Not to be cited without prior reference to the author

ICES CM 2010/A:13

Investigation of krill transport factors in the Scotia Sea for the fisheries and management application.

Kasatkina Svetlana and Vladimir Shnar

Data from acoustic surveys and oceanographic observations were used to estimate characteristics of krill transport across different polygons in the Scotia Sea. Krill flux over the study polygons was considered as a passive transport by water masses and assessed by the geostrophic transport. Estimates of water velocity, krill biomass transported across boundary (outflow and inflow) of these polygons were investigated. Variability of the spatial-temporal distributions of krill biomass and aggregations characteristics associated with multiple processes of krill inflow-outflow over the study areas were traced. It was revealed that krill transport across fishing grounds has affected operational indices of commercial vessels (mean catch per haul, mean catch per hour). The authors discuss the characteristics of krill transport as the important information for krill stock management in the Scotia Sea.

Key words: Antarctic krill flux, acoustic and oceanographic observations, geostrophic transport, fisheries

Contact author: *Svetlana Kasatkina: Atlantic Research Institute of Marine Fisheries and Oceanography (AtlantNIRO), 5, Dm. Donskoy Sr., Kaliningrad, 236022, Russia, fax: +7 4012 219997, e-mail: ks@atlant,baltnet.ru*

INTRODUCTION

The vital activity of marine hydrobionts, primarily plankton, is related to the oceanographic structure and variability of the water masses. The water masses structure and dynamics, the transport by the water flow determine the basic regularities of plankton spatial distribution. The numeric assessment of marine biomasses transport may be fulfilled on the basis of the complex analysis of acoustic and oceanographic observations obtained in the acoustic surveys process (Kasatkina et al, 1997, 2007).

In this study the results of investigation of the transport of the Antarctic plankton representative – kril *(Euphausia superba)* , being the key element of the Antarctic ecosystem and traditional and important commercial species in the Southern Ocean, is considered.

The geostrophic transport of krill along the "Scotian arch" is the integral part of krill distribution formation in the Scotia Sea, where the traditional areas of krill fishery are located (Trathan et al, 1998; Murphy et al, 2004). At present the quantitative understanding krill flux dynamic and its effect upon the krill distribution patterns in the Scotia Sea is the important information for krill stocks management in the context of the spatially resolved management of krill harvesting in Area 48 developing by SC-CCAMLR (the Scientific Committee for the Conservation of Antarctic Marine Living Resources) based on subdividing the allowable catch limit for krill among 15 small-scale management units (SSMU). These SSMU were established in Area 48 to preclude the inadvertent concentration of catches in a small portion in a certain area (Hewitt et al, 2004a).

The authors present the results of assessment of krill transport characteristics in the Scotia Sea, paying special attention to the polygons located in the South Georgia area, the South Orkneys and the Antarctic Peninsular, which cover the traditional fishing grounds with the highest catches during the latest three decades. The presented estimates of geostrophic circulation of the water masses and respective estimates of krill biomass inflow and outflow through the boundaries the specified polygons were obtained on the basis of the long-term researches made by AtlantNIRO in the Scotia Sea.

MATERIAL AND METHODS

For estimating krill flux between subareas in the Scotia Sea we have used the information (acoustic and CTD samples) based on the data of the international krill survey CCAMLR 2000, which covered the Scotia Sea ((Hewitt et al, 2004b, Kasatkina et al, 2007).

Changes in krill distribution in the fishing grounds associated with krill flux were analyzed using data from the Russian surveys data obtained in 1990-2002 in the South Georgia and the South Orkneys areas (Kasatkina et al, 1997, Kasatkina and Shnar, 2007). The repeated acoustic surveys fulfilled in the study areas were used as the methodical basis of the experiments, which allowed considering krill transport dynamics in relation to variability of krill distribution on the one hand, and variability of the fishing indices provided by commercial vessels, on the other hand. These multiple acoustic surveys accompanied with trawl and CTD samples were conducted under condition of the total replacement of the water masses in each study area by the next survey start.

To assess the geostrophic circulation in the study areas, the data of 3012 hydrological stations (temperature and salinity) fulfilled in AtlantNIRO cruises during 1962-2002 were used.

Currents velocity were estimated on the basis of the following data :

- Antarctic Peninsular (Subarea 48.1) - 655 stations;
- South Orkneys (Subarea 48.2) – 464 stations;
- South Georgia (Subarea 48.3) – 1893 stations.

Statistical characteristics of currents velocity were estimated by bootstrap procedures (Efron B., Tibshirani R.J. 1993).

Krill transport through the study area boundary was considered as a passive transport with the water flow assessed as the geostrophic transport (Kasatkina et al, 1997):

$$W_i = E_i \cdot \rho_i \qquad (1)$$

where

- W_i - krill biomass, transported per second through the *i*-th section of the polygon boundary of 1 n.mile in length in the layer 10-200 m;
- $\cdot\ \rho_i$ - density of krill biomass (g/m^3) , transported per second through the *i*-th section of the polygon boundary of 1 n.mile in length in the layer 10-200 m
- E_i – water flow in Sv (m^3/sec), i.e. the water volume transported per second through the polygon boundary section of 1 n.mile in length in the layer 10-200 m.

The lower boundary of the above said depths range (10-200m), was selected as the lower boundary of the layer within which above 95% of all krill biomass in the Scotia Sea were distributing (Demer, 2004), while the upper boundary (10m) corresponded to the upper boundary of the integration range, determined by the vessel draught and the near-surface noise level.

Besides, in this work catch statistics in the form of haul by haul data (i.e. coordinates at trawling start, time of trawling start, trawling duration, vessel speed during trawling, catch per trawling) has been used, obtained from the trawls fishing in the experimental investigation area. Standardization of the fishing effort data obtained from vessels of different types was carried out in reference to the trawl system with the largest proportion in the total catch (Kasatkina and Ivanova, 2003).

RESULTS AND MATERIAL

Geostrophic krill transport between subareas in the Scotia Sea

The analysis of geostrophic circulation in the Scotia Sea revealed the expected prevalence of the water masses transport from the west to the east associated with the Antarctic Circumpolar Current (Fig.1), which corresponded to the available knowledge about the ways of krill drift, when krill transported from the western Antarctic Peninsular became the source of krill in the South Georgia area (Hofman et al, 1998; Murphy et al, 2004). As is seen from Fig. 1, we have considered three study areas: SSMUs (2)-(7) in Antarctic Peninsular Subarea (48.1) ; SSMUs (10)-(12) in Subarea 48.2; SSMUs (14)-(15) in Subarea 48.3. These SSMUs are the area of traditional krill fishery.

The location of stations in these Subareas 48.1-48.3 is shown in Fig. 2. The surface geostrophic current velocity in the prevailing direction within each of the study areas varied from 5 to58 cm/s (Fig.3). Note that in Subdivision 48.3 krill transport velocity was estimated in the west and east parts separately in view of different origin of krill transported to the South Georgia area by different water masses, i.e. by the Weddell Sea water mass - to the eastern part of the South Georgia area and by the Antarctic Circumpolar Current water mass – to the western part of the South Georgia area (see for example Sushin and Shulgovski, 1999), as well as because of the available knowledge on a weak transport from the east to the west. The results of statistic characteristics estimation (mean, standard error, coefficient of variance, 90% and 95% confidential intervals) are presented in Table 1. The respective frequency functions of mean velocities distribution and *q-q* diagrams are shown in Fig.4a, 4b, 4c, 4d.

The geostrophic circulation of the water masses between subareas in the Scotia Sea were assessed on the basis of CCAMLR 2000 data. The krill transport velocity was estimated by us as the geostrophic drift without taking in account the Surface Ekman drift. This is assumed in view of incomparability of geostrophic and wind-induced currents, e.g. according to Hoffman et al (1998) the mean wind-induced current velocity along the Antarctic Peninsular coast varied from 0.2 to 0.3 cm/s as compared to 8.8 - 20cm/s for geostrophic currents. According to our survey carried out in Subarea 48.2 , the geostrophic water transport across the study area was 0.77Sv for “inflow” and -0.82 Sv for “outflow” and Ekman transport was 0.00036 Sv (Kasatkina et al, 1997). In Table 2, 3 the estimates of potential krill flux across the boundaries of Subareas and fishing grounds are presented.

The estimations fulfilled indicated that within the traditional fishing areas and SSMU the multiple total exchanges of the water masses is possible for the fishing season (Kasatkina et al, 2007). These processes of the water masses exchange will be accompanied by krill inflow-outflow through the boundaries of these areas. For example, during the fishing season the potential transport of krill biomass may constitute 1.283 mln.t. in the Elefant's Island area (the 7th SSMU) and 2.109 mln.t. for fishing grounds in the South Orkneys area (11th and 12th SSMUs) (Fig.1). . These estimates of krill transport exceed krill biomass and maximum catch within any SSMU in the Scotia Sea (Hewitt, et al, 2004b). The fishing season included the following periods: November-March in Subarea 48.1; November-April in Subarea 48.2; April-September in the eastern South Georgia and June-September in the western South Georgia.

The total outflow of krill biomass through the boundaries of the above mentioned 3 SSMUs (7th, 11th, 12th) may constitute 3.392 mln.t (Table 3), which is comparable to the krill allowable catch 3.47 mln.t, adopted for Subareas 48.1-48.4 in 2007-2009 (SC-CCAMLR-XXVII Annex 3).

Estimates of krill transport obtained for the fishing season appeared comparable neither with the historical annual catch from each SSMU, nor with the annual catch from the Scotia Sea for the latest 3 decades. Note that the highest annual krill catches were recorded in 1987-1990, when its removal attained 400 thous.t per year.

Discussing krill transport estimates it is necessary to take into account the fact, that we considered neither seasonal nor inter-annual variability of krill transport dynamics. At the same time it is reasonable to expect that their effect will be significant. This is evidence by the results of the survey 1996, when krill flux across 80-mile boundary of the study area in the South Orkneys could provide outflux of 8, 46 mln.t of krill during the fishing season (Kasatkina et al, 1997). This estimate exceeds by 2.6 times the precautionary yield value in the Scotia Sea.

Changes in krill distribution in the fishing grounds associated with krill flux

Investigations of the temporal variability of krill transport characteristics based on multiple acoustic surveys in the local areas of the Scotia Sea, indicated that krill transport is of a pulsatory pattern, i.e. krill influx-outflux occurred by uneven portions (Kasatkina and Shnar, 2007, 2008). The results of these researches are discussed by the example of krill transport assessment during 1 week through the local polygon in the Southern Georgia area (Fig. 5).

The location and orientation of the polygon for experimental works were selected taking in account the scheme of geostrophic circulation of water masses and the following basic requirements: the lack of sharp heterogeneity of the current field and fishing grounds in the polygon; location of the fishing grounds «downstream» in reference to the polygon. The study polygon was selected as a part of the reconnaissance polygon (using the survey results (Fig.5).

The study polygon was characterized with the uniform water dynamics regime. The geostrophic circulation was actually similar in the beginning and end of the observation period; the water flow was of the stable north-western direction with the mean velocity of 49cm/s and 43cm/s respectively in the layer 0-100m.

During the observation period 8 acoustic surveys (4 in the day-time and 4 at night) were carried out, which indicated considerable changes of krill biomass spatial distribution in the polygon after each water mass replacement (Fig.6,7). The latter can be illustrated with the five-fold change of the krill biomass density in the period between 2 consecutive surveys with CV=57% for the observation period (Fig.8).

The pulsatory pattern of krill biomass variability in the polygon, observed against the background of the multiple replacements of water masses is also traced in the dynamics of krill aggregations characteristics forming this biomass. In general, krill aggregations in the depths layer of 10-200m were formed from small swarms. However, while the swarm parameters varied insignificantly from survey to survey, the number of swarms per m.mile^2 varied considerably (Table 4). The variation coefficient of the mean number of swarms per m.mile^2 amounted to 62.8%. Evidently, that such dynamics of the parameter «number of swarms per m.mile^2» could not be stipulated by the aggregation structure variability (primarily by swarms disintegration) in the polygon, and was related to transport of new krill portions from outside and krill transport across the polygon by the current.

The lack of sharp heterogeneity in the current field resulted in the steady krill transport with the main current to the north-west and subsequent krill occurrence in the fishing grounds located downstream at the distance passed by the water flow during 5-6 hours (Fig.5). In the fishing grounds 17 commercial vessels were operating and the catch statistics from these vessels in the form of haul by haul data was used in this work. Standardization of the fishing effort, obtained by this group of different vessels, was made in relation to the trawlers with the main engine power of 3000-3100 h.p. with the highest proportion in the total catch. The variation coefficient of the mean daily standardized catch per hour trawling was CV=29.3% for the considered period.

Our observations revealed that krill transport dynamics is of a pulsatory pattern, i.e. krill transport outside-inside the experimental polygon occurs by non-uniform portions. Here not only the pulsatory pattern of the biomass value (in our case, $CV_{biomass}$=57%) is important, but also the observed differences in krill aggregation patterns forming the transported biomass (in our case, $CV_{swarms/mile^2}$ =63%). It is reasonable to note that the commercial importance of krill biomass is determined by its density, as well as by the distribution patterns of krill aggregations forming this biomass (Kasatkina and Ivanova, 2003). Therefore, it is possible to expect that due to the transport processes, krill biomass portions with different commercial importance were entered into the areas of fishing fleet operation. As is seen from Fig.9, the pattern of CPUE variability corresponded to the dynamics of krill biomass density and distribution of krill, transported to the fishing grounds from the polygon (Fig. 5). The observed dynamics of CPUE allows speaking about the impact of krill transport on the fishing conditions formation in the fishing fleet operation areas.

Consequently,

The important factor of uncertainty in quantitative understanding krill spatial - temporal distribution in the Scotia Sea is dynamics of krill spatial patterns under the impact of the geostrophic transport.

For developing krill fishery management there is needs for characterizing the krill transport factors in relation to variability of the spatial patterns of krill biomass in various areas of the Scotia Sea.

REFERENCE

Demer D.A., 2004. An estimate of error for the CCAMLR 2000 Survey estimate of krill biomass. Deep-Sea Research. Part II. Volume 51, Number 12-13:1237-1252.

Hewitt R., Watters G., Trathan P., Croxall J., Goebel M., Ramm D., Reid K., Trivelpice W. and J.Watkins. 2004a. Options for allocating the precautionary catch limit of krill among small-scale management units in the Scotia Sea. CCAMLR Science, vol. 11 :81-98.

Hewitt R. et al. 2004 b. Biomass of Antarctic krill in the Scotia Sea in January/February 2000 and its use in revising an estimate of precautionary yield. Deep-Sea Research II 51 (2004) 1215–1236

Hofmann E., Klinck J., Locarnini R., Fach B and E. Murphy, 1998. Krill transport in the Scotia Sea and environs. Antarctic Science 10 (4): 406-415.

Efron B., Tibshirani R.J. 1993. An introduction to the bootstrap. *Chapman & Hall*. New York. 436 p

Kasatkina S.M., V.N. Shnar, M.I. Polishuk, V.M. Abramov and V.A. Sushin.1997. Assessment of krill Flux Factors in Waters of the South Orkney Islands During Summer 1996 . CCAMLR *Science* , v.4: 194-204.

Kasatkina S.M. and Ivanova V.F. 2003. Fishing intensity of Russian fleet in krill fishery in Subareas 48.2 and 48.3 . CCAMLR *Science*, vol.10: 15-36.

Kasatkina S.M., Shnar V.N. and Berezhinsky O.V., 2007. Estimating of krill transport by current as an important factor to manage its stock in the Scotia Sea. In: Fisheries and biological research by AtlantNIRO in 2004-2005, Kaliningrad, Russia, vol.1: 39-45.

Kasatkina S.M. and V.N. Shnar, 2008. Properties of krill distribution in pelagic and coastal SSMUS of the South Orkney Islands Subarea according to the data of scientific observations and fishery. Document of WG-EMM -08/55, Hobart, Australia.

Mupphy E., Thope S., Watkins J. and R. Hewitt.2004. Modeling krill transport pathways in the Scotia Sea: spatial and environmental connections generating the seasonal distribution of krill. Deep-Sea Research II, vol.51, Nos.12-13: 1435-1456.

Sushin V. and K. Shulgovsky, 1999. Krill distribution in the western Atlantic sector of the Southern Ocean during 1983/84; 1984/85 and 1987/88 based on the results of Soviet mesoscale surveys conducted using an Assaks-Kidd midwater trawl. CCAMLR, *Science* Vol.6 :59-70.

Trathan P.N., Everson I., Murphy E.J. and G.B. Parkes, 1998. Analysis of haul data from the South Georgia krill fishery. CCAMLR *Science*, vol.5:9-30.

Table 1. Statistic characteristics of current velocities estimated with the bootstrap method

Parameter	Southwestern part of South Georgia	Southeastern part of south Georgia	South Orkneys subdivision	Antarctic peninsular subdivision
Mean	21.90	21.77	20.93	19.60
Bias	0.00161	-0.00101	0.01639	0.04651
Standard deviation	0.855	1.059	1.201	1.378
Coefficient of variance (CV)	0.0390	0.0486	0.0574	0.0703
Confidential interval (90%)	20.52 – 23.34	20.05 – 23.56	18.94 – 22.87	17.35 – 21.88
Confidential interval (95%)	20.20 – 23.61	19.67 – 23.90	18.62 – 23.31	16.93 – 22.41

Table 3. Statistical characteristics of mean krill flux across the boundary of the study areas

Parameters	Elepfant Island SSMU (APEI)	South Orkney North East (SONE) and South Orkney South East (SOSE)
Krill biomass transported from the study area across 1 nautical mile of its boundary, (tones/hour per mile) Mean Standard deviation	 2,97 0.776	 5,43 2.17
Krill biomass transported from the study area across the entire boundary of the study area during fishing season, mln. tonn Mean Standard deviation	 1,283 0.336	 2,109 0.844

Table 2. The drift time intervals were determined when geostrophic transport of krill by water mass through the study areas might occur

Parameters	Antarctic Peninsular Subarea			South Orkney Islands Subarea			SGW SSMU	SGE SSMU
	total area of (2)-(7) SSMUs	APW SSMU	APE SSMU (	total area of (10)-(12) SSMUs	SOW SSMU	SONE SSMU SOSE SSMU		
Displacement, km	**855,0**	**318.0**	**190.0**	**574**	**241.0**	**335.0**	**268,0**	**446,0**
Drift time, days Mean Lower 95% CI Upper 95% CI	 **50,7** **44,2** **58,5**	 **19.0** **16.5** **22.0**	 **11.0** **9.8** **13.0**	 **31,8** **28,5** **35,7**	 **13.3** **12.0** **15.0**	 **18.5** **20.8** **16.6**	 **11,2** **10,3** **12,0**	 **18,6** **16,6** **20,1**
Number of water replacements during fishing season Mean Lower 95% CI Upper 95% CI	 **3** **2,6** **3,4**	 **8.0** **7.0** **9.0**	 **13.0** **12.0** **15.0**	 **6** **5,0-** **6,3**	 **13.5** **12.0** **15.0**	 **10.0** **9.0** **11.0**	 **8,0** **7,5** **8,4**	 **10,0** **9,0-** **11,0**

Table 4. Characteristics of krill swarms within the study area over the span of acoustic surveys, the South Georgia area (Fig.5).

Number surveys	Characteristics of krill swarms			
	Length		Swarm number/mile^2	
	mean, m	CV,%	mean	CV,%
1n	17.6	13	68.7	35,5
2d	19.6	10.5	10.1	15.8
3n	18.8	15.3	28.5	25.6
4d	17.4	16.8	40.0	29.3
5n	23.0	23.3	52.4	22.3
6d	20.0	19.7	147.9	53.2
7n	18.6	20.3	70.6	49.2
8d	18.8	19.3	79.2	19.8

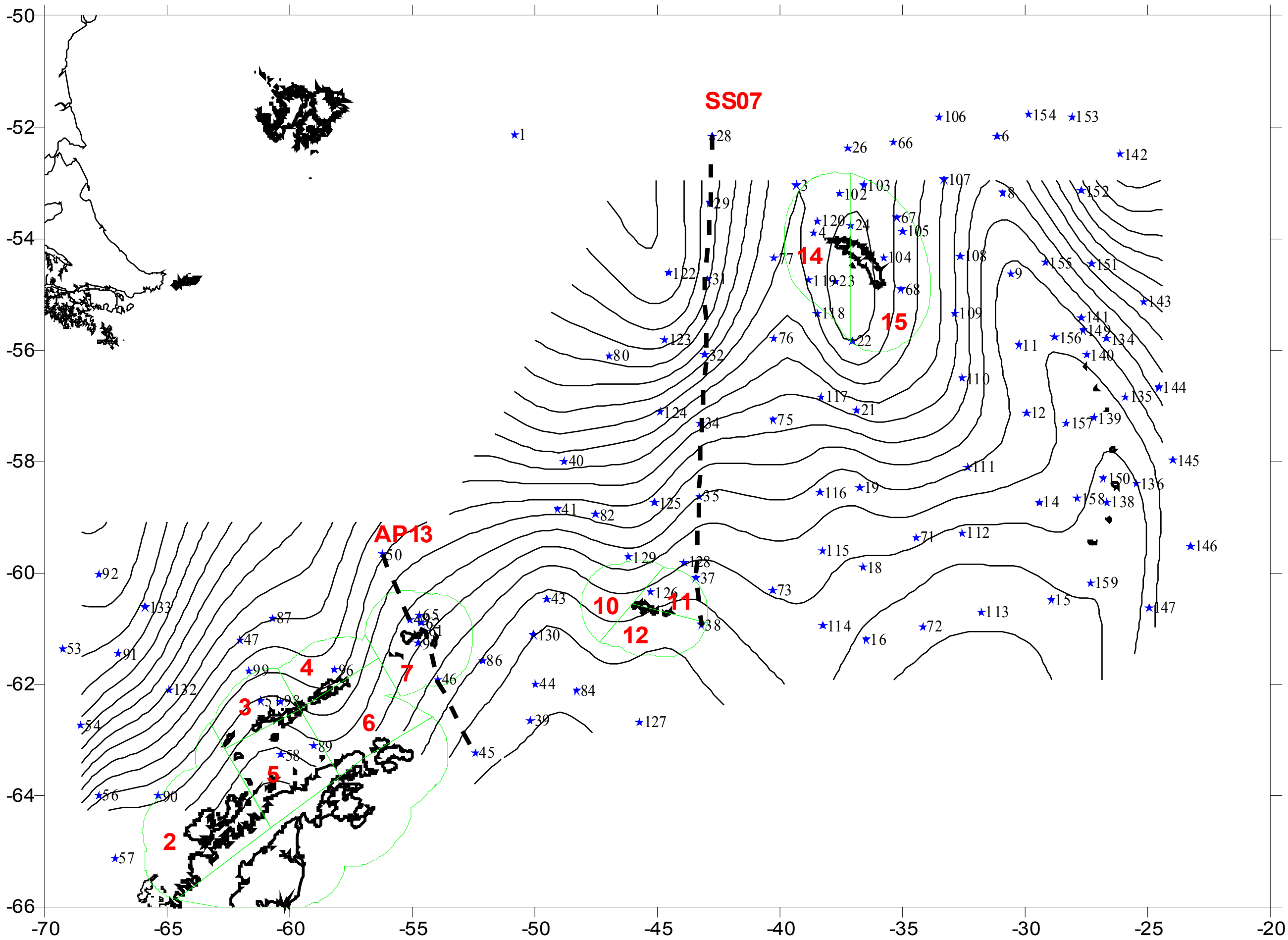

Fig. 1. Location of SSMUs, acoustic transects and CTD stations of the CCAMLR-2000 Survey.

(2) Antarctic Peninsula West (APW);
(3) Drake Passage West (APDPW);
(4) Drake Passage East (APDPE);
(5) Bransfi eld Strait West (APBSW);
(6) Bransfi eld Strait East (APBSE);
(7) Elephant Island (APEI);
(10) South Orkney West (SOW);
(11) South Orkney North East (SONE);
(12) South Orkney South East (SOSE);
(13) South Georgia Pelagic Area (SGPA);
(14) South Georgia West (SGW);
(15) South Georgia East (SGE).

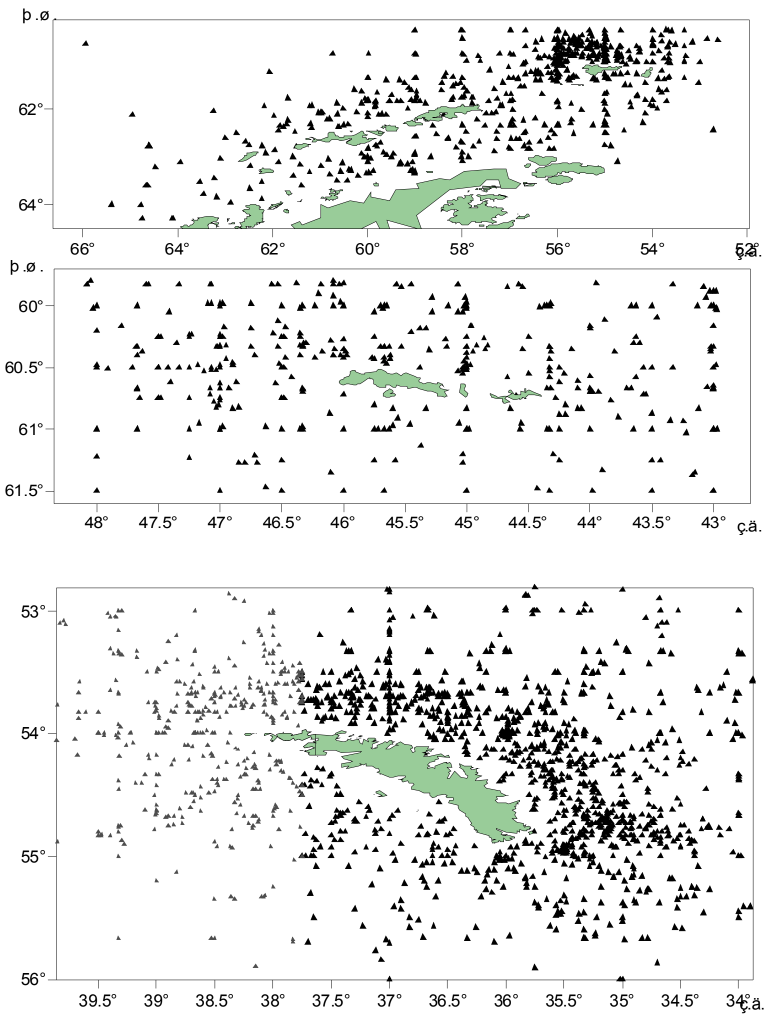

Figure 2. Location of CTD Station within the study areas.

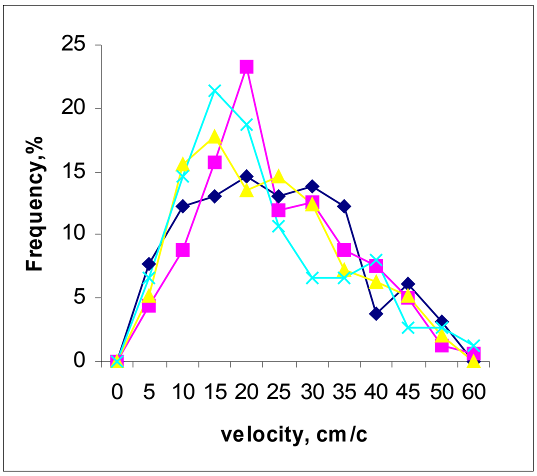

Figure 3. Frequency distributions of geostrophic velocity obtained from Russian Surveys carried out in Scotia Sea during 1962-2002.

Alice Blue – Antarctic Peninsula Subarea
Blue – Eastern part of South Georgia area
Red – Western part of South Georgia area
Buffy - South Orkney Island area

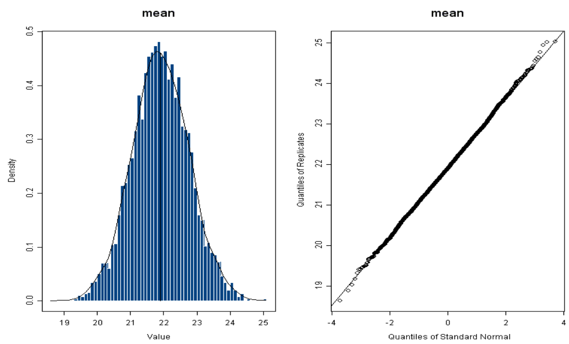

Fig.4a. Histograms and *q-q* diagram of mean current velocity in the western part of South Georgia

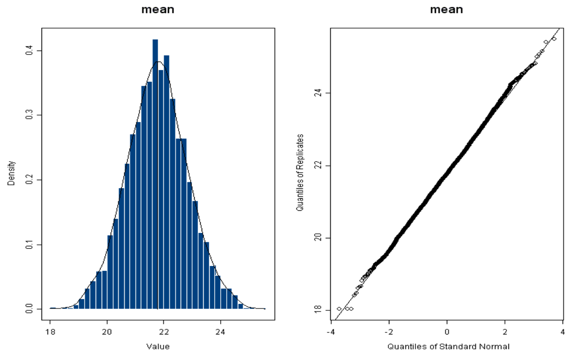

Fig.4b. Histograms and *q-q* diagrams of mean current velocity in the eastern part of South Georgia

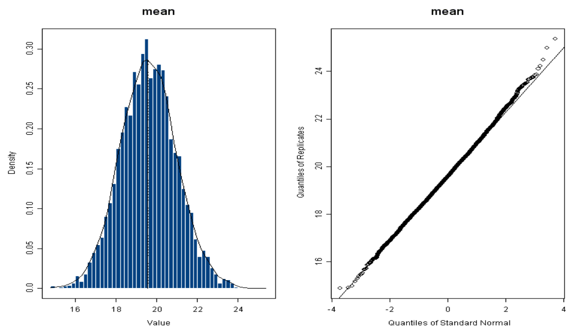

Fig.4c. Histograms and *q-q* diagram of mean current velocity in the Antarctic Peninsular area

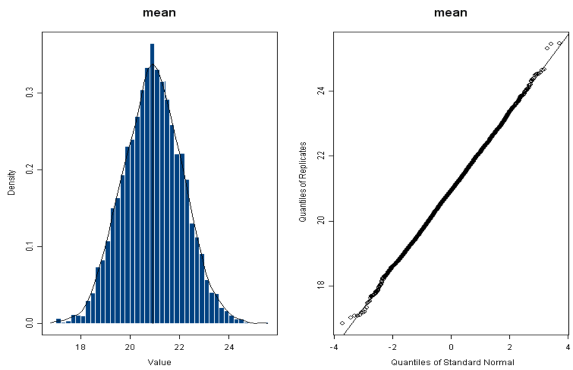

Fig.4d. Histograms and *q-q* diagram of mean current velocity in the South Orkney Islands area

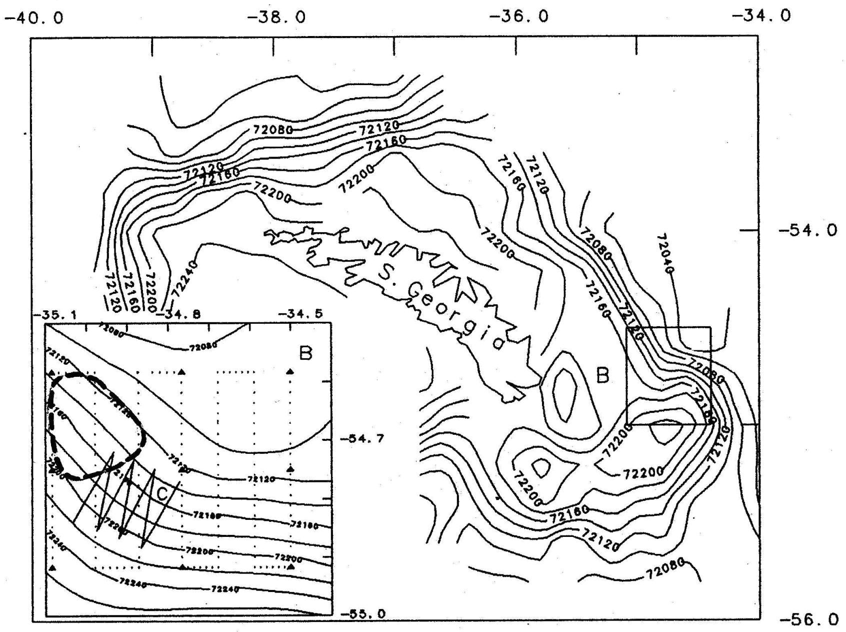

Fig5. Location of the study area and fishing grounds in the South Georgia Subarea in 1991 season.

B -recognition area

C- study area

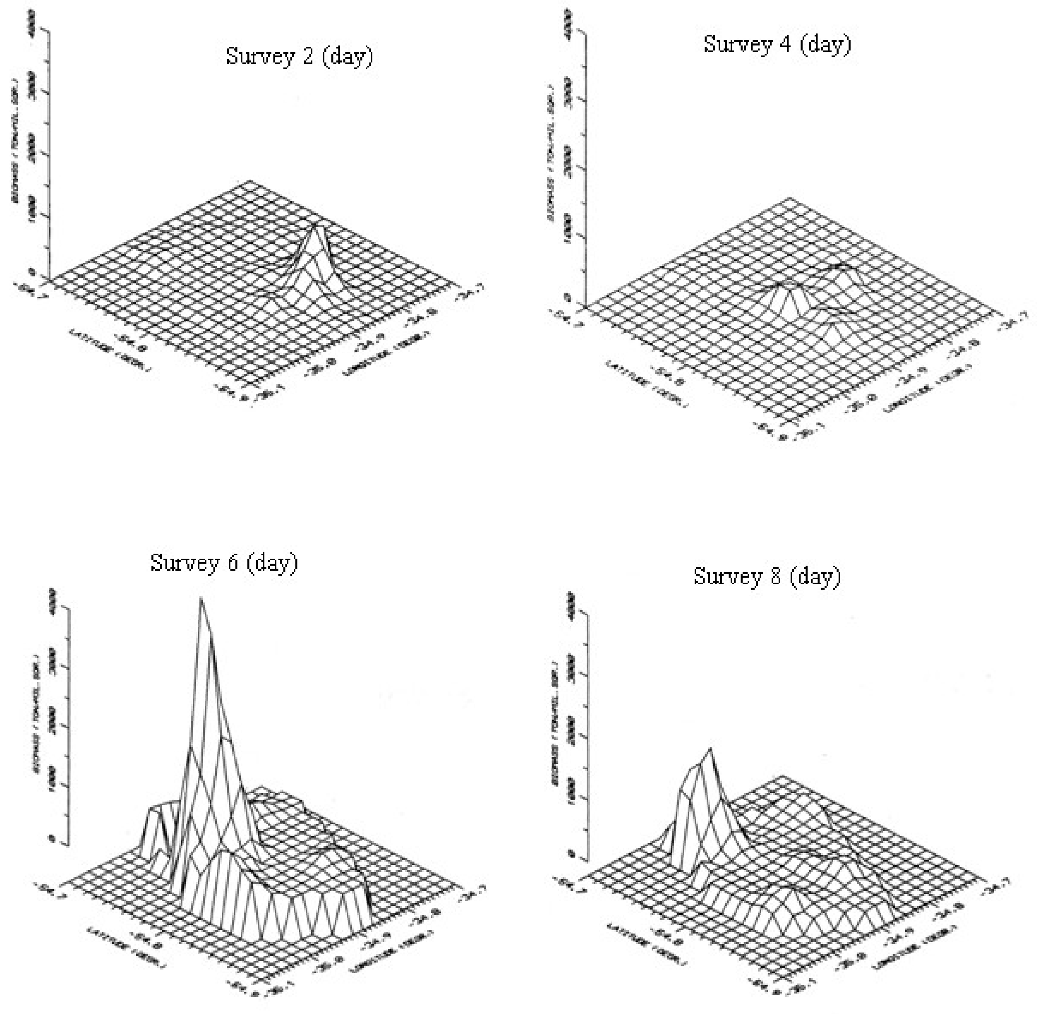

Figure .6 Variability of krill density distribution within the local study area in Subarea 48.3 from the span of daytime acoustic survey carried out after water mass replacements on the study (fig.5).

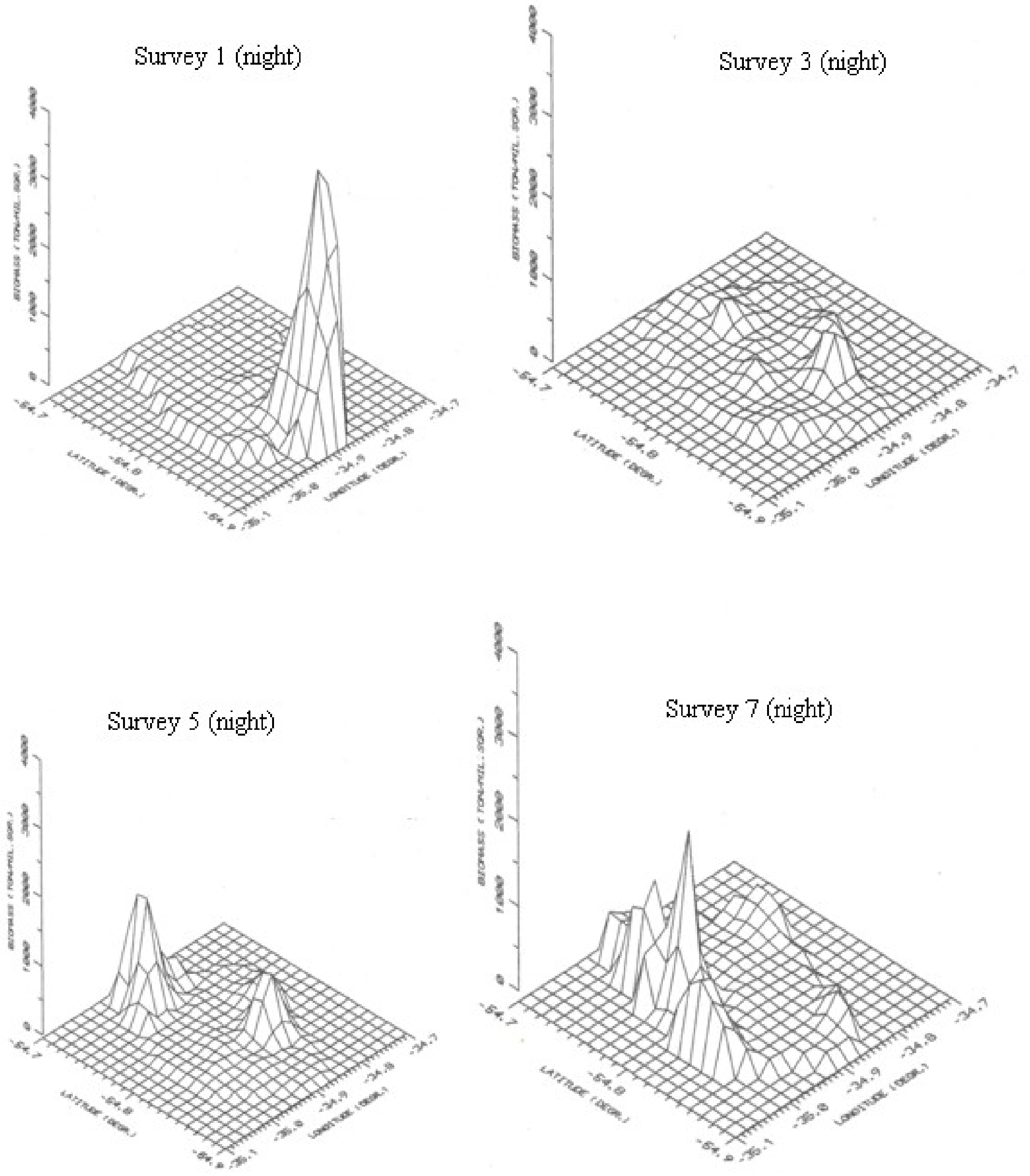

Fig. 7. Variability of krill density distribution on the local study area in the Subarea 48.3 (fig.5). Krill distribution patterns are based on the span of nighttime acoustic surveys carried out on the study area after water mass replacement.

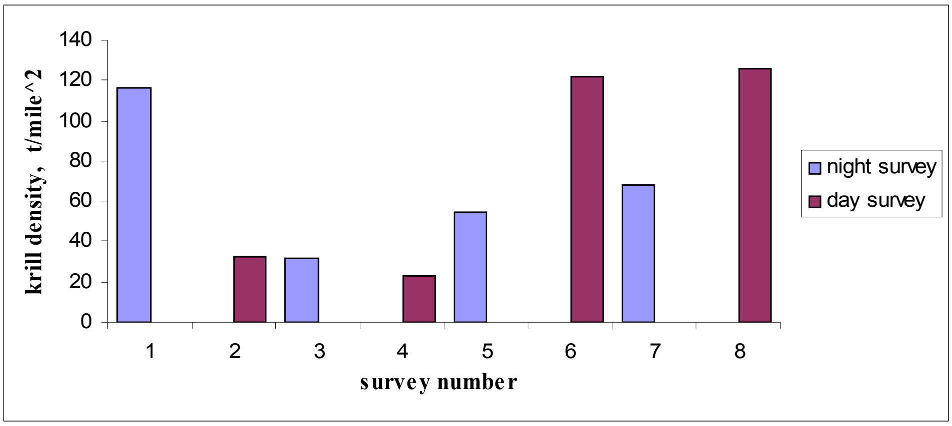

Fig.8. Variability of krill mean density within the study area from the span of acoustic surveys (local area in the 48.3 Subarea, fig.5).

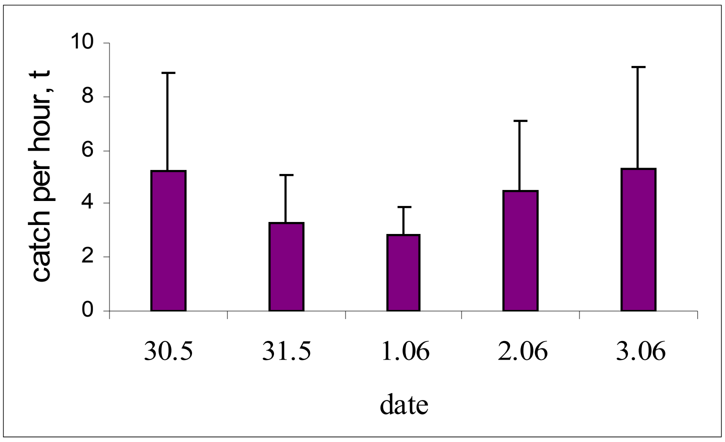

Fig.9. Changes of the fishery effort on the fishing ground in the Subarea 48.3. The fishing ground was located close to the study area downward the flow (Fig.5).