribution of operated areas, January–March

During this period the sea-ice is at its lowest ebb. In four regions, (1) off Kemp and Mac.Robertson Lands, (2) off Adelie Land, (3) the Ross Sea and (4) the southwestern Scotia Sea, the sea-ice retreats to south sufficiently to uncover the large portion of the continental shelf (Fig. 2). The Antarctic continental shelf, except in the vicinity of the Antarctic Peninsula, is characterized by its great depth (twice to three times deeper than other continental shelves), which is considered to be a consequence of depression of the continent by the thick inland ice sheet (DEACON, 1982; BRINTON, 1985). The continental slope is generally steep and marked by the relatively close topography of the 500- and 2000-m isobaths (TCHERNIA and JEANNIN, 1980). Figure 2 shows krill trawling

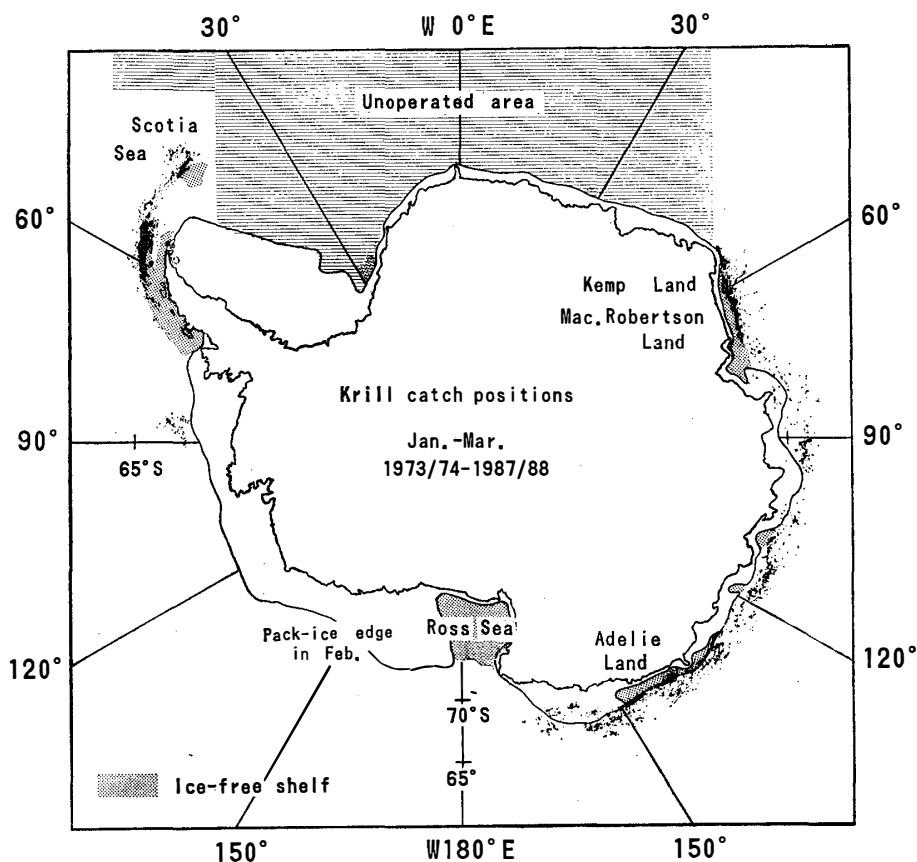


Fig. 2. Distribution of krill catch positions in January–March from 1973/74 to 1987/88 together with the mean pack-ice edge in February and with the ice-free continental shelf.

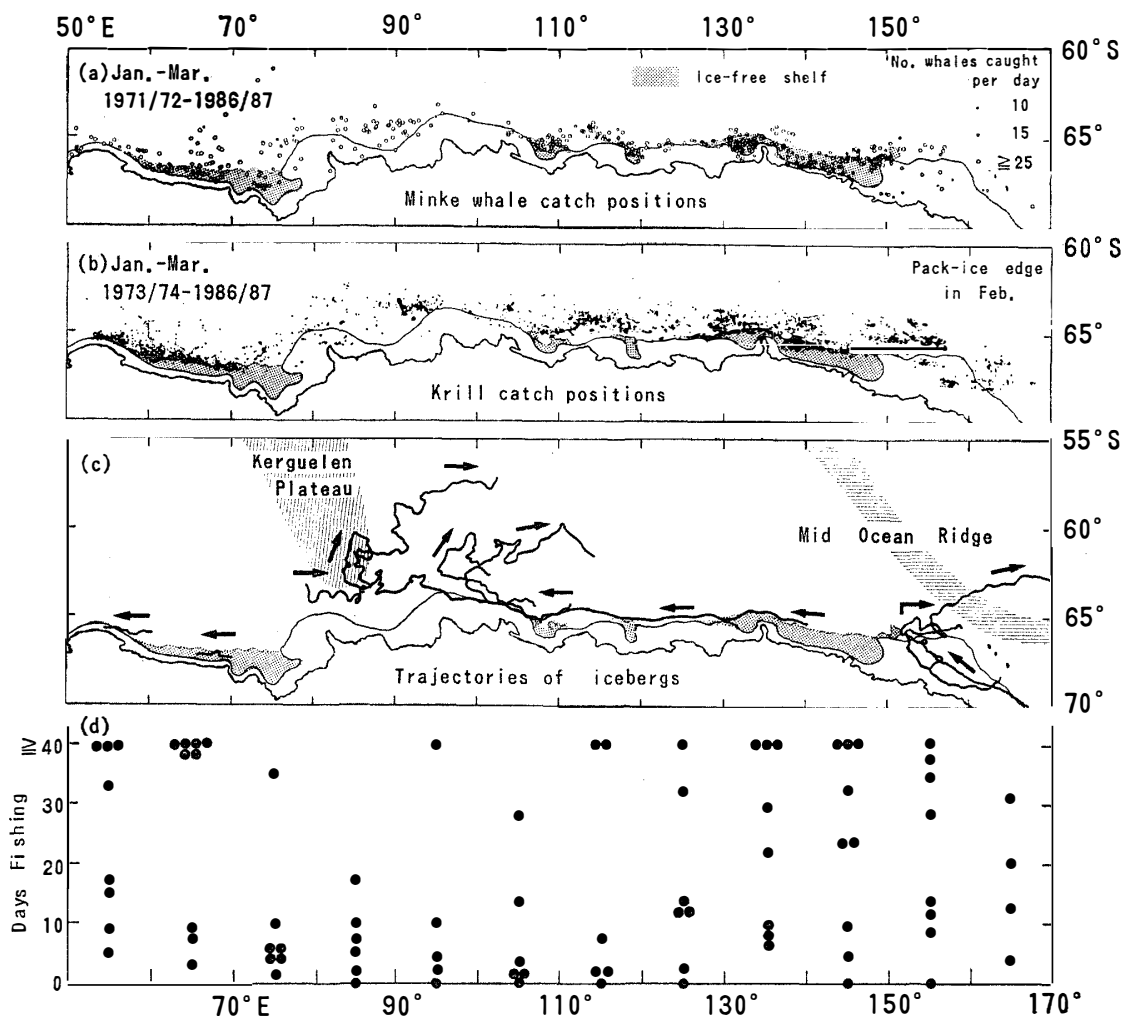


Fig. 3. (a) Distribution of minke whale catch positions (noon positions of factory ship) between 50°–170°E in January–March from 1971/72 to 1986/87 together with the mean position of the pack-ice edge in February and with the ice-free continental shelf. (b) Distribution of krill catch positions in January–March from 1973/74 to 1986/87. (c) Trajectories of icebergs from TCHERNIA and JEANNIN (1983). (d) Distribution of days spent krill fishing in January–March for each 10-degree longitude during the period 1973/74–1986/87. If a 10-degree longitude was fished by two trawlers, one during February 1–10 and the other during February 5–10, then days spent fishing is considered to be 10.

positions during 15 seasons together with the mean pack-ice edge and the ice-free continental shelf. Krill trawlings were most frequent along the shelf breaks. The three major fishing grounds, (1) off Kemp and Mac.Robertson Lands, (2) off Adelie Land and (3) the southwestern Scotia Sea, correspond to three out of the four major ice-free shelf regions mentioned above.

On the other hand, in areas where ice-edge extends northward and covers the shelf (*i.e.* between 70°–180°W and around 80°E and 100°E), krill trawling was not frequent. In areas between 70°–180°W harvestable concentrations of krill were found only around Peter I Island (69°S, 91°W).

Minke whaling was actively conducted in the area between 50°E and 170°E. Minke

whale catch positions nearly overlap with krill trawling positions (Fig. 3a, b). The continental shelf regions around 55°E , 110°E , 120°E and $130^{\circ}\text{--}150^{\circ}\text{E}$ were frequently whaled and trawled, while those around 80°E and 100°E , where sea-ice extends northward and covers the continental shelf, were the least exploited.

Figure 3c shows the features of surface current in operated areas (*i.e.* the East Wind Drift current) by drift tracks of icebergs (TCHERNIA and JEANNIN, 1983). The drift is seen to hug the general trend of the coast line over long distances. Between 80°E and 100°E , however, this drift shows a northward recurvature, possibly due to the topographic

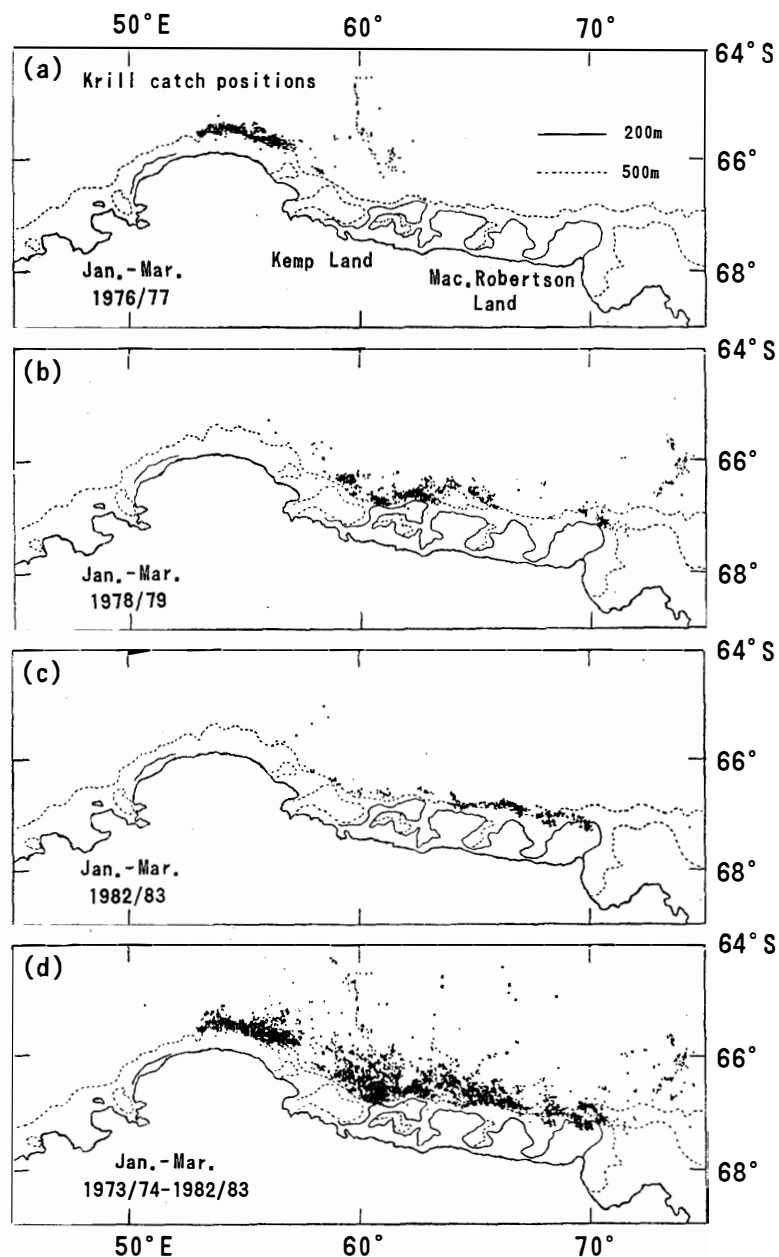


Fig. 4. (a)–(d) Distribution of krill catch positions for January–March in 1976/77, 1978/79, 1982/83 and 1973/74–1982/83 together with bottom topography off Kemp and Mac.Robertson Lands.

effect of the Kerguelen Plateau (TCHERNIA and JEANNIN, 1984). There is also a sharply-turning current at 150°E , probably due to the topographic effect of northward extension of the continental margin (Plate XII(B) in TCHERNIA and JEANNIN, 1983). As an indicator of the formation and persistence of fishing grounds, the number of days spent in fishing in January–March is shown for each 10-degree longitude during 14 seasons (Fig. 3d). The number tends to be smaller in the area between 80°E and 100°E where the large-scale northward recurvature occurs.

Thus, krill fishing and minke whaling grounds are most likely to be formed in the vicinity of the above-mentioned shelf regions, and hydrodynamic features seem to affect the formation and persistence of the grounds. These shelf regions as well as the Ross Sea region will be considered in more detail.

3.2.1. Region off Kemp and Mac.Robertson Lands

The most prominent topographical features in this region are relatively shallow banks on the continental shelf on which there are a number of deep trenches (Fig. 4). The shallow topography of the banks is a major factor in the accumulation of grounded icebergs, which otherwise would have drifted westward with the littoral current (SMITH *et al.*, 1984).

Trawling positions regularly concentrated around the continental shelf break, but varied in space from year to year. For example, annual fishing grounds were located off western Kemp Land in 1976/77 (Fig. 4a), off the area between Kemp and Mac.Robertson Lands in 1978/79 (Fig. 4b) and off Mac.Robertson Land in 1982/83 (Fig. 4c). In January 1981 R.V. KAIYO MARU made oceanographic observations along a latitudinal section in the area off Fram Bank ($67^{\circ}30'\text{S}$, 69°E) where Japanese trawlers

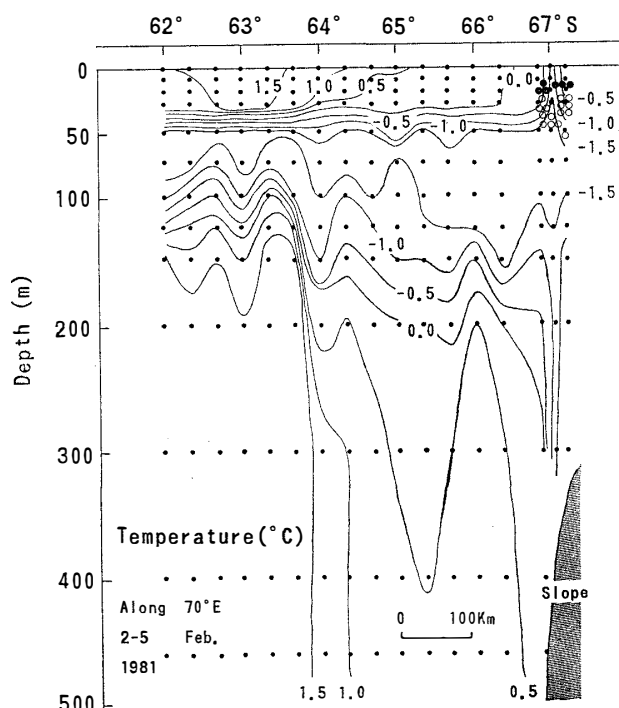


Fig. 5. Vertical distribution of temperature along $70^{\circ}00'\text{E}$ (from SUISANCHŌ, 1983) compared with krill trawl positions along the meridian in February 2–5, 1981. Daytime and nighttime trawls are shown in open and closed circles, respectively.

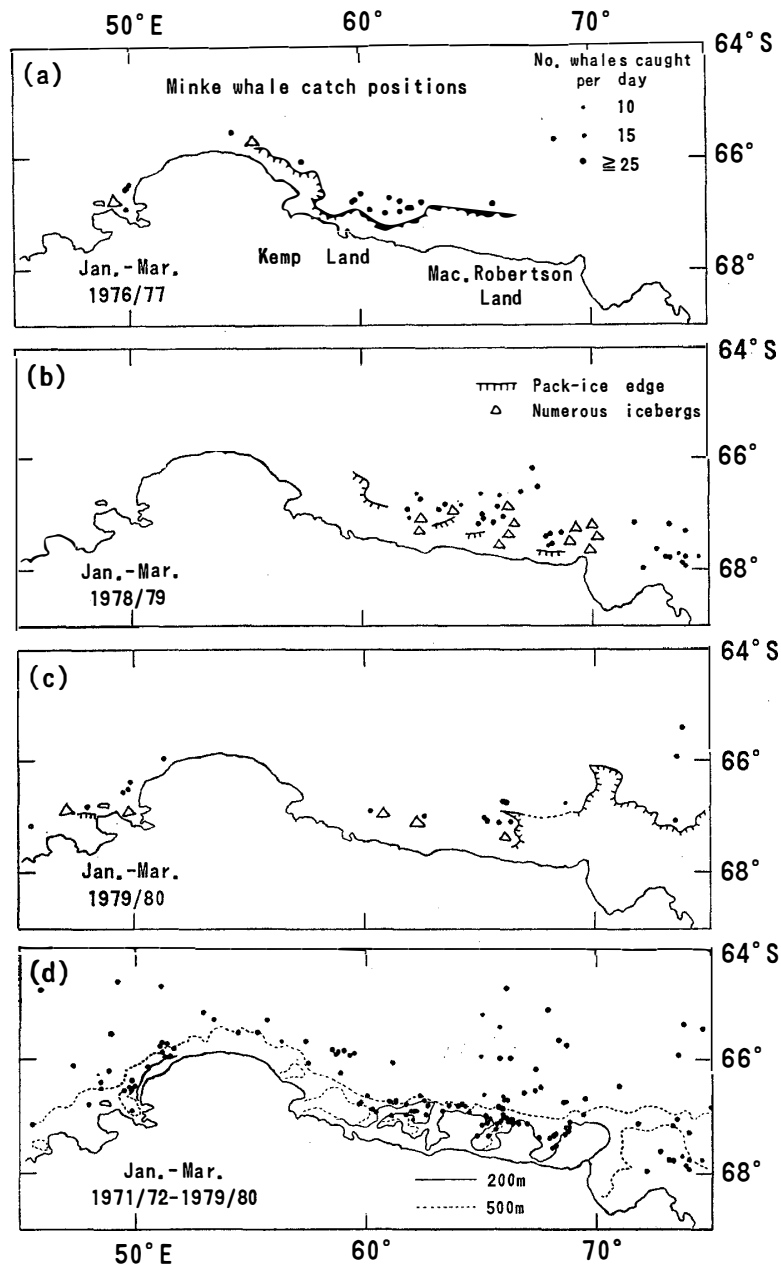


Fig. 6. (a)–(d) Distribution of minke whale catch positions (noon positions of factory ship) for January–March in 1976/77, 1978/79 and 1979/80 together with the sea-ice and in 1971/72–1979/80 together with bottom topography off Kemp and Mac.Robertson Lands.

and the Soviet fleet were operating. Trawling positions were observed to be coincident with a marked frontal feature over the continental shelf break (Fig. 5). Trawling depth tended to be shallower at night than by day probably due to a diel vertical migration of krill.

The locations of minke whaling are shown together with sea-ice observed from catcher boats (Fig. 6a–c). Catches were frequent near the pack-ice or icebergs. KASAMATSU (1988) reported that in the Prydz Bay (69°S, 75°E) region the density of minke whales was extremely high in 1978/79 (Fig. 6b) while not as high in 1979/80 (Fig. 6c).

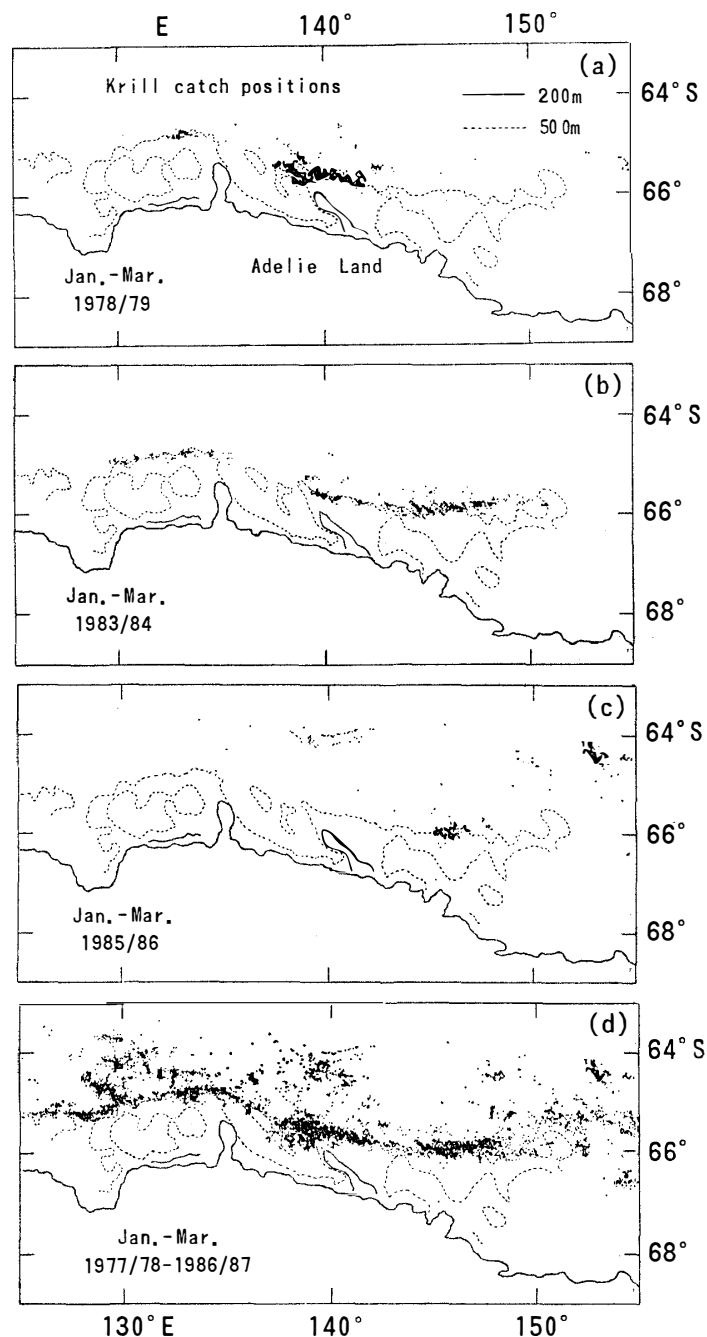


Fig. 7. (a)-(d) Distribution of krill catch positions for January-March in 1978/79, 1983/84, 1985/86 and 1977/78-1986/87 together with bottom topography off Adelie Land.

He speculated that in 1979/80 the topography of the pack-ice edge adjacent to the Prydz Bay region may have been partly responsible for low whale densities. Comparison between the location of minke whale catches and features of bottom topography indicates that the catch positions also seem to be associated with shallow banks on the shelf and the shelf margin (Fig. 6d). It is still not certain whether *E. superba* predominantly populates the areas around banks on the inner shelf. According to stomach

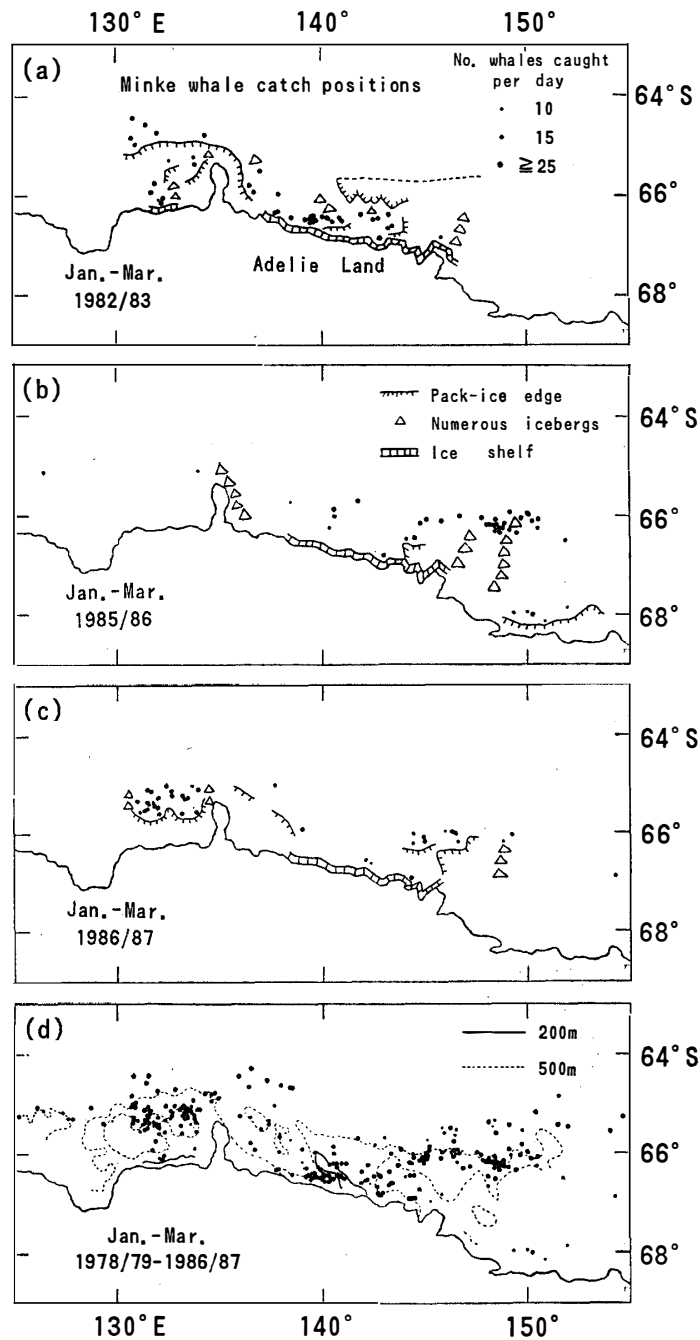


Fig. 8. (a)–(d) Distribution of minke whale catch positions (noon positions of factory ship) for January–March in 1982/83, 1985/86 and 1986/87 together with the sea-ice and in 1978/79–1986/87 together with bottom topography off Adelie Land.

content records, however, the minke whales often fed on krill larger than 50 mm in body length, which suggests that *E. superba* is likely to populate banks on the inner shelf as well.

3.2.2. Region off Adelie Land

The continental shelf off Adelie Land is characterized by deep topography, which comprises either large enclosed depressions isolated from the open ocean or elongated

troughs open to the ocean (Fig. 7). Waters in the area between 135° – 145° E are usually open to the Antarctic Continent or ice shelf (MACKINTOSH and HERDMAN, 1940; SHIMADZU and KASAMATSU, 1984; KASAMATSU and SHIMADZU, 1985) and large numbers of icebergs have been observed to be grounded in shallow areas on the continental shelf (GORDON and TCHERNIA, 1972).

The distributions of krill trawling and minke whaling grounds in relation to the bottom topography and sea-ice are similar to those observed in the area off Kemp and Mac.Robertson Lands. The sites of krill trawling were usually concentrated along the continental shelf break, but did vary in space from year to year. The main fishing ground was confined to a relatively narrow belt in 1983/84 (Fig. 7b), while it was restricted to the area between 145° – 147° E in 1985/86 (Fig. 7c). In 1978/79 it gradually shifted westward (Fig. 7a). Minke whale catch positions were also variable in space but were usually located near the ice (Fig. 8a–c). The catch positions of minke whales can be seen to lie further southward, and also seem to be linked to the edges of depressions or troughs situated landward of the continental rise and the shelf margin (Figs. 7d and 8d). Since stomach contents of minke whales are reported to contain krill larger than 50 mm, it is suggested that *E. superba* is abundant not only along the continental shelf margin but also around other topographic features in the shelf region.

Meridional temperature sections were available from data collected by trawlers themselves and by the R. V. UMITAKA MARU. These show that the krill fishing area coincided with what seems to be a V-shaped frontal zone (the dipping of the isotherms) at the shelf edge along 141° E in January 1979 (Fig. 9), and a slope front along $147^{\circ}30'$ E in February 1984 (Fig. 10). The V-shaped front is one of the typical frontal features

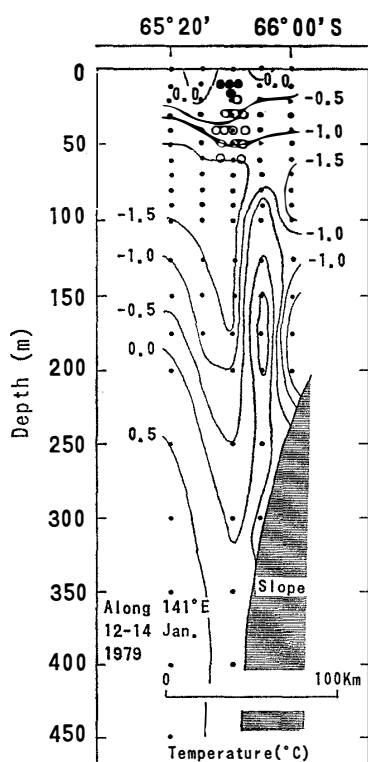


Fig. 9. Vertical distribution of temperature along $141^{\circ}00'E$ (from JAMARC, 1980b) compared with krill trawl positions along the meridian for the period January 12–14, 1979. Daytime and nighttime trawls are shown in open and closed circles, respectively.

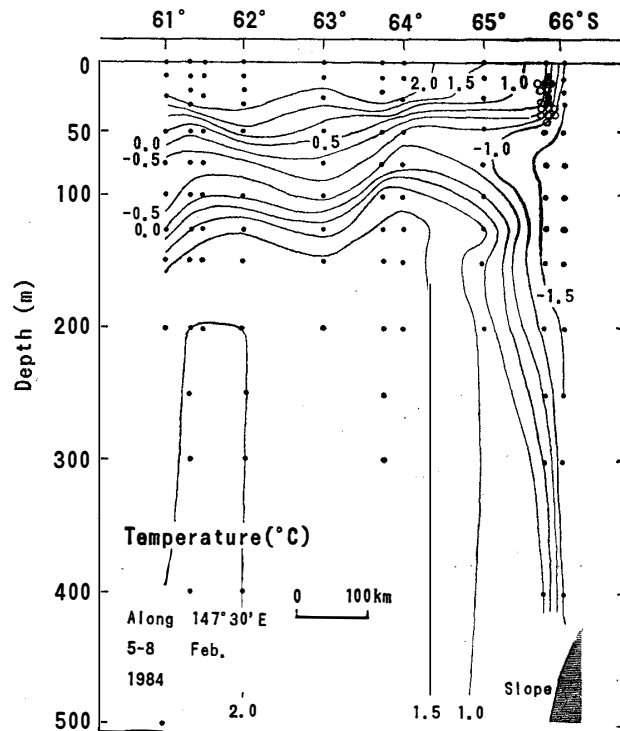


Fig. 10. Vertical distribution of temperature along $147^{\circ}30'E$ (modified from MATSUURA *et al.*, 1985) compared with krill trawl positions along the meridian between February 5-8, 1984. Daytime and nighttime trawls are shown in open and closed circles, respectively.

in the vicinity of the continental slope (GORDON and TCHERNIA, 1972; GILL, 1973; CARMACK and KILLWORTH, 1978; JACOBS, 1986).

3.2.3. The southwestern Scotia Sea region

Relatively shallow continental shelf (*ca.* 200 m depth) is the characteristic feature of this region, where the shelf has been least depressed by ice loads (Fig. 11). In summer the Bransfield Strait is clear of ice, and much of the west coast of the Antarctic Peninsula is also free of ice (MACKINTOSH and HERDMAN, 1940; ZWALLY *et al.*, 1983).

Krill fishing grounds were formed almost in the same areas over the past four years; the shelf slopes north of the South Shetland Islands, north and west of Elephant Island, and north of the South Orkney Islands (Fig. 11b-e). One exception is the 1987/88 season when fishing was not undertaken in the area north of the South Orkney Islands, probably as a result of a delay in the breakup of sea-ice (Fig. 11e).

According to the oceanographic observations made by R. V. KAIYO MARU in January 1987, the fishing ground north of the South Shetland Islands was coincident with a frontal area known as the Continental Water Boundary (CWB) (Fig. 12). The CWB is characterized by a relatively sharp southward increase in salinity and is restricted to a narrow band near the continental slope, separating offshore waters from the continental waters (SIEVERS and NOWLIN, 1984). Trawling positions were also observed to be concentrated near CWB, which was located according to GORDON (1988), between

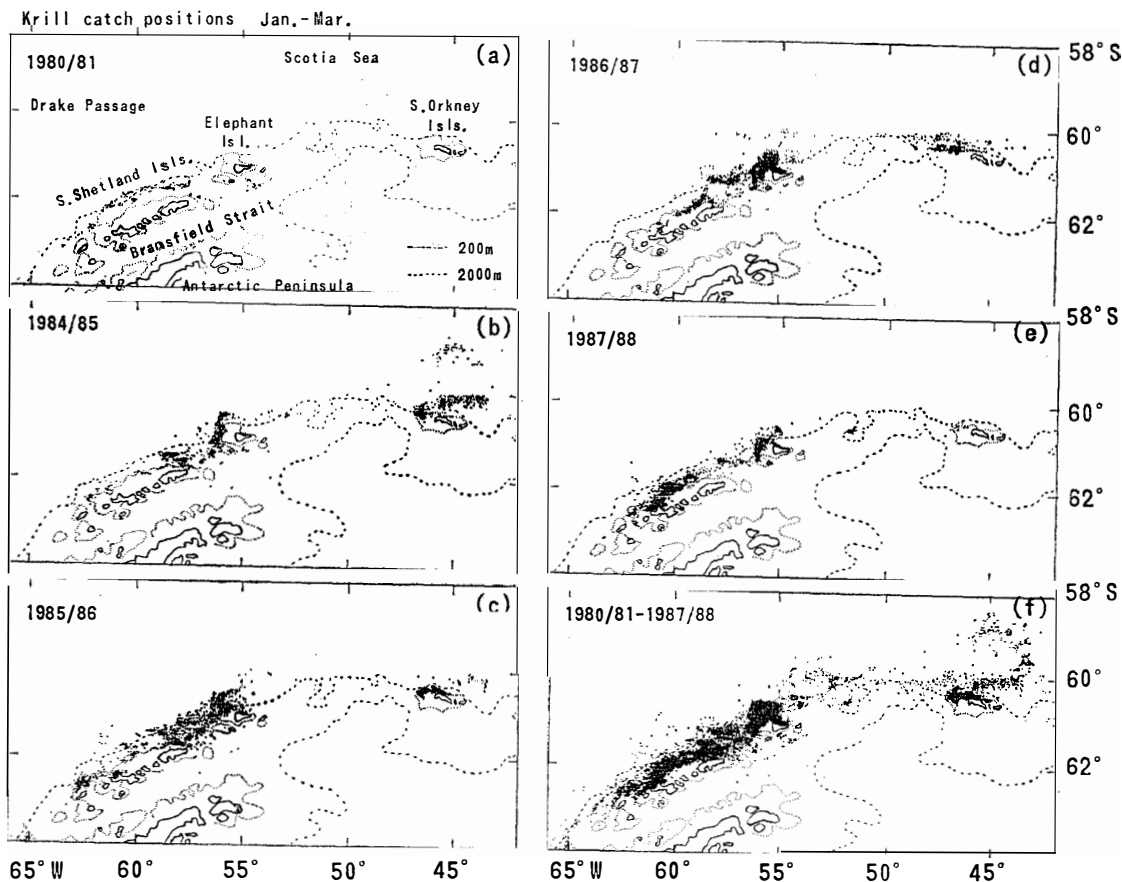


Fig. 11. (a)–(f) Distribution of krill catch positions for January–March in 1980/81, 1984/85, 1985/86, 1986/87, 1987/88 and 1980/81–1987/88 together with bottom topography of the southwestern Scotia Sea.

Elephant Island and the South Shetland Islands in January 1987 (Fig. 13).

In spite of its high krill abundance, the southwestern Scotia Sea region was reported to be sparsely populated by minke whales (KASAMATSU, 1988).

3.2.4. The Ross Sea region

An extension of the continental shelf occupies most of this sea and contains several shallow banks (Figs. 14 and 15). The pack ice usually remains in the eastern Ross Sea with a belt often extending from east to west seaward of the continental shelf and along the Victoria Land coast in summer (AINLEY *et al.*, 1984).

In 1986/87 limited minke whaling was conducted in the eastern Ross Sea and whale catches were concentrated around the bank in the southeast shelf. Extremely large numbers were sighted there (*ca.* 1500 per day) (Fig. 14). The stomach content of captured whales in that area consisted exclusively of krill larger than 50 mm, suggesting the concentration of *E. superba* around the bank on the shelf. In 1988/89 the Japanese feasibility study on southern minke whales covered the western Ross Sea (KATO *et al.*, 1989). It is clear that minke whales were concentrated near the continental slope (Fig. 15). Records of stomach content indicate that captured whales over the slope exclusively fed krill larger than 50 mm.

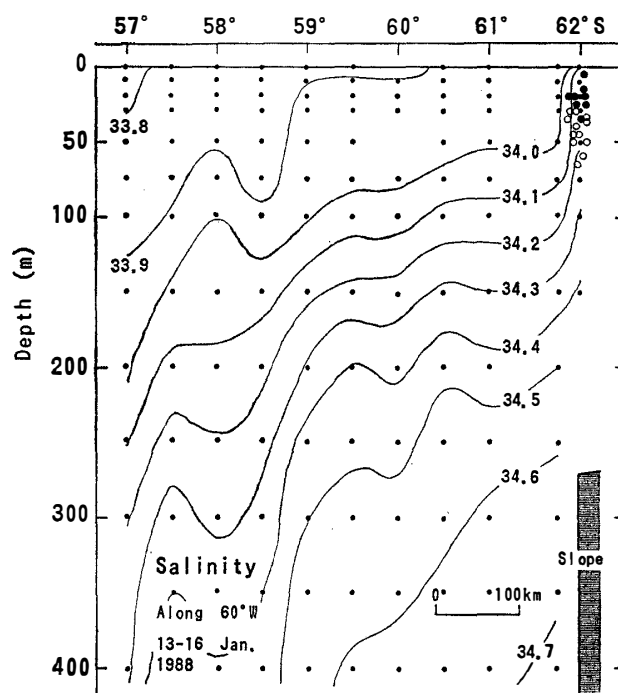


Fig. 12. Vertical distribution of salinity along 60°00'W (SUISANCHÔ, 1989) compared with krill trawl positions along the meridian between January 13-16, 1988. Daytime and nighttime trawls are shown in open and closed circles, respectively.

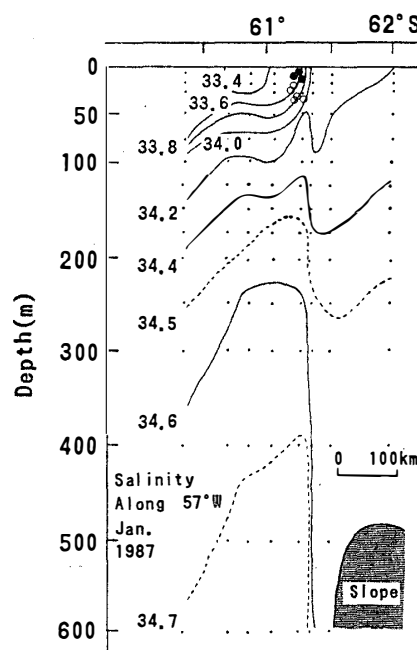


Fig. 13. Vertical distribution of temperature along 57°W (modified from GORDON, 1988) compared with krill trawl positions along the meridian January 1987. Daytime and nighttime trawls are shown in open and closed circles, respectively.

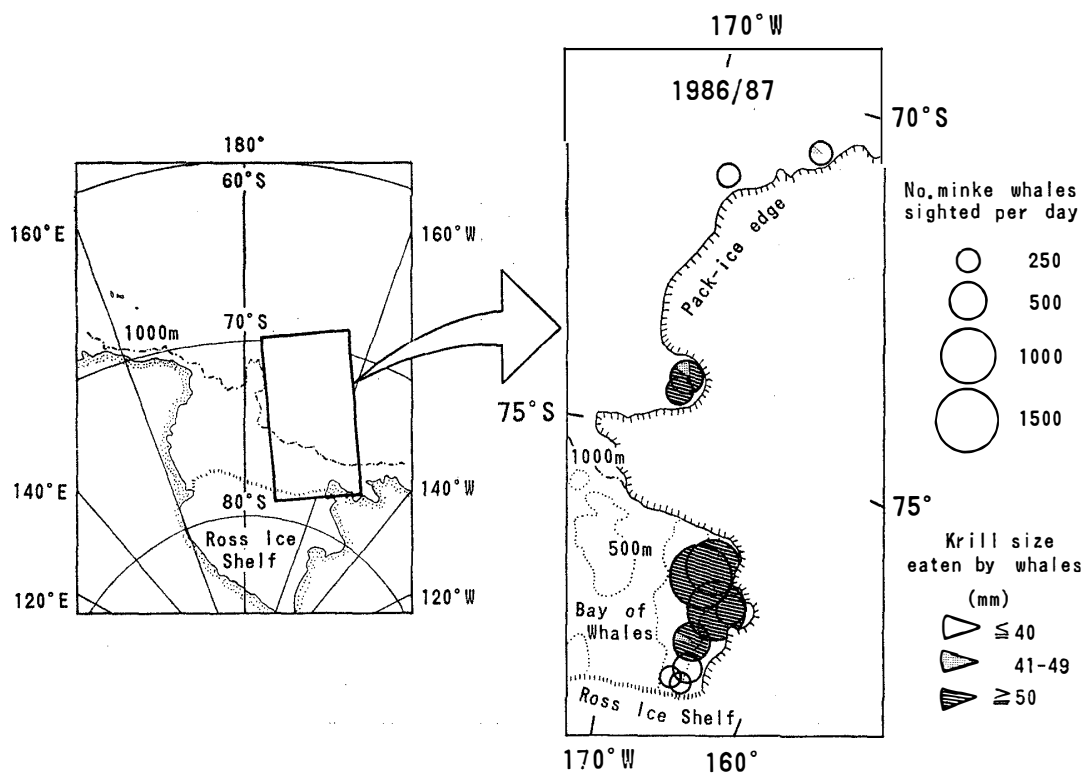


Fig. 14. Distribution of the number of minke whales sighted per day for the period February 22 to March 6, obtained from the 1986/87 Japanese minke whaling expedition. Sizes of krill in the stomachs of minke whales are also shown. Circle centers represent the noon positions of factory ship.

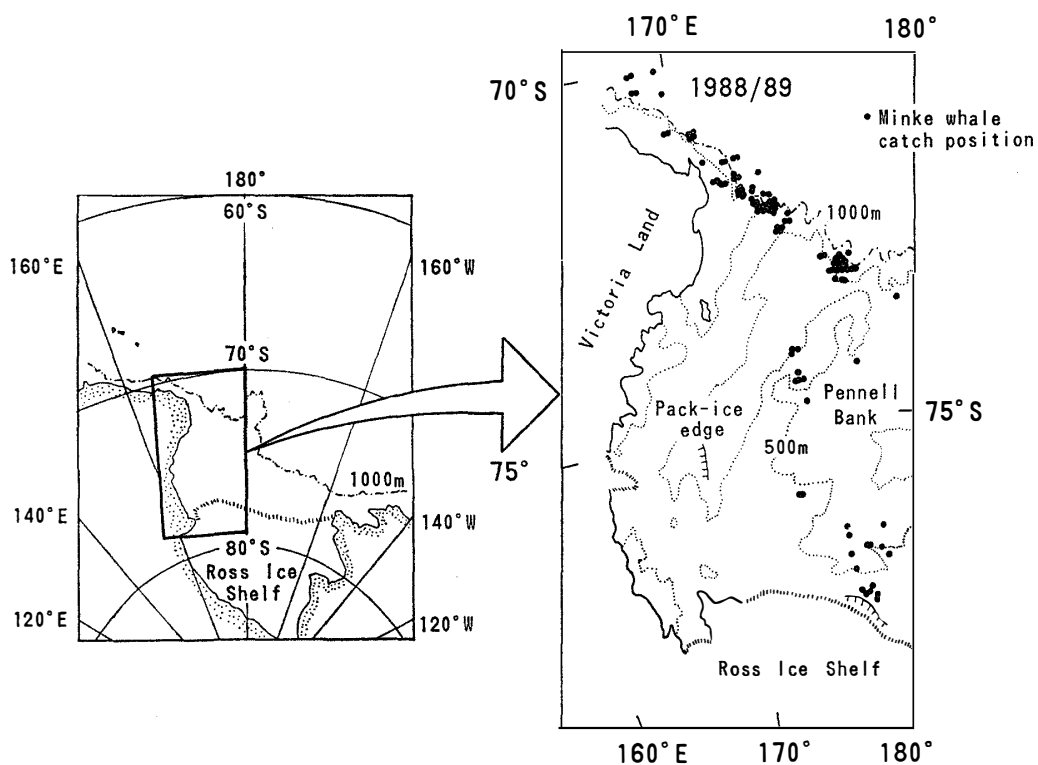


Fig. 15. Distribution of minke whales taken based on their sighted position for January–March obtained from the 1988/89 Japanese feasibility study on minke whales (modified from KATO et al., 1989).

4. Discussion

There are some latitudinal separation of the operational areas of two fisheries: whaling area positioned more southward than krill trawling area (Figs. 4d and 6d, 7d and 8d). The reason for this may be as follows. Minke whales tend to be distributed densely near the pack-ice edge, but scarcely in waters far away from ice-edge even if krill are abundant (*e.g.*, KASAMATSU, 1988). Therefore, minke whaling was frequent near the ice-edge. On the other hand, krill trawlers avoid operation near the ice-edge even if krill are abundant because trawling in the icy waters may cause a lot of trouble. Therefore, krill trawling was frequent in the areas of high krill abundance far away from ice-edge. So far it is not known which area tends to be more abundant with krill, favorite area of minke whaling or that of krill trawling. Operational areas of both fisheries seem to give us a realistic picture of the distribution of krill concentrations.

4.1. *Distribution of krill concentrations, December*

The formation of krill concentrations appears to be affected by the distribution of the pack-ice edge, *i.e.* the latitudinal position and shape of the pack-ice edge.

Krill trawlers prefer to operate in the areas where ice-edge retreats rapidly so that they can reach near the continent as early as possible (SUGIMOTO, 1977). The trawlers chartered by JAMARC reported that there tended to be fewer fishable aggregations of krill in the vicinity of northerly positioned ice-edge based on their research activities (JAMARC, 1976, 1977, 1978, 1980a, b, 1981, 1983a, b). Southerly positioned pack ice-edge is also favorable for whaling due to the high density of whales and milder weather (FURUKAWA, 1981; SHIMADZU and KASAMATSU, 1983). Therefore, krill are considered to be abundant near southerly positioned pack ice-edge. It may be partly because of its closer location to the continental break where krill concentrations regularly occur.

Minke whaling data have suggested that krill are also abundant in large embayments. SMITH and NELSON (1986) suggested that productivity within ice-edge zone is affected by the following factors: the release of ice algae into surface waters from melting ice; the input of the low-density water from melting ice (which increases the water column stability, thereby improving the environment for phytoplankton growth); and, local wind stress and horizontal flow, etc. (which destroy the water column stability). Being semi-surrounded by ice, areas within deep embayments are expected to be a favorable environment for phytoplankton growth and therefore for feeding areas of krill.

4.2. *Distribution of krill concentrations, January–March*

Krill trawling data indicated that harvestable areas most frequently occur around the ice-free continental and insular shelf breaks, not in the vicinity of pack-ice edge. Minke whaling data suggested that, although the distribution of minke whales is strongly affected by sea-ice, bottom topography such as the continental shelf breaks and banks may also be an important factor determining minke whale distribution in the pack-ice zone.

MARR (1962) and MACKINTOSH (1973) also showed that krill sparsely populate in the Pacific sector (80°–180°W), where sea-ice extends northward and wholly covers the

continental shelf. According to catch statistics (Anonymous, 1988), the west Pacific sector (105° – 170° W) is one of the least harvested areas by all the krill fishing nations with accumulated catch between 1973/74 and 1987/88 being only 47 tonnes. Recently it has been suggested that minke whales are not only less densely distributed (KASAMATSU, 1988) but also smaller in mean body length at physical maturity in the area between 60° W and 170° W (H. KATO, pers. commun.), which also supports less krill near the pack-ice edge in the Pacific region.

MARR (1962) and MACKINTOSH (1973), however, did not show abundant areas of krill off Kemp and Mac.Robertson Lands and off Adelie Land deduced from this study. They speculated that nearly all the krill and most of the whales in these regions may be confined to a narrow belt near the coast, since they could not collect/encounter large numbers of krill and whales in oceanic waters. If they had sampled frequently in the coastal waters in these regions, they could have located the abundant areas of krill.

The results of the present study is consistent with other workers (*e.g.*, KALINOWSKI, 1982; HAMPTON, 1983; BRINTON, 1985), most of which are confined to the western Atlantic sector, in that krill concentrations generally occur around islands and over shelf areas, and less frequently in deep waters. Thus, there seem to be favorite areas (*e.g.* the continental and insular shelf slopes, and banks) for krill to form dense concentrations. The reasons for this, however, are still subject to speculation.

In the Antarctic, standing crop of phytoplankton generally shows higher values in coastal waters than oceanic waters (EL-SAYED, 1988). Higher chlorophyll *a* concentrations are reported in the shelf-slopes of the above-mentioned four regions; region off Kemp and Mac.Robertson Lands (FUKUI *et al.*, 1986; WRIGHT, 1987), region off Adelie Land (H. TOMINAGA, unpublished), region north of the South Shetland Islands (KOPCZYŃSKA, 1985) and the Ross Sea region (AINLEY and JACOBS, 1981). It would appear, therefore, that there are good biological reasons for krill to stay there.

DEACON (1984a) indicated that near the continent, both southward Ekman transport and southward Coriolis forces on the predominantly westward flow of the East Wind Drift may be partly responsible for concentrating krill adjacent to the continental margin. His idea is supported by the result of this study that the area between 80° E and 100° E (where large-scale northward flow is predominant and hence krill is expected to be dispersed further northward) is characterized by the formation of less persistent concentrations (Fig. 3c, d).

Fronts commonly occur in the vicinity of the continental and insular shelf slopes in the Antarctic (SIEVERS and NOWLIN, 1984; JACOBS, 1986). Both insular shelf slope front (CWB) and continental shelf slope front are considered to be involved in the formation and maintenance of krill concentrations since trawling grounds often coincided with them. According to JACOBS (1986), temperature-salinity characteristics of the continental shelf slope front may vary considerably in space and time. Namely, the front appears to weaken temporarily or absent at some locations. This temporal variability may lead to the annual variation in the location of harvested areas observed in regions off Kemp and Mac.Robertson Lands, and off Adelie Land.

In Admiralty Bay, the South Shetland Islands, krill aggregations were most frequently associated with eddies resulting from the bottom configuration and tidal currents (RAKUSA-SUSZCZEWSKI, 1980). Therefore, in the proximity of uneven bottom

topography on the continental shelf where minke whaling was frequently conducted, eddies are also thought to play an important role in the formation of krill concentrations.

Assuming that krill are sensitive to marked current gradient (MAUCHLINE, 1981), MACAULAY *et al.* (1984) and WITEK *et al.* (1988) regarded the large velocity gradients of stationary nature caused by topographic slopes as an important factor in the formation of krill aggregation. The former authors speculated that krill orient themselves to stationary current gradients and this may lead to the development of krill aggregations. The latter authors speculated that krill are able to perceive and react to water velocity gradients in such a way that they tend to concentrate in quiescent regions which are most likely to exist in the center of localized eddies or current meanders developed near islands and submarine elevations.

The continental slope is suggested to be a favorable spawning area since early larval stages of krill are regularly abundant there (MARR, 1962; WITEK *et al.* 1980; DEACON, 1984b; SAMYSHEV, 1984). Near the shelf slope the eggs may not sink too deep, and also vertical water circulation (*i.e.* upward movement of the warm deep water as well as downward movement of the cold shelf water) may affect favorably the ascent of the larvae (DEACON, 1984b).

SIEGEL (1988) suggested the presence of spawning migration in the southwest Scotia Sea. He observed that during summer the insular slopes were abundant with gravid and spawning adults, while during winter these areas were abandoned.

In 1976/77 Japanese krill trawlers tracked a huge krill swarm which migrated southward (60°E) against currents in the area off Kemp and Mac.Robertson Lands (KANDA *et al.*, 1982). This swarm turned into a layer near the continental slope where sea-surface temperature decreased (SUGIMOTO, 1977). Layers, which are defined as krill aggregations of more than 1000 m long (KALINOWSKI and WITEK, 1985), are a typical form of krill aggregation in the vicinity of the continental slope there (SUGIMOTO, 1977). SUGIMOTO (1977) and KANDA *et al.* (1982) considered that this active horizontal movement of krill may be a spawning migration because the proportion of gravid females in samples from catches increased during repeated operations on this migrating swarm (KANDA *et al.*, 1982). The change in aggregation pattern of the swarm observed with a decrease in sea-surface temperature may imply that frontal features associated with the shelf slopes are important for krill as a cue to locate their favorable spawning areas, *i.e.* the shelf slopes.

4.3. Possible existence of krill concentrations on the Ross Sea shelf

MARR (1962) showed that *E. superba* is almost completely absent on the Ross Sea shelf and that another euphausiid, *E. crystallorophias*, replaces on the shelf. He speculated that the absence of *E. superba* may be partly ascribed to the failure of the warm deep current, which carries ascending larvae, to penetrate onto the shelf. However, abundance and distribution of minke whale and their stomach contents suggest the existence of *E. superba* concentration near the bank on the southeastern part of the Ross Sea shelf (Fig. 14). Recent research has also shown that the warm current reaches all the way to the Ross Sea shelf (JACOBS *et al.*, 1979; AINLEY and JACOBS, 1981). Thereby, the warm deep current, contrary to MARR's indication, can transport *E. superba* larvae onto the shelf.

Acknowledgments

My sincere thanks are due to Dr. Y. ENDO of Tohoku University and Mr. D.G. M. MILLER of Sea Fisheries Research Institute (South Africa) for their critical comments on the manuscript. I would also like to express my thanks to Mr. F. KASAMATSU, the Whales Research Institute, for providing me information on minke whales. Drs. H. KATO, T. KASUYA, S. WADA and Mr. T. MIYASHITA of my laboratory kindly permitted me to use minke whaling data. Dr. Y. KOMAKI of the same laboratory provided useful information.

References

- AINLEY, D. G. and JACOBS, S.S. (1981): Sea-bird affinities for ocean and ice boundaries in the Antarctic. *Deep-Sea Res.*, **28**, 1173–1185.
- AINLEY, D. G., O'CONNOR, E. F. and BOEKELHEIDE, R.J. (1984): The marine ecology of birds in the Ross Sea, Antarctica. *Am. Ornithol. Union Monogr.*, **32**, 97 p.
- Anonymous (1988): Summary of krill catches. Pap. SC-CAMLR, VII/BG/1, 17 p.
- BRINTON, E. (1985): The oceanographic structure of the eastern Scotia Sea—III. Distributions of euphausiid species and their developmental stages in 1981 in relation to hydrography. *Deep-Sea Res.*, **32**, 1153–1180.
- BUSHUEV, S. G. (1986): Feeding of minke whales, *Balaenoptera acutorostrata*, in the Antarctic. *Rep. Int. Whaling Comm.*, **36**, 241–245.
- BUTTERWORTH, D.S. (1988): A simulation study of krill fishing by an individual Japanese trawler. *Select. Pap. Present. Sci. Comm. CCAMLR*, 1988, Part 1, 1–96.
- BUTTERWORTH, D.S. and MILLER, D. G. M. (1987): A note on relating Antarctic krill catch-per-unit-effort measures to abundance trends. *S. Afr. J. Antarct. Res.*, **17**(2), 112–116.
- CARMACK, E. C. and KILLWORTH, P. D. (1978): Formation and interleaving of abyssal water masses off Wilkes Land, Antarctica. *Deep-Sea Res.*, **25**, 357–369.
- DEACON, G. E. R. (1982): Physical and biological zonation in the Southern Ocean. *Deep-Sea Res.*, **29**, 1–15.
- DEACON, G. E. R. (1984a): The Antarctic Circumpolar Ocean. Cambridge, Cambridge Univ. Press, 180 p.
- DEACON, G. E. R. (1984b): Water movements and Antarctic krill. *J. Crust. Biol.*, **4** (Spec. No. 1), 13–15.
- EL-SAYED, S. Z. (1988): Seasonal and interannual variabilities in Antarctic phytoplankton with reference to krill distribution. *Antarctic Ocean and Resources Variability*, ed. by D. SAHRHAGE. Berlin, Springer, 101–119.
- FUKUI, F., OTOMO, K. and OKABE, S. (1986): Nutrients depression in the blooming area of Prydz Bay, Antarctica. *Mem. Natl Inst. Polar Res., Spec. Issue*, **44**, 43–54.
- FURUKAWA, F. (1981): Minke whaling in the 34th Antarctic whaling season, 1979/80. *Rep. Int. Whaling Comm.*, **31**, 359–361.
- GILL, A. E. (1973): Circulation and bottom water production in the Weddel Sea. *Deep-Sea Res.*, **20**, 111–140.
- GORDON, A. L. (1988): Physical oceanographic setting of the Siedlecki January 1987, South Shetland data set. *Select. Pap. Present. Sci. Comm. CCAMLR*, 1988, Part 2, 161–182.
- GORDON, A. L. and TCHERNIA, P. (1972): Waters of the continental margin off Adelie Coast, Antarctica. *Antarctic Oceanography II; The Australian-New Zealand Sector*, ed. by D.E. HAYES. Washington, D.C., Am. Geophys. Union, 59–69 (*Antarct. Res. Ser.*, Vol. 19).
- HAMPTON, I. (1983): Preliminary report on the FIBEX acoustic work to estimate the abundance of *Euphausia suprema*. *Mem. Natl Inst. Polar Res., Spec. Issue*, **27**, 165–175.
- ICHII, T. (1987): Observations of fishing operations on a krill trawler and distributional behavior of

- krill off Wilkes Land during the 1985/86 season. Select. Pap. Present. Sci. Comm. CCAMLR, 1987, 335–363.
- JACOBS, S. S. (1986): The Antarctic Slope Front. *Antarct. J. U. S.*, **21**(5), 123–124.
- JACOBS, S. S., GORDON, A. L. and ARDAI, J. L. (1979): Circulation and melting beneath the Ross Ice Shelf. *Science*, **203**, 439–444.
- JAMARC (1976): Shôwa-50-nendo Okiami Shingyojyô Kigyôka Chôsa Hôkokusho (Report of Feasibility Study on Krill Fisheries in the Antarctic in 1975/76). (S50/11), 1–153.
- JAMARC (1977): Shôwa-51-nendo Okiami Shingyojyô Kigyôka Chôsa Hôkokusho (Report of Feasibility Study on Krill Fisheries in the Antarctic in 1976/77). (S51/12), 1–205.
- JAMARC (1978): Shôwa-52-nendo Okiami Shingyojyô Kigyôka Chôsa Hôkokusho (Report of Feasibility Study on Krill Fisheries in the Antarctic in 1977/78). (S52/15), 1–109.
- JAMARC (1980a): Shôwa-53-nendo Okiami Shingyojyô Kigyôka Chôsa Hôkokusho (Report of Feasibility Study on Krill Fisheries in the Antarctic in 1978/79). (S53/14), 1–313.
- JAMARC (1980b): Shôwa-53-nendo Bosensiki Okiami Gyogyô Kigyôka Chôsa Hôkokusho (Report of Feasibility Study on Mother Ship Type Krill Operation in 1978/79). (S53/15), 1–138.
- JAMARC (1981): Shôwa-54-nendo Bosensiki Okiami Gyogyô Kigyôka Chôsa Hôkokusho (Report of Feasibility Study on Mother Ship Type Krill Operation in 1979/80). (S54/17), 1–117.
- JAMARC (1983a): Shôwa-54-nendo Okiami Shingyojyô Kigyôka Chôsa Hôkokusho (Report of Feasibility Study on Krill Fisheries in the Antarctic in 1979/80). (S54/16), 1–43.
- JAMARC (1983b): Shôwa-52-nendo Bosensiki Okiami Gyogyô Kigyôka Chôsa Hôkokusho (Report of Feasibility Study on Mother Ship Type Krill Operation in 1977/78). (S52/16), 1–50.
- KALINOWSKI, J. (1982): Distribution and stocks of krill in the Drake Passage and the Bransfield Strait, during the BIOMASS-FIBEX expedition 1981. *Pol. Polar Res.*, **3**, 243–251.
- KALINOWSKI, J. and WITEK, Z. (1985): Scheme for classifying aggregations of Antarctic krill. *BIO-MASS Handb.*, **27**, 1–9.
- KANDA, K., TAKAGI, K. and SEKI, Y. (1982): Movement of the larger swarms of Antarctic krill *Euphausia superba* population off Enderby Land during 1976–1977 season. *J. Tokyo Univ. Fish.*, **68**, 25–42.
- KASAMATSU, F. (1988): Minami hankyu minku kujira asesumento kôkai no jyûnen (A brief summary of the IWC/IDCR Southern Hemisphere Minke Whale Assessment Cruises during the first 10 years). *Geiken Tsûsin (Whales Res. Inst. Newslett.)*, **374**, 19–42.
- KASAMATSU, F. and SHIMADZU, Y. (1985): Operating pattern of Antarctic minke whaling by the Japanese expedition in the 1983/84 season. *Rep. Int. Whaling Comm.*, **35**, 283–284.
- KATO, H., HIROYAMA, H., FUJISE, Y. and ONO, K. (1989): Preliminary report of the 1987/88 Japanese feasibility study of the special permit proposal for southern hemisphere minke whales. *Rep. Int. Whaling Comm.*, **39**, 235–248.
- KOPCZYŃSKA, E. E. (1985): Correlation of krill abundance with chlorophyll *a*. Atlas of Polish oceanographic observations in Antarctic waters 1981. *BIOMASS Spec. Issue*, 47–50.
- MACAULAY, M. C., ENGLISH, T. S. and MATHISEN, O. A. (1984): Acoustic characterization of swarms of Antarctic krill (*Euphausia superba*) from Elephant Island and Bransfield Strait. *J. Crust. Biol.*, **4** (Spec. No. 1), 16–44.
- MACKINTOSH, N. A. (1973): Distribution of post-larval krill in the Antarctic. *Discovery Rep.*, **36**, 95–156.
- MACKINTOSH, N. A. and HERDMAN, H. F. P. (1940): Distribution of the pack-ice in the southern ocean. *Discovery Rep.*, **19**, 285–296.
- MARR, J. W. S. (1962): The natural history and geography of the Antarctic krill (*Euphausia superba* DANA). *Discovery Rep.*, **32**, 33–464.
- MATSUURA, N., INAGAKE, D., FUKUOKA, J. and KITAZAWA, A. (1985): Oceanographic conditions of the Southern Ocean south of Australia during the summer of 1984. *Trans. Tokyo Univ. Fish.*, **6**, 9–22.
- MAUCHLINE, J. (1981): Studies on patches of krill, *Euphausia superba* DANA. *BIOMASS Handb.*, **16**, 1–36.
- RAKUSA-SUSZCZEWSKI, S. (1980): Environmental conditions and the functioning of Admiralty Bay

- (South Shetland Islands) as part of the near shore Antarctic ecosystem. *Pol. Polar Res.*, **1**, 11–27.
- SAMYSHEV, E. R. (1984): Distribution of eggs and larvae and functional structure of the distribution range of *Euphausia superba* DANA. *Oceanology*, **24**(3), 385–390.
- SHIMADZU, Y. (1985): A brief summary of Japanese fishing activity relating to Antarctic krill, 1972/73–1982/83. *Select. Pap. Present. Sci. Comm. CCAMLR*, 1982–1984, Part 1, 439–452.
- SHIMADZU, Y. and KASAMATSU, F. (1981): Operating pattern of Japanese whaling expeditions engaged in minke whaling in the Antarctic. *Rep. Int. Whaling Comm.*, **31**, 349–355.
- SHIMADZU, Y. and KASAMATSU, F. (1983): Operating pattern of Antarctic minke whaling by the Japanese expedition in 1981/82. *Rep. Int. Whaling Comm.*, **33**, 389–391.
- SHIMADZU, Y. and KASAMATSU, F. (1984): Operating pattern of Antarctic minke whaling by the Japanese expedition in the 1982/83 season. *Rep. Int. Whaling Comm.*, **34**, 357–359.
- SIEGEL, V. (1988): A concept of seasonal variation of krill (*Euphausia superba*) distribution and abundance west of the Antarctic Peninsula. *Antarctic Ocean and Resources Variability*, ed. by D. SAHRHAGE. Berlin, Springer, 219–230.
- SIEVERS, H. A. and NOWLIN, W. D. (1984): The stratification and water masses at Drake Passage. *J. Geophys. Res.*, **89**(C6), 10489–10514.
- SMITH, N. R., ZHAOQIAN, D., KERRY, K. R. and WRIGHT, S. (1984): Water masses and circulation in the region of Prydz Bay, Antarctica. *Deep-Sea Res.*, **31**, 1121–1147.
- SMITH, W. O. and NELSON, D. M. (1986): Importance of ice edge phytoplankton production in the Southern Ocean. *BioScience*, **36**(4), 251–257.
- SUGIMOTO, S. (1977): Shôwa-51, 52-nendo gyoki no nankyokuyô okiami gyokyô ni tsuite (On the fishing conditions of the Antarctic krill fishery in 1976/77 and 1977/78). *Rep. Meet. Fish. Top.*, *Jpn. Soc. Sci. Fish.*, **11**, 58–70.
- SUISANCHÔ (1983): Shôwa-55-nendo KAIYO MARU Chôsa Kôkai Hôkokusho; Dai-2-ji Nankyokukai Chôsa (Preliminary Report of JFA R.V. KAIYO MARU's Second Cruise in 1980 Fiscal Year, the Second Antarctic Ocean Survey Cruise). 321 p.
- SUISANCHÔ (1989): Shôwa-62-nendo KAIYO MARU Chôsa Kôkai Hôkokusho; Dai-5-ji Nankyokukai Chôsa (Preliminary Report of JFA R.V. KAIYO MARU's Second Cruise in 1987 Fiscal Year, the Fifth Antarctic Ocean Survey Cruise). 301 p.
- TCHERNIA, P. and JEANNIN, P. F. (1980): Observations on the Antarctic East Wind Drift using tabular icebergs tracked by satellite NIMBUS F (1975–1977). *Deep-Sea Res.*, **27A**, 467–474.
- TCHERNIA, P. and JEANNIN, P. F. (1983): Quelques Aspects de la Circulation Océanique Antarctique Révélés par l'Observation de la Dérive d'Icebergs (1972–1983). Toulouse, Centre National d'Etudes Spatiales, 93 p.
- TCHERNIA, P. and JEANNIN, P. F. (1984): Circulation in Antarctic waters as revealed by iceberg tracks 1972–83. *Polar Rec.*, **22**(138), 263–269.
- WITEK, Z., KORONKIEWICZ, A. and SOSZKA, G. J. (1980): Certain aspects of the life history of krill *Euphausia superba* DANA (Crustacea). *Pol. Polar Res.*, **1**, 97–115.
- WITEK, Z., KALINOWSKI, J. and GRELOWSKI, A. (1988): Formation of Antarctic krill concentrations in relation to hydrodynamic processes and social behaviour. *Antarctic Ocean and Resources Variability*, ed. by D. SAHRHAGE. Berlin, Springer, 237–244.
- WRIGHT, S. W. (1987): Phytoplankton pigment data; Prydz Bay region—SIBEX II, MV NELLA DAN, January 1985. *ANARE Res. Notes*, **58**, 1–102.
- ZWALLY, H. J., COMISO, J. C., PARKINSON, C. L., CAMPBELL, W. J., CARSEY, F. D. and GLOERSEN, P. (1983): Antarctic Sea Ice, 1973–1976; Satellite Passive-microwave Observations. Washington, D.C., NASA SP-459, 206 p.

(Received May 17, 1989; Revised manuscript received December 28, 1989)