

SHORT NOTE

CHARACTERISTICS OF SEASONAL VARIATION IN DIURNAL VERTICAL MIGRATION AND AGGREGATION OF ANTARCTIC KRILL (*EUPHAUSIA SUPERBA*) IN THE SCOTIA SEA, USING JAPANESE FISHERY DATA

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Abstract

Seasonal variation in the diurnal vertical migration and aggregation of Antarctic krill (*Euphausia superba*) associated with the daylight phase over the diurnal cycle (i.e. brightness categories) was examined for the Scotia Sea (South Shetland Islands (SS), South Orkney Islands (SO) and South Georgia (SG) areas) using Japanese fishery data. Average trawling depth usually showed a marked diurnal change during summer and winter in SS and SO. Daily average trawling depth tended to be shallower during austral summer and early autumn, deepened gradually from autumn and reached maximum depth in winter in the Scotia Sea, shifting to shallower depths again in early spring. The average catch-per-unit-effort (CPUE) was highest during the day and lowest at night in autumn and winter in each area, but lower during the day in summer in SS and SO. It is suggested that the seasonal and diurnal changes in vertical migration and aggregation of krill are closely related to its feeding and spawning ecology and avoidance of visual predators.

Résumé

La variation saisonnière de la migration verticale diurne et de la concentration du krill antarctique (*Euphausia superba*) liée à la phase de jour du cycle diurne (à savoir, les différentes catégories d'éclairement) est examinée pour la mer du Scotia (îles Shetland du Sud (SS), îles Orcades du Sud (SO) et Géorgie du Sud (GS)) au moyen des données de la pêche japonaise. La profondeur moyenne des chalutages mettait le plus souvent en évidence un changement très marqué entre l'été et l'hiver dans les SS et les SO. La profondeur journalière moyenne des chalutages tendait à être moins importante pendant l'été et le début de l'automne australs, pour augmenter progressivement en automne et atteindre une profondeur maximale en hiver dans la mer du Scotia, avant de diminuer de nouveau au début du printemps. La capture moyenne par unité d'effort (CPUE) était plus importante de jour et moins de nuit en automne et en hiver dans chaque secteur, mais moins importante de jour en été dans les SS et les SO. Il est suggéré que les variations saisonnières et diurnes de la migration verticale et de la concentration de krill sont étroitement liées à son écologie alimentaire et reproductrice et à l'évitement des prédateurs visuels.

Резюме

По данным японского промысла была исследована сезонная изменчивость в суточной вертикальной миграции и скоплениях антарктического криля (*Euphausia superba*) в море Скотия (районы Южных Шетландских о-вов (SS), Южных Оркнейских о-вов (SO) и Южной Георгии (SG)), связанная с дневной фазой суточного цикла (т.е. с категориями освещенности). Средняя глубина траления обычно характеризовалась заметными суточными изменениями в течение лета и зимы в районах SS и SO. Средняя суточная глубина траления обычно была мельче во время австралийского лета и в начале осени, постепенно становилась глубже начиная с осени и достигала максимальной глубины зимой в море Скотия, вновь становясь мельче в начале весны. Средний улов на единицу усилия (CPUE) был

самым высоким в течение дня и самым низким ночью осенью и зимой в каждом районе, но ниже в течение дня летом в SS и SO. Предполагается, что сезонные и суточные изменения в вертикальной миграции и скоплении криля тесно связаны с экологией его питания и нереста и избеганием визуально различных хищников.

Resumen

Se estudió la variación estacional de la migración vertical diurna y la concentración del kril antártico (*Euphausia superba*) en función de las fases de la luz durante el día (es decir, las categorías de la intensidad luminosa) en el Mar de Escocia (en las áreas de las islas Shetland del Sur (SS), Orcadas del Sur (SO) y Georgia del Sur (SG)), utilizando los datos de las pesquerías japonesas. Por lo general, el promedio de la profundidad de arrastre en las áreas SS y SO cambió marcadamente durante el día en el verano e invierno. La profundidad media diaria de los arrastres en el Mar de Escocia tendió a ser menor durante el verano austral y principios del otoño, aumentando luego gradualmente al transcurrir el otoño para alcanzar un máximo en el invierno, disminuyendo nuevamente a principios de la primavera. La captura promedio por unidad de esfuerzo (CPUE) fue máxima durante el día y mínima durante la noche otoñal e invernal en ambas áreas, pero más baja durante el día estival en las áreas SS y SO. Se sugiere que los cambios estacionales y diarios de la migración vertical y la concentración de kril se relacionan estrechamente con la ecología de la alimentación y desove del recurso, y con el comportamiento para eludir los depredadores discernibles visualmente.

Keywords: Antarctic krill, CPUE, Japanese fishery data, Scotia Sea, trawling depth, vertical distribution, CCAMLR

Introduction

Much has already been written on diurnal variations in the behaviour of krill aggregations (Mauchline, 1980; Everson, 1983; Siegel and Kalinowski, 1994). It would appear that all swarming krill also migrate vertically, at least to some extent (Mauchline, 1980), and it is likely that both diurnal migration and swarming are linked to feeding or predator avoidance mechanisms (Ritz, 1994). Recently, Lascara et al. (1999) have studied the seasonal variation in diurnal vertical migration and aggregation of Antarctic krill (*Euphausia superba*) west of the Antarctic Peninsula using hydroacoustic techniques. However, acoustic measurements were restricted to depths shallower than 200 m and the extent to which krill move below 200 m remains unknown. Furthermore, there are few studies which examine the vertical migration and swarming associated with variations in daylight levels.

In this study, average seasonal variation in diurnal vertical migration and aggregation of Antarctic krill associated with the daylight phase over the diurnal cycle (hereinafter referred to as the brightness categories) in the Scotia Sea were examined using Japanese fishery data.

Materials and methods

The krill catch datasets (total of 93 181 tows) recorded in logbooks of a total of 14 Japanese krill trawlers operating in the South Shetland

Islands (Subarea 48.1; SS), South Orkney Islands (Subarea 48.2; SO) and South Georgia (Subarea 48.3; SG) areas from 1980 to 2003 were examined.

On the fishing grounds, detection by echo sounder and sonar, leading to the capture of individual aggregations, are the basic activities of the harvesting operation on each vessel. Adjustments to the trawl depth are made by tracking the swarm depth as seen on the echo sounder and net sounder. The net sounder, which relies on vertically scanning transducers attached to the headline of the trawl net, has two principal functions: to indicate the net depth in relation to the surface and the quantity of krill that has actually entered the net. Trawling depth was recorded in the logbooks as the depth from the surface to the groundrope of the net. Trawling was conducted continuously throughout the day and night, enabling processing to be conducted in an unbroken sequence.

For krill harvesting, midwater trawl nets with a mouth opening of 235.5–1 256 m² were used. Because krill appears to take no effective action to avoid commercial nets, towing speeds were approximately 2.5 knots, which were similar between months and areas. Haul duration varied between months and areas and averaged 49 minutes (± 26 min; SD). Catch-per-unit-effort (CPUE) was defined in this study as catch per volume of trawled water (g/m³). The volume of trawled water was

Table 1: Diurnal vertical range of average trawling depth and ratio of maximum to minimum diurnal CPUE in the brightness categories. SS – South Shetland Islands area; SO – South Orkney Islands area; SG – South Georgia area.

Month	Range (m)			Max. CPUE/min. CPUE		
	SS	SO	SG	SS	SO	SG
December	22.1	24.5		1.4	2.2	
January	23.5	14.9		1.2	1.4	
February	21.2	74.9		1.3	1.6	
March	14.8	31.7		1.4	1.8	
April	20.4	37.1		1.8	2.0	
May	6.3	29.8		2.1	2.0	
June	16.4	42.6	33.1	1.4	2.1	2.3
July		83.3	24.5		1.9	2.2
August			35.5			1.8
September			31.8			2.5

calculated as (tow speed) \times (haul duration) / (net mouth area), and filtration efficiency was assumed in this study to be 100%. The volume of trawled water varied between months and areas and averaged 2.3×10^3 tonnes ($\pm 1.4 \times 10^3$ tonnes; SD).

To examine the diurnal cycle of trawling depth and CPUE, the angle between the centre of the sun and the celestial horizon for each tow was calculated using local real time and location recorded in the logbooks, and converted to brightness categories that corresponded to the diurnal cycle based on the criteria detailed in Watanabe (1990).

The colour of the hepatopancreas has been recorded for about 100 individuals for each tow in the logbooks from 1998 to 2003, to investigate the intensity of krill feeding on phytoplankton. The colour was divided into three types: level 1 – transparent or light green; level 2 – green; level 3 – dark green. The feeding index for each tow was calculated as (occurrence of frequency (%) of level 1) $\times 1 / 6$ + (occurrence of frequency (%) of level 2) $\times 1 / 2$ + (occurrence of frequency (%) of level 3) $\times 5 / 6$.

Results

Vertical distribution of trawling depth

The average trawling depth in SS showed a marked diurnal change in each month except May, being deepest during the day and shallowest at night (Figure 1). Marked diurnal vertical migration was not observed in May. The average trawling depth in SO showed a marked diurnal change in each month, being deepest during the day and shallowest at night (Figure 2). The pattern of diurnal change in average trawling depth in SG

was different from that of the other two areas, being deepest during morning twilight and shallowest at dusk from June to September (Figure 3).

Average diurnal trawling depth ranged from 6 to 24 m during December and June in SS, and the range during each month tended to be smaller than that in the same months in SO (15–83 m) (Table 1). The range of average trawling depth in February and July in SO was significantly greater (75–83 m) than in the other months in the same area and also in the same months in other areas. The average trawling depth ranged from 25 to 36 m in SS.

The average daily trawling depth was approximately 55 m from December to March in SS, but gradually became deeper after April and attained a maximum depth of 178 m (± 5.1 m; SE) in August (Figure 4). Trawling depth in February was considerably deeper than in January and March in SO. This was due to the migration toward much deeper layers during the day (Figure 2). The depth increased gradually from April as observed in SS, and reached 162 m (± 1.6 m) and 187 m (± 2.0 m) in June and July respectively, which were deeper than the depths in the same season in the other two areas. The depth was approximately 100 m (± 2.6 m) in May, and decreased after that in SG. It reached a maximum depth of 144 m (± 2.2 m) in August but it shifted to a shallower depth (87 m (± 1.0 m)) in September.

Average CPUE in relation to brightness categories

The average CPUE in SS was highest during the day and lowest at night from February to June (Figure 1), however it was lower during the day in

December and January. The average CPUE in SO was highest during the day and lowest at night from March to July, however it was lower during the day from December to February (Figure 2). The average CPUE in SG was highest during the day and lowest at night during each month, as in winter in the other areas (Figure 3).

The ratio of maximum CPUE to minimum CPUE by brightness category was 1.2–2.1 in SS, and the ratio for each month tended to be smaller than that of the same month in SO (1.4–2.2) and SG (1.5–2.5) (Table 1).

Feeding index

In SS, the feeding index was high in December and January, but decreased after February and was at its lowest level (0.17) from April to August (Figure 5). In SO, the index was highest (0.8) in December, but decreased significantly in February and was at its lowest level from March to July. In SG, the index was at its lowest level from May to August, but increased in September (0.25) and October (0.46).

Discussion

According to published results, Antarctic krill are found closer to the surface at night than during the day (Loeb and Schulenberger, 1987; Fraser et al., 1989; Demer and Hewitt, 1995). The results of these studies were from individual cruises isolated in space and time and did not cover all seasons and hydrographic regimes. In this study, more general patterns were considered. On the basis of diurnal changes in average trawling depth, it was found that swarming Antarctic krill show marked diurnal vertical migration, being deepest during the day and shallowest at night during summer and winter in SS and SO. However, such a diurnal pattern of change was not recognised during winter in SG.

The diurnal range of average trawling depth varies from 6 to 83 m in the Scotia Sea, which is very small in comparison to distances of more than 200 and 400 m described for temperate and tropical euphausiids respectively (Brinton, 1967; Andersen et al., 1997). Godlewska (1996) considered that phytoplankton is the principal food item for krill and related chlorophyll concentrations in the surface layer to the amplitude of vertical migration. He suggested that the amplitude of migration of Antarctic krill increased in good feeding conditions, but decreased when food became more limited, in order to reduce the energy cost. However, the amplitude in winter was not remarkably smaller

than that in summer or autumn in this study. Antarctic krill consumes several prey items other than phytoplankton, such as ice biota (Marschall, 1988), seabed detritus (Kawaguchi et al., 1986) and zooplankton (Hopkins et al., 1993), including cannibalism (Nishino and Kawamura, 1994) in winter. It is concluded that several environmental factors other than the abundance of phytoplankton may affect the amplitude of vertical migration.

Diurnal depths in February in SO were significantly deeper than those in the preceding and following months in the same area and the same month in SS. It has been postulated in several studies (e.g. Bollens and Frost, 1989) that zooplankton descend to deeper layers during the day to escape visual predators. Therefore, this result might be related to the existence of predators which forage intensely on krill toward the deeper layers.

The hepatopancreas of krill turns dark green when krill feeds intensively on phytoplankton (Ichii, 2000). In the Scotia Sea area, hepatopancreas were darker green (indicating a high feeding index) in summer and turned transparent during autumn and winter, but began to colour again in early spring. This seasonal change corresponds to the daily change in average trawling depth. Nishino and Kawamura (1994) reported cannibalism in Antarctic krill feeding during mid-winter but the hepatopancreas began to colour in late summer when phytoplankton in the surface water began to proliferate in SG in 1992. It is suggested that the seasonal vertical distribution is closely correlated with switching to alternative foods.

Ichii (1987) found that the pattern of diurnal changes in CPUE showed a seasonal shift off Wilkes Land; CPUE was observed to be high during evening twilight to night-time in January and February, but was found to be higher during the day in March. In this study, the shift of the pattern of diurnal change was also found between February and March in SS and SO. Because the biomass of phytoplankton decreases remarkably, turning of the hepatopancreas to a pale green and spawning almost finishes in March (Makarov et al., 1990), this shift may be related to the feeding and spawning ecology of krill.

Conclusions

- (i) Average trawling depth usually showed a marked diurnal change during summer and winter in SS and SO, being deepest during the day and shallowest at night from summer to winter, but the average trawling depth did not

show such diurnal vertical change in winter in SG, being deepest during morning twilight and shallowest during evening twilight.

- (ii) Daily average trawl depth was shallow during summer and early autumn; it deepened from mid-autumn and reached its maximum in winter, but soon shifted to shallower depths in early spring in the Scotia Sea.
- (iii) The average CPUE was highest during the day and lowest at night in autumn and winter in each area, but was lower during the day in summer in SS and SO.

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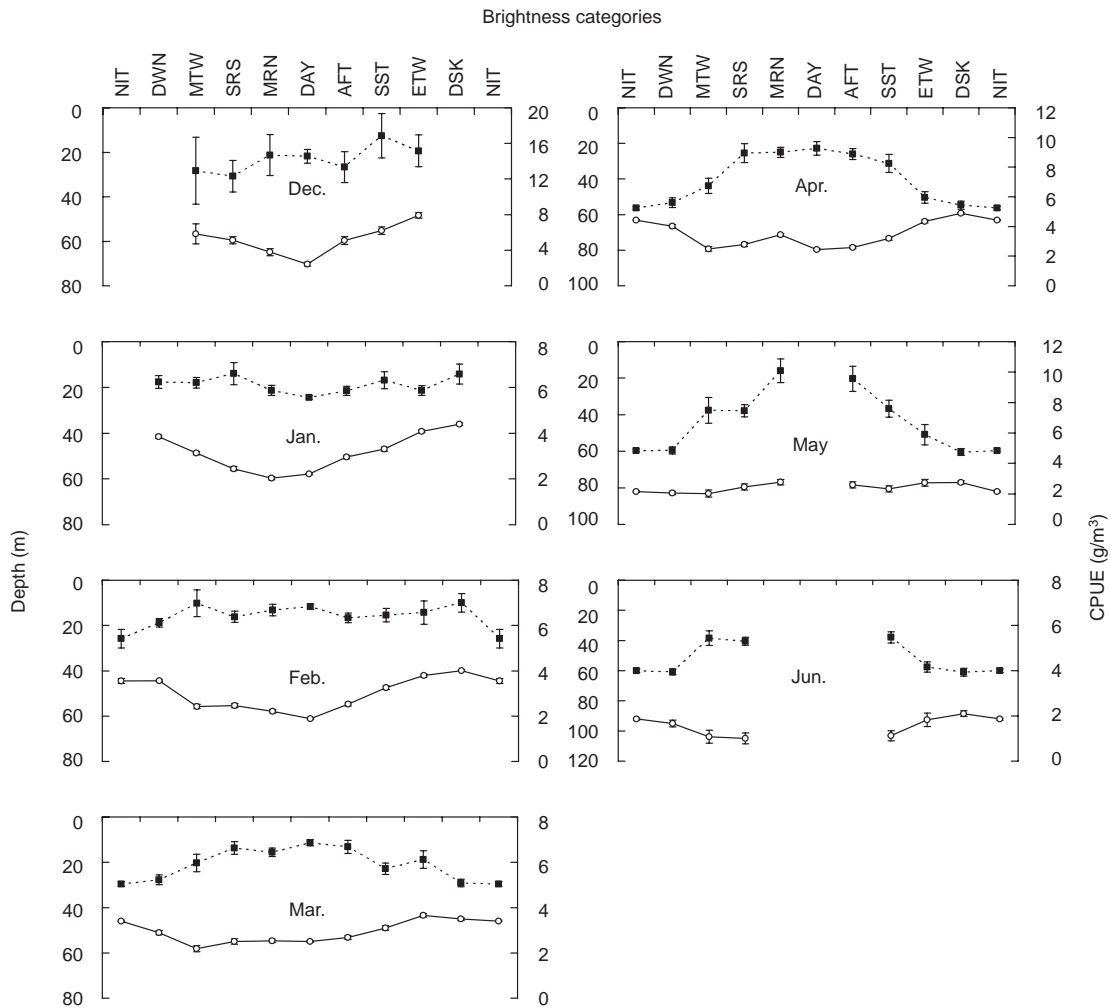


Figure 1: Diurnal variations in average trawling depth (-○-) and CPUE (-■-) from December to June in the South Shetland Islands (SS) area. Vertical bars show \pm SE. Brightness categories: NIT – night-time, DWN – dawn, MTW – morning twilight, SRS – sunrise, MRN – morning, DAY – daytime, AFT – afternoon, SST – sunset, ETW – evening twilight, DSK – dusk.

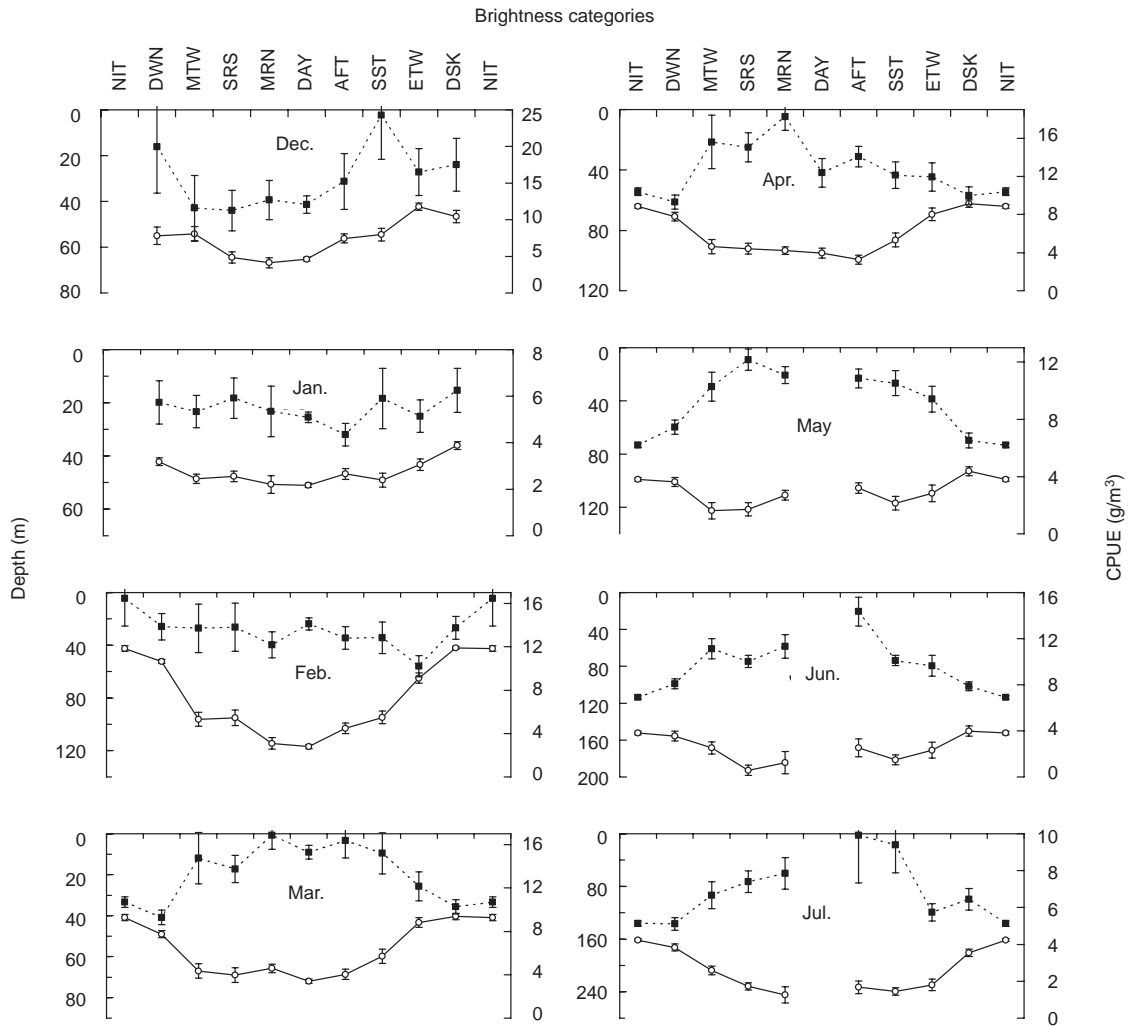


Figure 2: Diurnal variations in average trawling depth (-o-) and CPUE (--■--) from December to July in the South Orkney Islands (SO) area. Vertical bars show \pm SE. For the abbreviations of brightness categories see Figure 1.

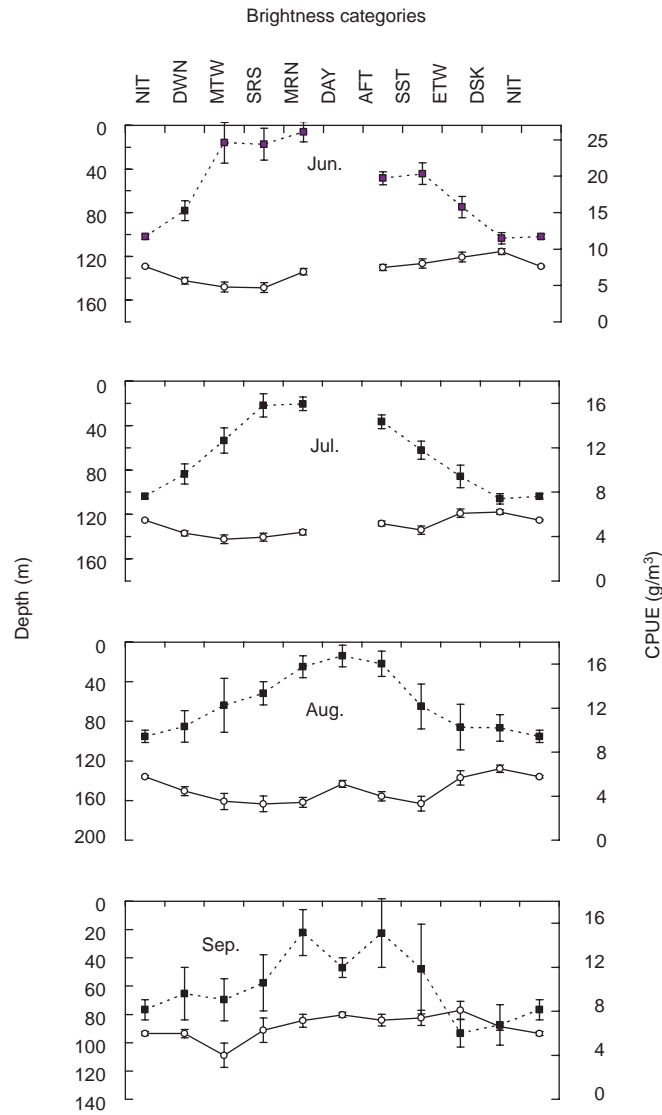


Figure 3: Diurnal variations in average trawling depth (-○-) and CPUE (--■--) from June to September in the South Georgia (SG) area. Vertical bars show \pm SE. For the abbreviations of brightness categories see Figure 1.

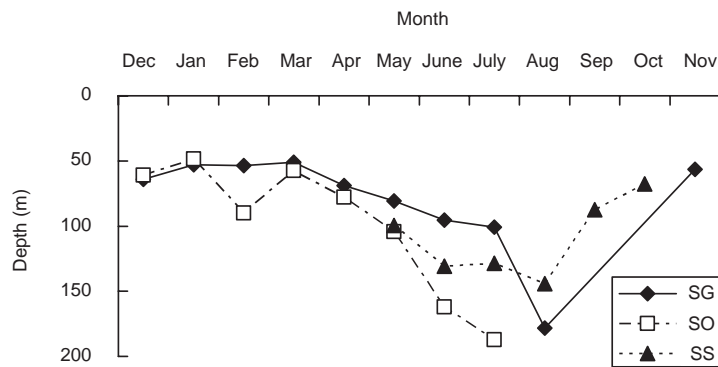


Figure 4: Monthly changes in daily (24-hour period) average trawling depth.

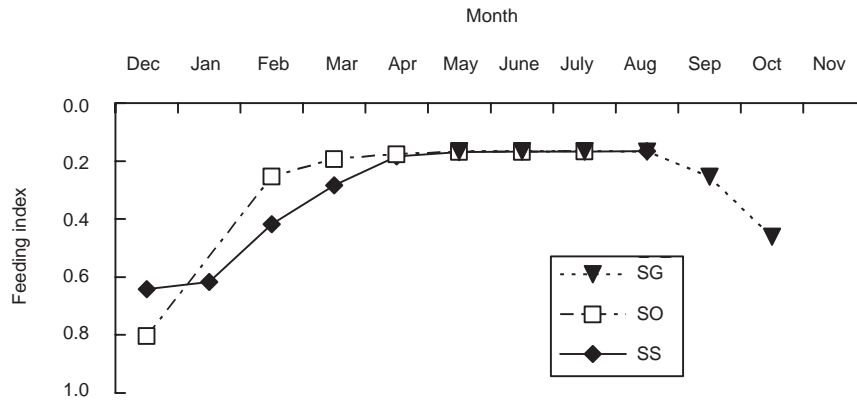


Figure 5: Monthly changes in feeding index of phytoplankton based on frequency of occurrence (%) of three levels of hepatopancreas colour.

Liste des tableaux

Tableau 1: Intervalle vertical diurne de la profondeur moyenne des chalutages et rapport entre les CPUE diurnes maximale et minimale concernant les catégories d'éclaircissement. SS – secteur des îles Shetland du Sud; SO – secteur des îles Orcades du Sud; SG – secteur de la Géorgie du Sud.

Liste des figures

- Figure 1: Variations diurnes de la profondeur des chalutages (-o-) et de la CPUE (--■--) de décembre à juin dans le secteur des îles Shetland du Sud (SS). Les barres verticales indiquent \pm erreur standard. Catégories d'éclaircissement: NIT – nuit, DWN – aube, MTW – crépuscule du matin, SRS – lever du soleil, MRN – matin, DAY – journée, – AFT – après-midi, SST – coucher du soleil, ETW – crépuscule du soir, DSK – tombée de la nuit.
- Figure 2: Variations diurnes de la profondeur moyenne des chalutages (-o-) et de la CPUE (--■--) de décembre à juillet dans le secteur des îles Orcades du Sud (SO). Les barres verticales indiquent \pm erreur standard. Pour les abréviations des catégories d'éclaircissement, se référer à la figure 1.
- Figure 3: Variations diurnes de la profondeur moyenne des chalutages (-o-) et de la CPUE (--■--) de juin à septembre dans le secteur de la Géorgie du Sud (SG). Les barres verticales indiquent \pm erreur standard. Pour les abréviations des catégories d'éclaircissement, se référer à la figure 1.
- Figure 4: Variation mensuelle de la profondeur moyenne des chalutages sur une journée (24 heures).
- Figure 5: Variation mensuelle de l'indice de consommation du phytoplancton, à partir de la fréquence d'observation (%) des trois teintes différentes de l'hépatopancréas.

Список таблиц

Табл. 1: Суточный вертикальный диапазон средней глубины траления и отношение максимального суточного CPUE к минимальному по категориям освещенности. SS – район Южных Шетландских о-вов; SO – район Южных Оркнейских о-вов; SG – район Южной Георгии.

Список рисунков

Рис. 1: Суточная изменчивость средней глубины траления (-o-) и CPUE (--■--) с декабря по июнь в районе Южных Шетландских о-вов (SS). Вертикальные отрезки показывают \pm SE. Категории освещенности: NIT – ночь, DWN – рассвет, MTW – утренний полумрак, SRS – восход солнца, MRN – утро, DAY – день, AFT – послеполуденное время, SST – закат солнца, ETW – вечерний полумрак, DSK – сумерки.

Рис. 2: Суточная изменчивость средней глубины траления (-o-) и CPUE (--■--) с декабря по июль в районе Южных Оркнейских о-вов (SO). Вертикальные отрезки показывают \pm SE. Сокращенные обозначения категорий освещенности объясняются на рис. 1.

Рис. 3: Суточная изменчивость средней глубины траления (-o-) и CPUE (--■--) с июня по сентябрь в районе Южной Георгии (SG). Вертикальные отрезки показывают \pm SE. Сокращенные обозначения категорий освещенности объясняются на рис. 1.

Рис. 4: Ежемесячные изменения средней суточной (24-часовой период) глубины траления.

Рис. 5: Ежемесячные изменения в индексе потребления фитопланктона, основанные на частоте встречаемости (%) трех уровней окраски гепатопанкреаса.

Lista de las tablas

Tabla 1: Intervalo vertical diario de la profundidad de arrastre promedio y razón entre el CPUE diario máximo y mínimo por categoría de intensidad luminosa. Áreas: SS – Islas Shetland del Sur; SO – Islas Orcadas del Sur; SG – Islas Georgia del Sur.

Lista de las figuras

Figura 1: Variaciones diurnas de la profundidad de arrastre promedio (-o-) y del CPUE (--■--) desde diciembre hasta junio en el área de las Islas Shetland del Sur (SS). Las barras verticales representan el \pm SE. Las categorías de intensidad luminosa son: NIT – noche, DWN – alba, MTW – crepúsculo del amanecer, SRS – salida del sol, MRN – mañana, DAY – día, AFT – tarde, SST – puesta del sol, ETW – crepúsculo del atardecer, DSK – anochecer.

Figura 2: Variaciones diurnas de la profundidad de arrastre promedio (-o-) y del CPUE (--■--) desde diciembre hasta julio en el área de las Islas Orcadas del Sur (SO). Las barras verticales representan el \pm SE. Refiérase a la figura 1 para ver las categorías de la intensidad luminosa.

Figura 3: Variaciones diurnas de la profundidad de arrastre promedio (-o-) y del CPUE (--■--) desde junio hasta septiembre en el área de Georgia del Sur (SG). Las barras verticales representan el \pm SE. Refiérase a la figura 1 para ver las categorías de la intensidad luminosa.

Figura 4: Cambios mensuales del promedio diario (período de 24 horas) de la profundidad de arrastre.

Figura 5: Cambios mensuales del índice de consumo de fitoplancton, sobre la base de observaciones de la frecuencia de la ocurrencia (expresada en %) de tres colores de hepatopáncreas del kril.