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Advances in Polar Science
doi: 10.3724/SP.J.1085.2012.00217
December 2012 Vol. 23 No. 4: 217-224

Influence of sea ice and sea surface temperature on the abundance of Antarctic krill in Area 48.2

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Received 22 October 2012; accepted 6 December 2012

Abstract In this paper we examine the relationship between Antarctic krill catch, sea ice concentration, and sea surface temperature (SST). Data on the Antarctic krill catch from 2003 to 2010 in CCAMLR Area 48.2 were combined with sea ice and SST data. Results showed that krill fishing in Area 48.2 took place from February to August each year but the catch was concentrated from March to July, with production during this period accounting for about 99.3% of the annual catch. Regression analysis showed that the catch per unit effort (*CPUE*) was clearly related to sea ice concentration and SST intervals. *CPUE* was negatively correlated with the area of sea ice among years (R^2=0.64), and the correlation was strongest (R^2=0.71) when sea ice concentration was greater than 90%. Over the months the *CPUE* initially increased, then decreased as the area of sea ice increased. The relationship was strongest (R^2=0.88) when the concentration of sea ice was 60%—70%. There was no negative correlation among years between *CPUE* and the ice-free area when SST was between -2℃ and 3℃ (R^2=0.21), but there was a significant negative correlation when SST was between 1℃ and 2℃ (R^2=0.82). Over the months, *CPUE* initially increased then decreased with increasing sea ice-free area, and the relationship was strongest (R^2=0.94) when SST was between 0℃ and 1℃. This study shows that sea ice concentration and SST have significant effects on the abundance of krill in Area 48.2, and the findings have practical significance for the use and conservation of Antarctic krill resources.

Keywords **sea ice, SST, Antarctic krill, *CPUE*, abundance, Area 48.2**

Citation: Dai L F, Zhang S M, Fan W. Influence of sea ice and sea surface temperature on the abundance of Antarctic krill in Area 48.2. Adv Polar Sci, 2012, 23:217-224, doi: 10.3724/SP.J.1085.2012.00217

0 Introduction

Antarctic krill, Euphausia superba, has an important role in the marine ecosystem of the Southern Ocean, and is currently the planet's largest single biological resource[1-4]. Since the 1960s, a number of countries have developed commercial fisheries in the Southern Ocean, and have used Antarctic biological resources. In recent years, the annual Antarctic krill catch has been more than 1×10^5 t, and the fishery has been concentrated in CCAMLR Area 48, near the Antarctic Peninsula[5]. The marine environment of the Southern Ocean is complex, and it has a significant influence on the abundance and distribution of Antarctic krill. There have been many studies on the impacts of sea ice, chlorophyll, and SST[6-11], and results have shown that the abundance of Antarctic krill in Area 48 is influenced by sea ice concentration[12-14]. Other features of the marine environment also affect the distribution of Antarctic krill, including the extent and density of sea ice, the circulation mode, and submarine structures[15]. This paper focuses on the main krill fishing ground, CCAMLR Area 48.2, and looks at the influence of sea ice and SST on the abundance of Antarctic krill. We also examine the impact of different sea ice concentrations and SST ranges, and aim to provide some scientific basis for the use and conservation of Ant-

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arctic krill resources.

1 Materials and methods

1.1 Data sources

Data on the Antarctic krill fishery were obtained from CCAMLR (http://www.ccamlr.org), and included information on fishing years and months, yield, fishing effort, and fishing zones. For our analysis we combined data for the fishing zone Area 48.2 (30°—50°W, 57°—64°S) (Figure 1), with yield data from 2003 to 2010, at a temporal resolution of one month.

Sea ice concentration data were obtained from the Institute of Environmental Physics, University of Bremen, Germany (http://www.iup.uni-bremen.de:8084/amsr/). We used data for the years 2003 to 2010, with a temporal resolution of one day, and a spatial resolution of 6.25 km. Sea surface temperature data were acquired from the National Aeronautics and Space Administration (NASA) (http://oceancolor. gsfc.nasa.gov/), for the years 2003—2010, with a temporal resolution of 1 month, and a spatial resolution of 9 km.

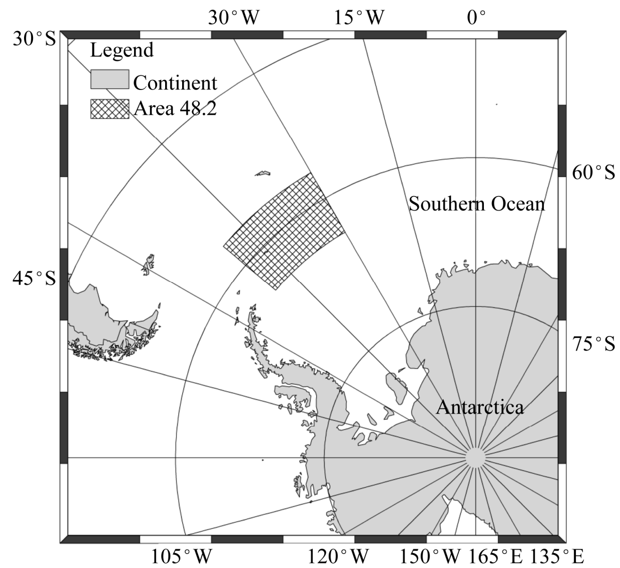

Figure 1 Map of the study area.

1.2 Analytical methods

At present, Antarctic krill fishing is carried out by large stern ramp trawler and processing ships trawling at mid-water levels of around 200 m. Fishing takes place mainly around the sea ice edge and in peripheral waters[16]. Catch per unit effort (*CPUE*) is an index for evaluating fishery resources[17], and the value of *CPUE* is often used as an index to express changes in abundance. To calculate production data for this study, we used *CPUE* ($t \cdot h^{-1}$) as an index of abundance for the krill resource. The formula used is as follows:

$$CPUE = C/F \tag{1}$$

where F is effective trawling hours of fishing reflecting fishing effort (h), and C is the yield in tonnes during this time (t).

The calculation of the similarity coefficient B is based on the Bray-Curtis formula[18]:

$$B = 100 \times \left[1 - \frac{\sum_{i=1}^{s} \left| X_{ij} - X_{im} \right|}{\sum_{i=1}^{s} \left| X_{ij} + X_{im} \right|} \right] \tag{2}$$

where X_{ij} and X_{im} are the *CPUE* for the jth month and mth month in the ith year, respectively, and S is the number of fishing years. To minimize the gap of *CPUE* values between months, square root transformation of *CPUE* was used, and then the analysis was continued using cluster analysis and non-metric multidimensional scaling (nMDS). We used a stress coefficient to describe the results of nMDS. Values of the stress coefficient <0.05 implied excellent agreement, values >0.05 and <0.1 implied good agreement, values >0.1 and <0.2 implied general agreement, and values >0.2 implied poor agreement[19]. Cluster analysis was based on the cluster mode of the group average. Calculation of formula (2) above, nMDS, and cluster analysis were all carried out using the general software, PRIMER. In this paper, to investigate changes in the abundance of krill in Area 48.2 from February to August in the years 2003—2010, we combined calculated changes in yield and *CPUE* with data on sea ice concentration and SST for this fishery area.

To process the environmental data for this study, first we used Interactive Data Language (IDL) to carry out Southern Hemisphere Equal-Area Scalable Earth Grid (EASE-Grid)[20] projection transformation. Second, according to the scope of Area 48.2, we generated vector diagrams using ArcGIS. These images were then resized using vector layers based on IDL. Finally, the actual areas of the resized images were calculated.

Statistical results for SST in Area 48.2 show that the minimum temperature is -2℃. Results of previous research indicate that krill are found at temperatures between -1.3℃ and 3℃, therefore we selected a SST range of -2℃ to 3℃ to calculate the total sea ice-free area. To study the influence of different sea ice concentrations and SST on *CPUE*, in addition to calculating the total sea ice-covered and sea ice-free areas, we also calculated the areas at different concentration ranges and SST intervals. The interval step for sea ice concentration area used was 10%; that is, we took sea ice concentration between 0% and 10% to represent 10% sea ice concentration. The interval step for SST used for this study was 1℃.

Correlation analysis was carried out for the krill fishery *CPUE* and sea ice-covered and sea ice-free areas. Based on the best fit result, in this paper we used linear regression to establish a model of annual change:

$$CPUE = ax + b \tag{3}$$

and we used a quadratic polynomial regression to establish a model of monthly change:

$$CPUE = ax^2+bx+c \tag{4}$$

where *CPUE* ($t \cdot h^{-1}$) is the abundance index of Antarctic krill, *x* is the sea ice-covered area or sea ice-free area, and c is a constant.

We selected the average sea ice-covered and sea ice-free area from February to August every year as the independent variable, and then we established the regression model with the mean *CPUE*. We then selected the average sea ice-covered and sea ice-free area every month from 2003 to 2010 as the independent variable, then established a regression model again with the mean *CPUE*. Finally, we calculated the area of different sea ice concentration ranges and SST intervals and conducted regression analysis with *CPUE*, to determine which sea ice concentration and SST range had the highest correlation value.

Principal component analysis (PCA) was conducted to determine factors that influence the abundance of Antarctic krill. The factors investigated included *CPUE*, sea ice-covered area, and ice-free area. First, the analysis was conducted for years. The value of *CPUE* used was the mean value for the years included in the study, sea ice-covered area was the area where sea ice concentration was greater than 90%, and sea ice-free area was the area where SST was between 1℃ and 2℃. Second, an analysis of the same three factors by month was carried out. In this case, *CPUE* was the mean value for each month over the years of the study, sea ice-covered area was the area where sea ice concentration was 60%—70%, and sea ice-free area was the area where SST was between 0℃ and 1℃. When using PCA in SPSS, the original variables are standardized automatically, so the output results generally refer to standardized variables.

2 Results

2.1 Yield and *CPUE* of Antarctic krill

Figure 2a shows annual yield and average *CPUE* for Area 48.2 from 2003 to 2010. The annual yields ranged from 3.1×10^3 t in 2006 to 9.3×10^4 t in 2008, with an average yield of 5.5×10^4 t. Atypically, in 2006 fishing was only conducted in March and April, so we excluded the data for this year from our analysis. The average *CPUE* between 2003 and 2005 was 6.3 $t \cdot h^{-1}$, while the value rose to 14 $t \cdot h^{-1}$ between 2007 and 2009. Figure 2b shows the monthly average yield and *CPUE* derived from data for 2003 to 2010. The yield peaked from April to June, when the cumulative production accounted for 68.9% of total yield. Values for *CPUE* were all above 10 $t \cdot h^{-1}$ from March to July, while there were no data available for September and October.

2.2 Similarity analysis of fishing time

The stress coefficient determined with the calculation of nMDS was 0.05, so it could reflect the relationship of each month during the krill fishing period. The Bray-Curtis similarity index was high, and the months could be roughly divided into two groups (February to June and July to August) based on the level of the similarity coefficient being above 0.5. The results showed that the krill fishing times have significant similarity (Figure 3).

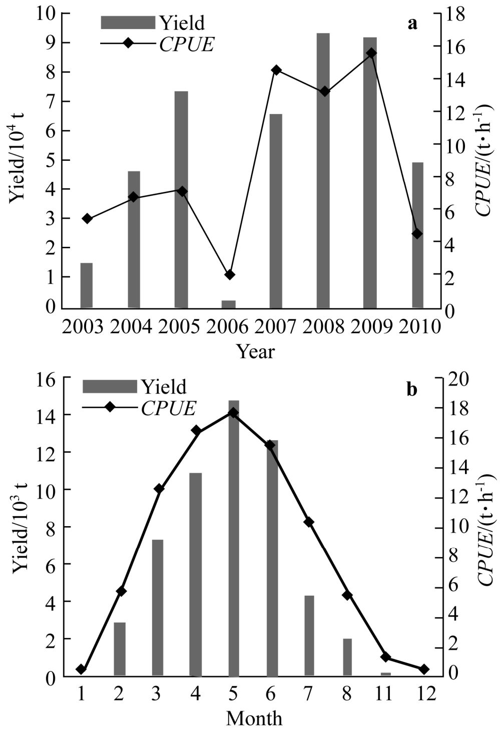

Figure 2 Annual yield and annual average *CPUE* (**a**) and average monthly yield and average monthly *CPUE* (**b**) for Antarctic krill in Area 48.2 from 2003 to 2010.

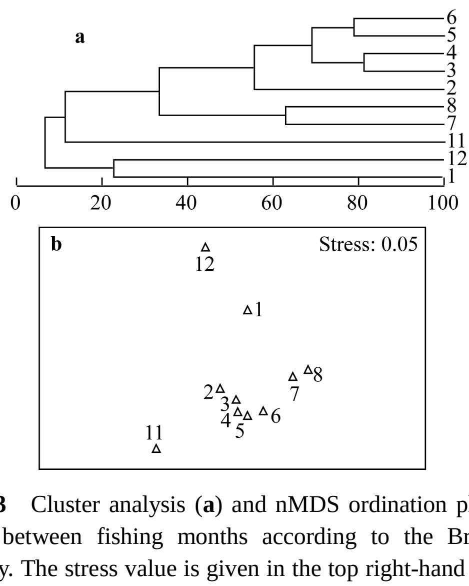

Figure 3 Cluster analysis (**a**) and nMDS ordination plot (**b**) of catches between fishing months according to the Bray-Curtis similarity. The stress value is given in the top right-hand corner of the ordination plot.

2.3 Fluctuation of sea ice-covered and sea ice-free areas

Figure 4a shows the changes in sea ice-covered area and sea ice-free area where SST was between -2℃ and 3℃ from 2003 to 2010. The sea ice-covered area increased sharply over the months, while the ice-free area (-2℃≤SST<3℃) decreased (Figure 4b). Statistical analysis showed that the annual fluctuation was larger than the monthly fluctuation.

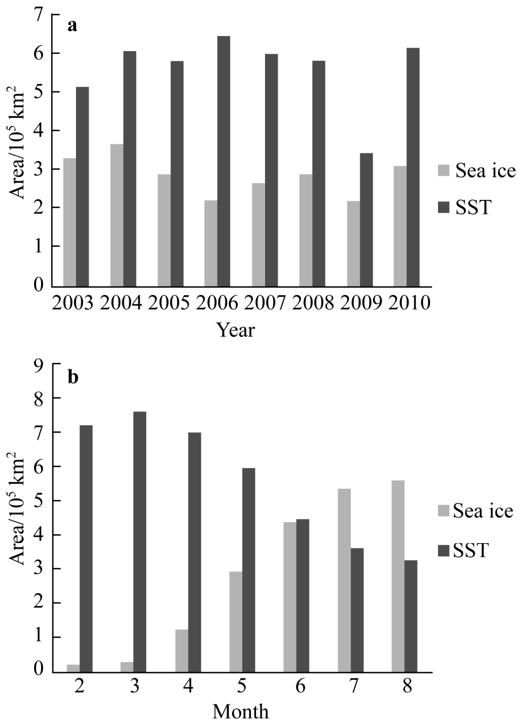

Figure 4 Annual (**a**) and monthly (**b**) fluctuations of average sea ice-covered and sea ice-free areas (-2℃≤SST<3℃).

2.4 Regression analysis between *CPUE* and sea ice-covered area

The results of regression analysis showed that average *CPUE* was negatively correlated with average sea ice-covered area among years (R^2=0.64), and this model explained 64% of the changes in the *CPUE* for the krill fishery (Figure 5a). Figure 5b shows a second polynomial regression model among months, and indicates that *CPUE* increased at first, then decreased with the increase in the sea ice-covered area.

Figure 6 illustrates the relationship between *CPUE* and sea ice concentration from annual and monthly changes, where sea ice concentration is the independent variable. As can be seen from the graph, the coefficient of determination for annual changes in *CPUE* increased with sea ice concentration, and the correlation reached a maximum when the concentration was greater than 90% (Figure 7a). In contrast, the coefficient of determination for monthly changes in *CPUE* was high when sea ice concentration was 50%—70%, and especially when the concentration was 60%—70% (Figure 7b).

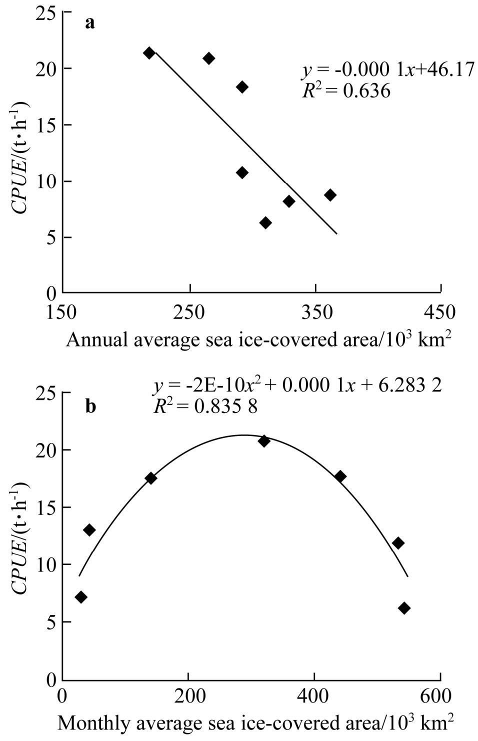

Figure 5 Linear (**a**) and polynomial (**b**) relationship between sea ice-covered area and *CPUE*.

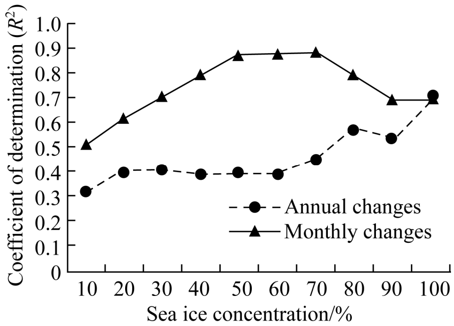

Figure 6 The coefficient of determination for *CPUE* at different sea ice concentrations.

2.5 Regression analysis between *CPUE* and sea ice-free area

Regression analysis results showed no clear negative correlation among years for *CPUE* and sea ice-free area where SST was between -2℃ and 3℃ (R^2=0.21) (Figure 8a). However, in a second polynomial regression model over the months, *CPUE* increased then decreased with the increasing sea ice-free area (-2℃≤SST<3℃) (Figure 8b).

Figure 9 reflects the relationship between *CPUE* and SST for annual and monthly changes, with SST as the independent variable. *CPUE* was significantly negatively correlated with sea ice-free area where SST was between 1℃ and 2℃ (R^2=0.82) (Figure 10a). The regression model performed best when SST was between 0℃ and 1℃.

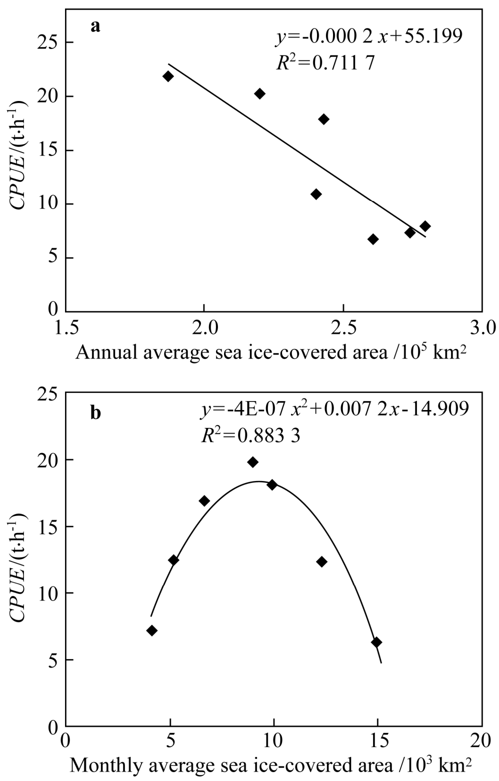

Figure 7 The relationship between *CPUE* and sea ice-covered area where sea ice concentrations were greater than 90% (**a**) and between 60% and 70% (**b**).

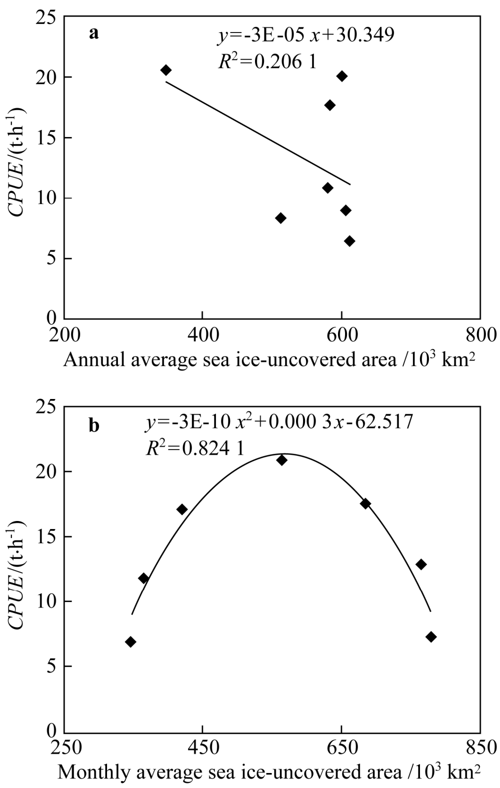

Figure 8 Linear (**a**) and polynomial (**b**) relationship between sea ice-free area (-2℃≤SST<3℃) and *CPUE*.

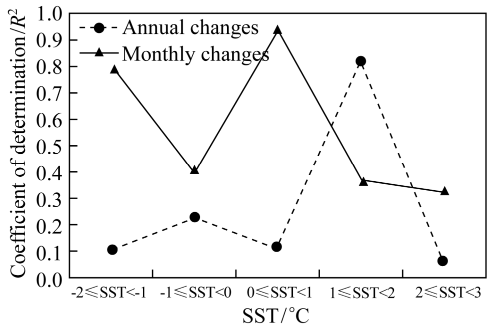

Figure 9 The changing coefficient of determination with different SST intervals.

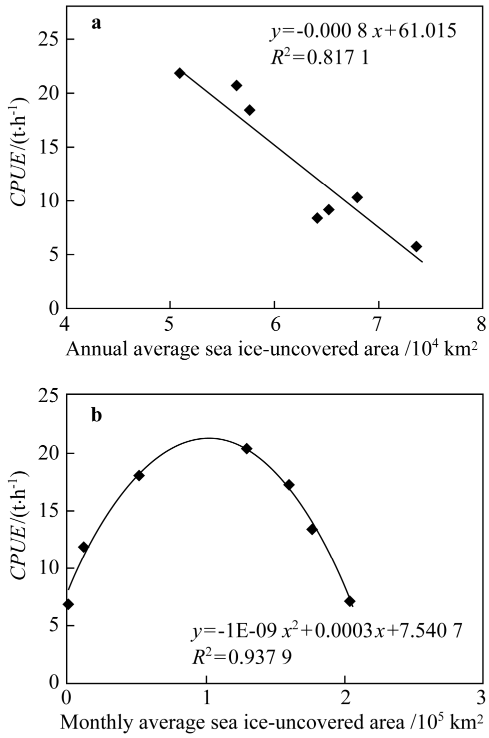

Figure 10 The relationship between *CPUE* and sea ice-free area where SST was between 1℃ and 2℃ (**a**) and between 0℃ and 1℃ (**b**).

2.6 Principal component analysis of influences of sea ice and SST on *CPUE*

Table 1 shows the correlation coefficient matrix of three primary variables. We can see that the direct correlations between variables are strong, and *CPUE* has a significant negative correlation with sea ice and SST.

Table 1 Correlation matrix

	CPUE	SST	Sea ice
CPUE	1.00	-0.91	-0.84
SST	-0.91	1.00	0.73
Sea ice	-0.84	0.73	1.00

Table 2 shows the variance contribution rate and the cumulative contribution rate of various components. From the Table, it can be seen that only the first characteristic root is greater than one, so SPSS only extracted the first principal component. The first principal component of the variance accounts for 88.59% of all principal component variance, so selecting the first principal component is enough to describe the Antarctic krill resource abundance in this situation.

Table 2 Total variance explained

Component	Initial eigenvalues			Extraction sums of squared loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.66	88.59	88.59	2.66	88.59	88.59
2	0.28	9.39	97.98			
3	0.06	2.02	100.00			

Table 3 is the principal component coefficient matrix, and it can explain the principal components based on various variables, and determine the expression of the main components:

$$F1 = –0.978ZX1+0.937ZX2+0.907ZX3$$

Where coefficients of X1, X2, and X3 are large, it can be regarded as a comprehensive index reflecting the relationships between *CPUE*, SST, and sea ice. The ultimate principal component expression derived from analysis over the months is as follows:

$$F1 = 0.276ZX1+0.979ZX2–0.982ZX3$$

Where coefficients of X2 and X3 are large, it can be regarded as a comprehensive index reflecting relationship between SST and sea ice.

Table 3 Component matrix

Component	*CPUE*	SST	Sea ice
1	-0.978	0.937	0.907

3 Discussion

According to statistical results provided by CCAMLR, the yield of Antarctic krill has shown a stable trend in recent years. The total yield was 1.5×10^5 t in 2008, which fell to 1.2×10^5 t in 2009, but rose sharply to 2.11×10^5 t in 2010. Much of the total yield came from Area 48. Area 48.2 is the main fishing zone in Area 48, and is also one of the main krill fishing areas. The krill catch is mainly concentrated from March to July, and the yield during these months accounts for about 90.2% of the total annual yield. The average *CPUE* reached 14.2 $t\cdot h^{-1}$ during these months.

3.1 Influence of sea ice on *CPUE*

Antarctic sea ice influences global climate, and the distribution, density, freezing and melting of Antarctic sea ice influences Southern Ocean primary productivity. Spatial and temporal changes in Antarctic krill abundance have a close relationship to the growth of sea ice[11,15,22]. The results of our study show that the *CPUE* for the krill fishery decreases with increases in the sea ice-covered area over years, first increasing then decreasing along with the increase in sea ice-covered area among months. The area of sea ice cover followed a negative linear relationship with *CPUE* among years with a correlation coefficient of 0.8. A second polynomial regression over the months had a correlation coefficient of 0.92. Correlation analysis between areas of different sea ice concentration and *CPUE* showed that annual changes and monthly changes all had a good correlation. *CPUE* had the highest correlation with sea ice-covered area where sea ice concentration was 60%—70% over the months, while *CPUE* increased along with the sea ice density among years and reached a maximum correlation when the sea ice coverage was greater than 90%. Results of this study are consistent with the findings by Chen et al.[14] that *CPUE* for the krill fishery over the summer in Area 48 had a significant negative correlation with the average area of sea ice during the previous winter and spring[14]. Changing results over the months also indicate that the krill fishery zone is restricted by seasonal variations in sea ice and the fishing season changes as a consequence[11,22].

Sea ice-covered area varies with different sea ice concentration, but in this study sea ice was mainly in the range where sea ice concentration was greater than 90% (Figure 11). The area of this concentration range can approximately represent the total sea ice-covered area, thus explaining the finding that over years *CPUE* had the best correlation with sea ice-covered area when concentration was greater than 90%. The coefficient of determination first increased then decreased with increasing sea ice concentration, and reached a maximum value when the concentration was 60%—70% (Figure 6). The regression model can explain 88.3% of the change in *CPUE*. This may also be connected to the choice of fishing type because of seasonal changes in sea ice density. Sea ice coverage of 60%—70% may be suitable for fishing where plankton is present in high concentrations and krill are most abundant.

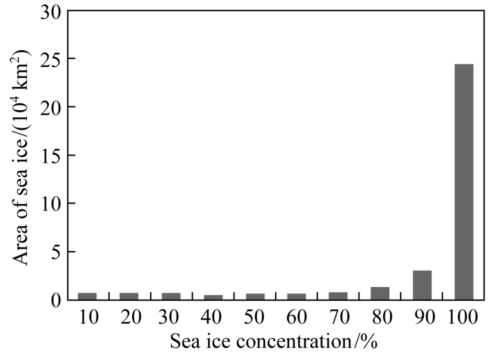

Figure 11 The sea ice-covered area at different sea ice concentration.

3.2 Influence of SST on *CPUE*

Previous studies have suggested that the krill catch rate is related to SST, and that SST measured by scientific and fisheries research can be used as an index to forecast the yield of Antarctic krill in Area 48.3[23]. Changes in SST showed a significant correlation with sea ice from February to August, and when the sea ice-free area (-2℃≤SST<3℃) became larger, the sea ice-covered area became smaller (Figure 4). The changing trend in *CPUE* along with changing sea ice-free area was similar to that of the sea ice-covered area. *CPUE* had a curve regression relationship with sea ice-free area (-2℃≤SST<3℃) over the months, and the correlation was highest when SST was between 0℃ and 1℃ (R^2=0.94). *CPUE* had a higher correlation with ice-free area when SST was between 1℃ and 2℃ over the years, but had no correlation with ice-free area (-2℃≤SST<3℃). This research is consistent with the findings by Zhu et al.[23] that average *CPUE* was high where SST was 0.5℃—1.0℃ and 1.0℃—1.5℃ when hauling nets and casting nets during krill fishing[23]. According to SST data from 2003—2010, the distribution of SST (-2℃ to 3℃) was wide with small changes in amplitude, and the influence on the change in krill abundance was small. Combined with regression analysis results, *CPUE* had a significant negative correlation with the ice-free area (1℃≤SST<2℃). The findings indirectly suggest that the water temperature is most suitable for the growth of krill when the SST is between 1℃ and 2℃.

3.3 Mutual influence of sea ice and SST on *CPUE*

Sea ice and SST are two closely related Southern Ocean physical factors, and they have important effects on the suitability of the environment for the growth of Antarctic krill. Over the years, as the area covered by sea ice becomes greater, and the ice-free area becomes smaller, more surface plankton will be covered by sea ice. In turn, SST will fall and plankton growth and reproduction will be limited, leading to a reduction in the nutrients needed for the growth of krill, and to migration of krill out to the open sea. In addition, an increase in sea ice-covered area will reduce the size of the accessible krill fishery zone, and fishing yield will decrease, requiring extended fishing time to maintain catch levels. These changes will all lead to a decrease in *CPUE*. In spring, SST increases gradually, causing sea ice to melt. Plankton under the sea ice will breed intensively[14], and krill will move towards the continental shelf to prey on the increased numbers of plankton as the sea ice melts. SST continues to rise in summer, sea ice disappears from many areas, and krill can spread to the edge of the continental shelf. At the same time, the melting of sea ice can increase algal density and the primary productivity level, so krill's prey resources are increased. In autumn, krill larvae are numerous, and they distribute along the whole shelf, especially in the continental slope break area where their density can be very high. In winter, SST falls and sea ice-covered areas increase sharply and reach a maximum. Krill move away from the continental shelf to the deep ocean once again, and maybe remain under the sea ice[11]. Seasonal variations in SST and sea ice concentration therefore underlie the seasonal migration of Antarctic krill. The extent of the sea ice not only affects the growth of adult krill and larval forms, but also influences access to areas where krill are abundant, in turn impacting fishing time and the *CPUE* for the Antarctic krill fishery.

4 Conclusions and prospects for future research

This paper studies the relationship between sea ice, SST, and Antarctic krill resources. The results show that sea ice concentration and SST influence the abundance and distribution of Antarctic krill. However, other environmental factors also have an impact on the abundance of Antarctic krill. For example, the distribution of chlorophyll influences the growth and reproduction of krill, and spatial and temporal changes in the abundance and distribution of krill are closely related to chlorophyll distribution[24]. In addition, the distribution of krill is influenced by the Antarctic circulation mode and the submarine landscape, and the influence of these factors on krill abundance can be complex. In future research it would be valuable to combine chlorophyll data acquired from remote sensing with data on other environmental variables to better explain the mechanisms underlying the abundance and distribution of Antarctic krill.

Acknowledgements This study was supported by the Special Research Fund for the National Non-profit Institute (Grant no. 2011T10), the Open Research Funding Program of KLGIS (Grant no. KLGIS2011A07), and the Chinese Polar Environment Comprehensive Investigation and Assessment Programs (Grant no. CHINARE 2012-01-06).

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