CCAMLR Science, Vol. 4 (1997): 195-204

SHORT NOTE

ASSESSMENT OF KRILL FLUX FACTORS IN WATERS OF THE SOUTH ORKNEY ISLANDS DURING SUMMER 1996

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Abstract

This paper describes the results of an experiment conducted from 19 February to 7 March 1996 to assess krill flux factors in Subarea 48.2. The study area (80 x 240 n miles) was located in the zone of interaction between waters of the Antarctic Circumpolar Current (ACC) and the Weddell Sea. The study area covered sites where high krill concentrations had often been observed in the past. The geostrophic transport of krill across boundaries of the study area was calculated as a product of two variables integrated over the depth range 0 to 200 m: krill density (g/m^3) and water mass transport (m^3/sec) per nautical mile of the study area boundary. Also given are the results of krill density assessment, evaluations of geostrophic and wind-induced water transport along the study area perimeter. Mean krill transport rate was 7.2 tonnes/hour/n mile with a standard deviation of 15.5 tonnes/hour/n mile. Significant variability of krill transport across the study area boundary was observed, both in terms of the amount of biomass transported and the direction of flux. Due to the location of the study area, it was only possible to assess krill flux caused by waters of the southern periphery of ACC. Based on estimations of krill density and geostrophic velocities obtained during the experiment, a preliminary estimate of krill outflow from the study area into adjacent areas would be approximately 9.2 million tonnes.

Résumé

Les auteurs donnent les résultats d'une étude menée du 19 février au 7 mars 1996 en vue d'évaluer les facteurs de flux de krill dans la sous-zone 48.2. La zone d'étude (80 x 240 milles) se situe à la confluence des eaux du courant circumpolaire antarctique et de la mer de Weddell. Elle couvre des sites où de fortes concentrations de krill ont souvent été observées par le passé. Le transport géostrophique du krill au-delà de la bordure de la zone d'étude est calculé par le produit de deux variables intégrées pour l'intervalle de profondeur 0 - 200 m : la densité de krill (g/m^3) et le transport des masses d'eau (m^3/sec) par mille de bordure de la zone d'étude. Les auteurs donnent également les résultats de l'estimation de la densité de krill et les évaluations du transport géostrophique des eaux et du transport des eaux causé par les vents le long du périmètre de la zone d'étude. Le taux moyen de transport de krill est de 7,2 tonnes/heure/mille avec un écart-type de 15,5 tonnes/heure/mille. Une variabilité importante du transport de krill au-delà de la bordure de la zone d'étude est observée, tant en fonction de la biomasse transportée que de la direction du flux. Vu la position de la zone d'étude, il n'a été possible d'évaluer que les flux de krill causés par les eaux de la périphérie sud du courant circumpolaire antarctique. Une première estimation du débit de krill de la zone d'étude aux secteurs adjacents fondée sur les estimations de la densité de krill et des vélocités géostrophiques obtenues durant l'étude s'élèverait à environ 9,2 millions de tonnes.

Резюме

В настоящей работе описаны результаты эксперимента по оценке факторов переноса криля в Подрайоне 48.2, проводившегося с 19 февраля по 7 марта 1996 г. Полигон площадью 80 х 240 миль располагался в зоне взаимодействия антарктического циркумполярного течения (АЦТ) и вод моря Уэдделла. Полигон включал в себя участки, на которых раньше наблюдались высокие концентрации криля. Геострофическое перемещение криля через участок границы полигона оценивалось как произведение двух величин, интегрированных по слою глубин 0–200 м: средней плотности криля (г/м^3) и расхода воды (м^3/с) через 1 милю границы полигона. Показаны результаты оценки плотности криля, геострофических скоростей, расходов воды по периметру полигона. Средняя интенсивность переноса криля составила 7,2 т/час/морскую милю, при стандартном отклонении 15,5 т/час/морскую милю. Для полигона характерна существенная изменчивость интенсивности перемещения криля через границы полигона как по величине переносимой биомассы, так и по направлению ее переноса. Особенности расположения полигона в поле основных течений позволяют оценить перенос криля только водами южной периферии АЦТ. По предварительным рассчетам плотности криля и геострофических скоростей биомасса криля, выносимая в соседние районы течением, составляет порядка 9,2 млн. тонн в год.

Resumen

Este documento describe los resultados de un experimento que fue llevado a cabo desde el 19 de febrero al 7 de marzo de 1996 a fin de evaluar los factores que afectan el flujo de kril en la Subárea 48.2. El área de estudio (80 x 240 millas naúticas) se encuentra en la zona de interacción entre las aguas de la Corriente Circumpolar Antártica (ACC) y el Mar de Weddell, y cubre áreas en las cuales a menudo se han observado altas concentraciones de kril. El transporte geostrófico de kril a través de los límites del área de estudio se calculó a partir del producto de dos variables integradas en el intervalo de profundidad de 0 a 200 m: la densidad de kril (g/m^3) y el transporte de la masa de agua (m^3/seg) por milla naútica del límite del área de estudio. También se dan los resultados de la evaluación de la densidad de kril y de las evaluaciones del transporte de agua debido al geostrofismo y al viento a lo largo del límite del área de estudio. La tasa promedio del transporte de kril fue 7.2 toneladas/hora/milla naútica con una desviación cuadrática media de 15.5 toneladas/hora/milla. Se observó una variabilidad significativa del transporte de kril a lo largo del límite del área de estudio, en lo que se refiere a la biomasa transportada y la dirección del flujo. Debido a la ubicación del área de estudio, sólo fue posible evaluar el flujo de kril causado por las aguas del extremo sur de la ACC. Basándose en las estimaciones de la densidad del kril y las velocidades geostróficas obtenidas en el experimento, la estimación preliminar del flujo de kril desde el área de estudio a las áreas adyacentes sería aproximadamente de 9.2 millones de toneladas.

Keywords: Ekman wind drift, flux, geostrophic water transport, krill, CCAMLR

INTRODUCTION

Local estimates of instantaneous biomass of krill in areas where krill is subject to significant transport by oceanic currents do not provide a basis for calculating actual total biomass of krill (SC-CAMLR, 1990 and 1991). Horizontal krill flux is especially significant in the Scotia Sea, i.e. in CCAMLR Statistical Subareas 48.1, 48.2, 48.3. Therefore, assessment methods should incorporate krill flux factors in order to improve the quality of krill stock assessments.

The major obstacles in making meaningful assessments of krill flux were the lack of a general concept for tackling the problem, as well as a lack of experimental data.

In recent years, most studies aimed at assessing krill transport by oceanic currents, i.e. passive krill flux, have concentrated on the velocity of water mass transport between different parts of the Scotia Sea (SC-CAMLR, 1991; Naganobu et al., 1992; Naganobu, 1993; Ichii and Naganobu, 1996). In general, most attention has been focused on Subareas 48.1 and 48.3 (South

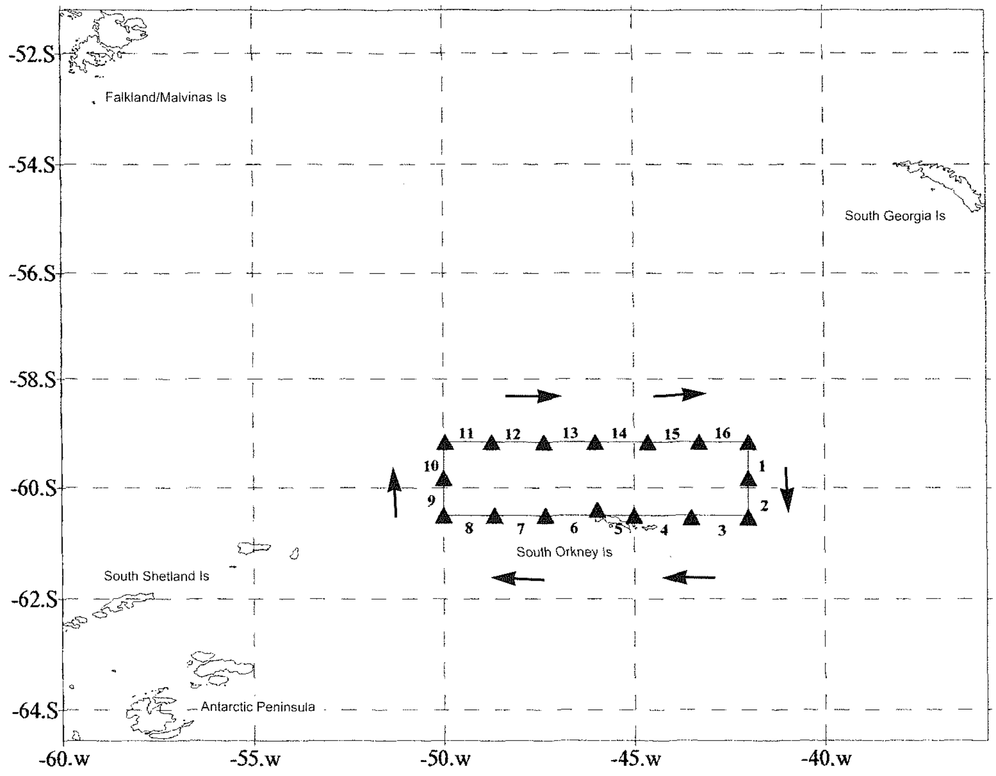

Figure 1: Location of the study area.

▲ oceanographic stations;

1-16 sections of the boundary of the study area used to estimate krill flux and water transport;

→ direction of the vessel's movement along the perimeter of the study area.

Shetlands and South Georgia). In order to assess the overall pattern of krill flux over the Atlantic Antarctic Section (AAS) of the Southern Ocean (Area 48), it is also necessary to take into account krill flux through Subarea 48.2 (South Orkneys). Subarea 48.2 is located in the zone where waters of the Antarctic Circumpolar Current (ACC) and the Weddell Sea interact and have a fundamental impact on the overall pattern of krill flux in the AAS.

On the basis of research carried out during 1992 and 1993, CCAMLR scientists developed a conceptual framework according to which krill flux factors could be evaluated from the results of a mesoscale *in situ* experiment (SC-CAMLR, 1993). This method involves the assessment of krill inflow and outflow across the closed contour boundaries of a sufficiently large study area (comparable in size to Subareas 48.1, 48.2 or 48.3) by means of evaluating geostrophic velocity profiles of water mass transport and krill density profiles, both integrated over the depth range from 0 to 200 m at a resolution of 1 n mile of the study area boundary.

The first experiment to comply with this conceptual framework was carried out in 1992 during a research cruise by RV *Dmitry Stefanov* in Subarea 48.2 (South Orkneys). The experiment was carried out in a small area (30 x 30 n miles), however, and the results obtained did not present an overall picture of krill flux across the entire Subarea 48.2 (Maklygin et al., 1992).

In 1996 krill flux in Subarea 48.2 was studied for the first time in full conformity with the guidelines recommended by CCAMLR (SC-CAMLR, 1993). This paper describes the results of that experiment.

MATERIAL AND METHODS

The experiment was carried out by RV *Atlantida* from 19 February to 7 March 1996 in a study area bounded by 59°10'S–60°30'S and 50°00'W–42°00'W, and located in Subarea 48.2 (South Orkneys) which is one of three AAS areas recommended by CCAMLR for krill flux research (SC-CAMLR, 1993). The study area (see Figure 1) was a rectangle of 19 200 n miles^2 (80 x 240 n miles) located in the zone of interaction between waters of the ACC and the Weddell Sea in the Secondary Frontal Zone. The study area covered sites where high krill concentrations had often been observed in the past. The size of the study area was chosen taking into account not only the need to comply with CCAMLR's requirements, but also the limited time available to conduct the cruise.

The perimeter of the area was subdivided into 16 sections, each 40 n miles long (Figure 1). Research was carried out in two stages. During the first stage (19 to 23 February), the vessel circumnavigated the perimeter of the study area at a speed of 8 knots, starting from the northeastern corner, to estimate parameters of water mass transport and krill flux across its boundaries. During the second stage (24 February to 7 March), a hydroacoustic survey and oceanographic stations were carried out (with meridional transects 40 n miles apart) to estimate krill biomass and to determine water circulation characteristics.

Hydroacoustic measurements were carried out using a Simrad echosounder EK-500, computer system BI-500, satellite navigation unit GP/303 and a Furuno log/current meter CI-30 (Japan). Equipment was calibrated by Simrad (Norway) using standard copper spheres.

The initial integration depth was set at 10 m below the surface after taking into account the vessel's draught (about 5 m) and aeration of the near-surface layer. Krill density was estimated using hydroacoustics over the depth range from 0 to 200 m, which was divided into integration layers of 25 m. The integration interval was 4 n miles.

Krill target strength was estimated at an operating frequency of 120 kHz using the following regression (SC-CAMLR, 1991):

$$TS\ (dB) = -127.45+34.85 \log L(mm).$$

Krill length composition was determined from control catches taken by a commercial midwater trawl 75/448.

Oceanographic stations were carried out using a Neil-Brown CTD probe MARK-IIIB. Geostrophic current velocities were calculated with a reference level of 1 000 m. Water mass transport was estimated between adjacent stations 40 n miles apart in terms of S_v units (1 $S_v = 10^6$ m^3/sec).

Since krill flux across the study area was considered as passive transport by water masses, it was estimated as a product of two variables integrated over the layer 0 to 200 m: i.e. krill density and water mass transport.

After converting water mass transport (S_{vi}) over a 40-n mile boundary section of the study area to mean water mass transport per nautical mile (E_i), the mean krill biomass (W_i) transported across 1 n mile of the boundary in the ith section in one hour was estimated as:

$$W_i = E_i \cdot p_i$$

where p_i is mean krill density in the ith section (g/m^3), E_i is mean water mass transport per nautical mile in the ith section between stations (m^3/sec), W_i is krill flux per nautical mile of the ith boundary section of the study area (g/sec).

The direction of krill flux was determined in relation to the direction of water mass transport, i.e. positive values of E_i corresponded to transport into the study area, negative values – away from the study area.

In addition to geostrophic factors, krill flux was also examined in the context of wind-induced water transport (Ekman transport). This parameter was assessed on the basis of data on wind strength and direction obtained during the study period.

RESULTS

The major features of the geostrophic current field in the South Orkneys (Subarea 48.2) are formed by interactions of the southern branch of the ACC and Weddell Sea currents (Figure 2).

The southern branch of the ACC was found to be responsible for maximum values of water 'inflow' (0.10 S_v) and 'outflow' (-0.2 S_v) estimated for the northern boundary (sections 11 to 16) of the study area. The highest geostrophic velocities (3 to 5 cm/sec) were observed in section 15 at points of water outflow away from the study area (Figure 2, Table 1).

The dynamic structure of the current field was more complicated along the southern boundary of the study area because of interactions with Weddell Sea waters. This area is characterised by a sequence of closed eddies, so frequent changes in the direction of geostrophic currents were observed along transects across the southern boundary. The highest velocities of inflow

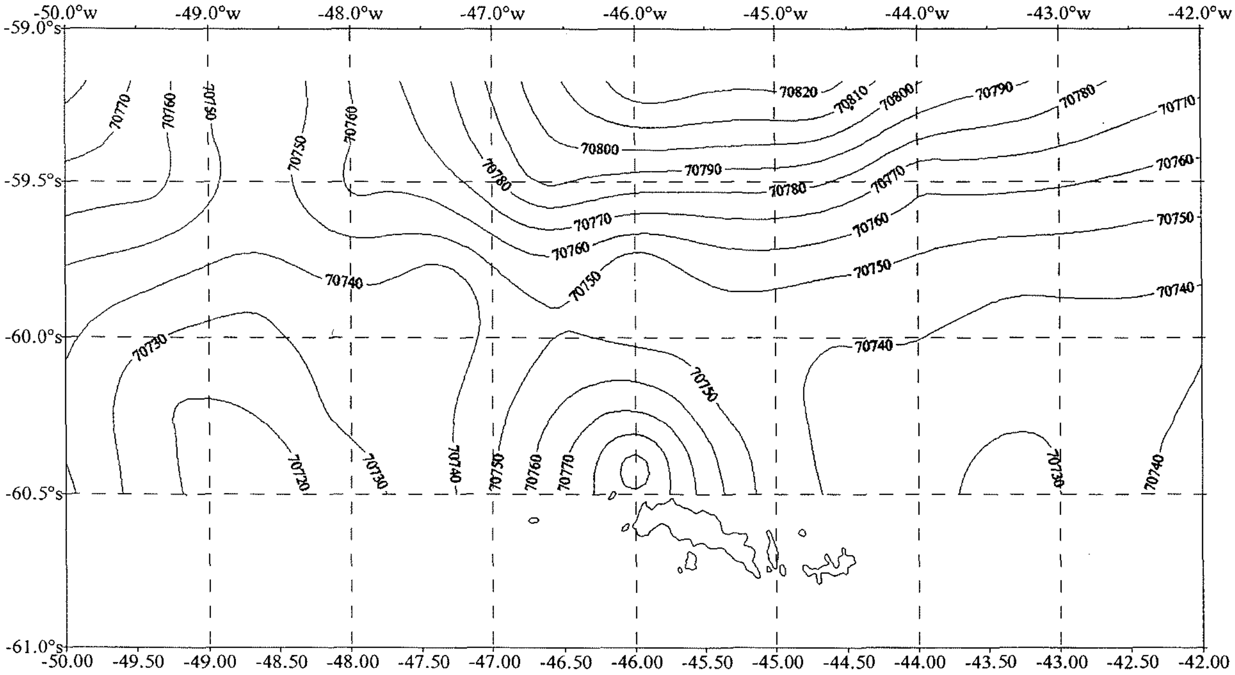

Figure 2: Surface geostrophic circulation with a reference level of 1 000 m in Subarea 48.2 during the survey (17 February to 7 March 1996).

Table 1: Mean water mass transport across the boundary of the study area (sections 1 to 16). Absolute value = 0.098 S_v; CV = 57%. Positive and negative values indicate directions of water transport and krill flux. S_{vi} – over a 40-n mile boundary section; E_i – per n mile; W_i – per n mile.

Section No.	Mean Krill Density, p_i g/m^3	Water Transport		Krill Flux (W_i)		
		Over Section, S_{vi} (S_v)	Per n mile, E_i (m^3/sec x 10^3)	Per n mile, w_i (g/sec x 10^3)	Per n mile, w_i (tonnes/hour)	Over Section (tonnes/hour)
1	0.174	-0.068	-1.70	-0.30	-1.11	-44.40
2	0.304	0.068	1.70	0.52	1.94	77.60
3	0.438	-0.092	-2.30	-1.01	-3.94	-159.20
4	1.070	0.106	2.65	2.84	10.19	407.60
5	4.980	0.141	3.53	17.58	63.5	2540.00
6	0.865	-0.162	-4.05	-3.50	-12.35	-494.00
7	0.290	-0.017	-0.45	-0.13	-0.46	-18.40
8	0.182	0.035	0.88	0.16	0.58	23.20
9	0.204	-0.035	-0.88	-0.18	-0.65	-26.00
10	0.093	0.141	3.53	0.33	1.18	47.20
11	0.103	-0.053	-1.33	-0.13	-0.49	-19.60
12	0.236	0.053	1.33	0.31	1.13	45.20
13	0.535	0.106	2.65	1.42	5.09	203.60
14	0.034	0.106	2.65	0.09	0.32	12.80
15	2.215	-0.211	-5.28	-11.70	-4.10	-164.00
16	0.568	-0.176	-4.40	-2.50	-9.07	-362.80

Table 2: Estimations of the mean density of krill along the boundary of the study area (sections 1 to 16). MSBS – mean surface backscattering strength, TS – target strength of krill.

Section No.	Mean MSBS (dB)	Mean TS (dB)	Mean Krill Density		Mean Krill Weight (mg)
			ind/m^3	g/m^3	
1	-78.70	-71.13	0.180	0.174	964
2	-74.58	-69.41	0.293	0.304	964
3	-75.39	-71.80	0.454	0.438	964
4	-71.42	-71.72	1.081	1.070	990
5	-63.28	-70.25	5.065	4.980	1017
6	-71.19	-70.59	0.855	0.870	1017
7	-76.16	-70.78	0.290	0.290	1005
8	-77.00	-69.58	0.154	0.181	1178
9	-76.09	-69.19	0.173	0.204	1178
10	-81.81	-71.49	0.079	0.093	1175
11	-81.26	-71.39	0.094	0.103	1100
12	-77.24	-70.97	0.215	0.236	1100
13	-74.24	-71.59	0.486	0.535	1100
14	-87.18	-72.49	0.034	0.034	1000
15	-66.66	-70.11	2.215	2.215	1000
16	-72.45	-69.99	0.568	0.568	1000

Table 3: Estimates of krill flux across the boundary of the study area (19 to 23 February 1996).

Krill biomass transported per nautical mile of the boundary of the study area (tonnes/hour):					
Outflow		Inflow		Absolute Value	
Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
4.0	88.5	10.5	207.6	7.2	215.2

Krill biomass transported across the entire boundary of the study area, (tonnes/hour):						Balance of Outflow/Inflow (tonnes/hour)	
Inflow			Outflow				
Mean	Var.	CL	Mean	Var.	CL	Mean	CL
3356.0	18826.0	1246.0	1268.0	6393.0	184.7	2088.0	831.0

CL – 95% confidence limit

(4.0 cm/sec) and outflow (3.0 cm/sec) were estimated for the northern slope of the South Orkneys. Water mass transport was 0.14 S_v in section 5 and -0.16 S_v in section 6 (Figure 2, Table 1).

At the western and eastern (meridional) boundaries of the study area, maximum inflow velocity was 5 cm/sec; this value was estimated for the western boundary in section 10.

The general balance of water mass transport across the study area boundaries was calculated to be -0.05 S_v based on values of 0.77 S_v for 'inflow' and -0.82 S_v for 'outflow'.

The greatest variations in krill density were observed along the southern boundary of the study area (Table 2), where the coefficient of variation for krill density CV(*p*) was 147%. For the northern boundary this value was CV(*p*)= 71%. Highest values of krill density were recorded in sections 4 to 6 at the northern slope of the South Orkneys where geostrophic velocities and water transport values were also highest (see Figure 2, Tables 1 and 2).

There was significant variability of krill flux along the study area boundaries, both in terms of the amount of transported biomass and the direction of the flux (Table 1). The largest quantity of krill entered the study area via sections 5 (2540.0 tonnes/hour) and 4 (407.6 tonnes/hour), while the highest outflow occurred via sections 6 (-494.0 tonnes/hour) and 16 (-362.8 tonnes/hour).

Summary data of krill biomass transported across boundaries of the study area are given in Table 3. The total krill biomass transported by water masses into the study area across its boundaries exceeded the biomass flowing out. The inflow–outflow balance in the study area was: mean = 2 088 tonnes/hour at CL 95% = 831.0 tonnes/hour.

It is well known that krill flux can be caused not only by geostrophic factors but also by wind drift. During the study period (19 to 23 February) the atmospheric field was uniform and prevailing northwesterly winds were observed with an average bearing of 300° (CV = 17%). Mean wind speed was 10 m/sec. Calculations of Ekman's parameters showed that the wind-induced current had a depth of 72 m and a surface current velocity of 12 cm/sec. According to the theory of Ekman transport and given the abovementioned wind direction, the entire flow of the wind-induced current in the depth range from 0 to 72 m would have been travelling in a northeasterly direction. Mean water turnover in the study area due to Ekman transport was 0.0036 S_v/mile.

DISCUSSION AND CONCLUSIONS

In accordance with current knowledge of factors governing krill flux in Subarea 48.2, transport of krill over the subarea is carried out by ACC waters originating from the Antarctic Peninsula area, as well as by waters of the northern periphery of the Weddell Gyre. Krill flux also takes place in the area of interaction between these two major currents (Gordon, 1967; Maslennikov, 1980; Sushin et al., 1985; Everson and de la Mare, 1996).

If the overall pattern of water circulation in Subarea 48.2 is taken into account, it is evident that krill flux in the study area is generally influenced by the ACC, which was clearly observed as a meandering current flowing from the west to the east in the northern half of the study area. Krill was mainly brought into the study area from the west across sections 10, 12 and 13 and was taken out to the northeast across sections 15 and 16. Based on estimations of krill density and water transport obtained during the experiment, an annual outflow of krill into adjacent areas via sections 15 and 16 would amount to approximately 9.2 million tonnes (based on data in Table 1).

Estimated geostrophic current velocities in the study area are commensurate with the mean values of mean surface geostrophic current velocity in Subarea 48.2 based on data obtained over a number of years (Naganobu, 1993).

The southern section of the study area was located outside the stationary current field in a dynamically active area formed by the doubling anticyclonic current flowing around the South Orkney Islands. This section overlapped a number of local anticyclonic eddies in which krill were retained and accumulated. Indeed, the maximum krill biomass was observed in the area occupied by one such eddy to the northwest of Coronation Island (Table 2). Results of studies carried out by AtlantNIRO Research Institute (Kaliningrad, Russia) during the period from 1981 to 1990 indicate the presence of a quasi-stationary, well-defined anticyclonic doubling current around Coronation Island which is located in an area of stable convergence. Unfortunately, the location of the southern section of the study area did not allow us to assess the role of Weddell Sea waters in overall krill flux. In future research the southern boundary of the study area should be located as far to the south of the South Orkney Islands as possible. The eastern boundary probably also ought to be situated further away from the islands in order to avoid bias in estimates.

Krill flux through the study area was influenced by wind drifts. The wind drift current was travelling in a northeasterly direction, which coincided with the direction of the geostrophic transport of the main krill mass. Mean water turnover brought about by the wind drift current was commensurate with the values for geostrophic turnover. The extent of the wind drift current (0–72 m depth range), however, did not encompass the entire depth range of krill distribution, therefore not all of the krill present were drawn into the wind drift. The wind drift would usually be responsible for the transport of krill in the aerated near-surface layer.

When assessing the results of these types of experiments, one should point out that any estimates obtained on krill flux through the study area are minimum values, since the actual volume of krill biomass transported into neighbouring areas may be much greater if a strong wind drift is present.

In our research krill was considered to be a passive object, at least in respect of horizontal transport, which is supported by a number of works which cite the virtual coincidence of krill transport velocity and current velocity in the relevant study area (Everson and Murphy, 1987; Kasatkina et al., 1993). Krill flux, however, is not necessarily an entirely passive phenomenon caused by water currents, and there are data on active krill migration (Kanda et al., 1982). Knowledge of the ability of krill to undertake prolonged active migration is a prerequisite for including this variable into assessments of overall krill transport.

The hydroacoustic integration range did not cover the near-surface layer of 0 to 10 m. The extent of this layer depends on the vessel's draught and aeration of surface waters. Krill in this layer is not recorded, which leads to the underestimation of krill density.

Therefore, assessments of water turnover and krill density are made over various depth ranges; this is especially important when working in the hours of darkness due to the fact that krill undertake active vertical migrations in the near-surface layer. Consequently, the problem of acoustic under-estimations of krill biomass in the near-surface layer is a very important consideration in examining krill flux factors such as geostrophic and wind-induced currents.

In our opinion, further studies should primarily focus on improving research methods. The interannual (seasonal) variability of krill flux should be studied with as many observations being made as possible. These observations should be accompanied by studies of the temporal and spatial variability in the retention of krill aggregations within a particular study area.

The most important current formations which lead to the long-term retention of krill aggregations are either eddies of diverse direction and scale or closed circulation systems around islands. These formations, in our view, keep a significant proportion of krill biomass out of circulation from the general flux of krill in the AAS waters of the Southern Ocean. The double anticyclonic current flowing around the Southern Orkneys represents one such circulation structure in Subarea 48.2 (Fedoulov and Shnar, 1990). Numerous closed and semi-closed microscale eddies in the South Shetlands area, discovered by Japanese scientists conducting experiments with drifting buoys (Ichii and Naganobu, 1996), may be regarded as examples of these structures.

ACKNOWLEDGEMENTS

We would like to thank AtlantNIRO oceanologists A.V. Remeslo, K.E. Shulgovsky and V.V. Devitsin for their assistance.

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