Consumption of Krill by Minke Whales in Areas IV and V of the Antarctic

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ABSTRACT

The consumption of Antarctic krill (*Euphausia superba*) by the southern minke whale (*Balaenoptera acutorostrata*) in Areas IV and V of the Antarctic was estimated from diurnal change in the forestomach content mass, standard metabolism and the body mass increase methods based on JARPA (the Japanese Whale Research Program Under Special Permit in the Antarctic) data. Estimates of the daily food consumption rate obtained from the three methods ranged from 3 to 4%. Consumption estimates during austral summer in Areas IV and V were $14.2\text{-}17.8 \times 10^5$t and $59.8\text{-}74.9 \times 10^5$t, respectively. The values in Area IV were equivalent to roughly one-fourth of a total estimate biomass of krill in Area IV. Consumption in Area V by minke whales was an order of magnitude greater than the estimated consumption by adelie penguins and crabeater seals. These results indicate the importance of minke whales to the ecosystems in Areas IV and V during the austral summer.

INTRODUCTION

The abundance of southern minke whales (*Balaenoptera acutorostrata*) in the Antarctic (south of 60°S) has been estimated to be as high as 760,396, including 74,692 in Area IV and 294,692 in Area V, during the austral summer (IWC, 1991). Minke whales are estimated to consume 95% of the total biomass of Antarctic krill (*Euphausia superba*) consumed by whales in the Antarctic (Armstrong and Siegfried, 1991). Thus, minke whales are considered one of the key species and play an important role during the austral summer in the food web of the Antarctic Ecosystem.

Some studies have estimated the consumption of krill by minke whales on the basis of energy-requirements calculations (Hinga, 1979; Lockyer, 1981a; Armstrong and Siegfried, 1991), however these estimates were based on guessed parameters. In this paper, we estimate the amount of krill consumed by different maturity stages of minke whales in Areas IV and V based on three methods and new data obtained from JARPA (stomach content mass, body mass, body mass gain, pregnancy rate and the composition of maturity stage of minke whales sampled).

MATERIALS AND METHODS

Data used in this study were collected during JARPA research from 1989/90 to 1995/96. A total of 2,363 minke whales were collected at random (Table 1). The amount of krill consumed by minke whales was estimated directly from information on the masses of forestomach contents (method-1), and indirectly by calculating the whales' energy requirements (method-2 and method-3).

Method-1 Estimation of daily consumption of krill from diurnal change in forestomach content mass

Miura (1969) proposed a method for estimating daily food consumption from diurnal changes in stomach content mass (V_i) with the passage of time based on a known digestion rate in the stomach. If the proportion of food digested during an interval is d, and the proportion of undigested food (S) is $1-d$, the amount of food consumed (C_i) is given by the following equations:

t_1: $C_1=V_1$
t_2: $C_2=V_2-SV_1$
t_3: $C_3=V_3-SV_2-S^2V_1$
t_i: $C_i=V_i-SV_{i-1}-S^2V_{i-2}\cdots S^{i-1}V_1$

Therefore, the daily food consumption ($\sum_{i=1}^{k} Ci$) is given by:

$$\sum_{i=1}^{k} Ci=V_1\frac{(1-2S+S^k)}{1-S} + V_2\frac{(1-2S+S^{k-1})}{1-S} + \cdots +V_k-1(1-S) + \cdots +V_k \quad (1)$$

In this study, we calculated the mean forestomach content mass as % of body mass (V_i) at 1 hour intervals based on the forestomach content mass (kg) and body mass (kg). Assuming that food takes 5 hours to go through the forestomach of minke whales (Bushuev, 1986) and that d is exponential (Elliott and Persson, 1978), we estimated S to be 0.55 and 0.63 if the proportion of undigested food after 5 hours is 5% and 10%, respectively.

We assumed that minke whales did not feed during 19:00-04:00 hrs, because *E. superba* disperses at night in the late summer (Ichii, 1987).

Method-2 Estimation of daily consumption of krill from the standard metabolism

The minke whales are thought to undertake seasonal migrations between winter breeding areas in tropical or subtropical waters and summer feeding areas in the Southern Ocean. Lockyer (1981b) reported that the daily food consumption in winter is equivalent to 10% of that in the austral summer.

We calculated the daily consumption of krill (F) during the austral summer by different maturity stages of minke whale from the standard metabolic rate (SMR) according to following equations:

Immature male or female:

$F(\text{kg day}^{-1})=\{SMR\times365/(D+265\times0.1)/E+G\}/A$

Mature male:

$F(\text{kg day}^{-1})=\{SMR\times365/(D+265\times0.1)/E\}/A$

Mature female:

$F(\text{kg day}^{-1})=\{SMR\times365/(D+265\times0.1)+R\}/E/A$

SMR :Standard metabolic rate (kcal day^{-1})
D :Residence time (days)
E :Caloric value of *E. superba* (kcal kg^{-1})
G :Growth cost (kg day^{-1})
R :Reproduction cost (kcal day^{-1})
A :Assimilation efficiency

We made the following additional assumptions:

(1) Mean body mass (*W*)

We calculated mean body masses of 3,000kg and 3,900kg for immature males and females, and 6,900kg and 8,100kg for mature males and females from JARPA data.

(2) Standard metabolic rate (*SMR*)

We calculated the basal metabolic rate (*M*) according to Kleiber's equation (Kleiber, 1961):

$$M=70W^{0.75}\ (\text{kcal day}^{-1})$$

where *W* is the minke whale body mass (kg).

To account for energy spent on activities such as foraging, moving between food patches and migration, we calculated the standard metabolic rate using the following equation (Markussen et *al*., 1992) :

$$SMR=1.45\times M\ (\text{kcal day}^{-1})$$

(3) Residence time in the Antarctic (*D*)

The encounter rate (as a simple index of density) of minke whales in the Antarctic increased from early November to late December and peaked in January, followed by a steady decrease through February (Kasamatsu *et al*., 1996). We assumed that both males and females minke whales spend about 100 days during the austral summer in the Antarctic.

(4) Caloric value of *E. superba* (*E*)

Minke whales feed mainly on *E. superba*. The mean caloric value of *E. superba* males and gravid females in early/mid February is 4,645.5kJ/kg (=1,110.3kcal/kg) (Clark, 1980).

(5) Growth cost (*G*)

The cost of growth was assumed to be 3kg krill per day (Armstrong and Siegfried, 1991).

(6) Reproduction cost (*R*)

The total reproductive cost for a female minke whales was re-calculated from the analysis by Lockyer (1981a) to be 1.89×10^7kJ (=0.45×10^7kcal), assuming a length at birth fetus of 273cm (Best, 1982). The pregnancy rate is 90% for mature females in the Antarctic (JARPA Data).

(7) Assimilation efficiency (*A*)

We assumed that minke whales have an assimilation efficiency of 84% (Lockyer, 1981a).

Method-3 Estimation of daily consumption of krill from body mass increase

Minke whales increase their body mass during the austral summer by approximately 32% of the minke whale's lean body mass (Ohsumi *et al.*, 1997). The lean body mass (*LW*) was calculated as 100/116×mean body mass. This equation assumes that the animals were caught half-way through the research period, when 50% of the stored body fat and meat would have been deposited already. The estimated caloric value of the body mass increase was 8,210kcal/kg, assuming that 71% of the increase was oil (9,450kcal/kg) and 29% of the increase was muscle (1,450kcal/kg) (Ash, 1955, 1956).

We calculated the daily consumption of krill (*F*) during the austral summer for different maturity stages of minke whales from the body mass increase according to following assumptions and equations:

Immature male or female:

$$F(\text{kg day}^{-1})=[\{SMR+(0.32\times LW\times 8{,}210)/D\}/E+G]/A$$

Mature male:

$$F(\text{kg day}^{-1})=\{SMR+(0.32\times LW\times 8{,}210)/D\}/E/A$$

Mature female:

$$F(\text{kg day}^{-1})=\{SMR+(0.32\times LW\times 8{,}210)/D+R\}/E/A$$

SMR :Standard metabolic rate (kcal day^{-1})
LW :Lean body mass (kg)
D :Residence time (days)
E :Caloric value of *E. superba* (kcal kg^{-1})
G :Growth cost (kg day^{-1})
R :Reproduction cost (kcal day^{-1})
A :Assimilation efficiency

RESULTS AND DISCUSSION

Daily food consumption rate of the minke whales

Fig. 1 shows the diurnal change in the mean forestomach content mass as % of body mass (V_i) from JARPA Data. The rate decreased after a peak at 04:00 hrs. This trend showed little change in the seasons and the regions sampled by the JARPA. Ohsumi (1979) indicated that the percentage of the "freshest" class of the stomach contents peaked at 04:00 hrs. Using equation (1), the daily food consumption rates were calculated to be 3.2 and 3.5% if the proportion of undigested food after 5 hours was 5% and 10%, respectively (Table 2). If feeding also occurred at night, these rates would underestimate the actual food consumption rates. Thus, the daily consumption rate was estimated to be at least 3.2%.

The estimated food consumption rates using method-2 and method-3 were 4.0-4.4% and 3.9-4.1% for immature males and females, respectively, and 3.3-3.5% and 3.8-4.0% for mature males and females, respectively (Table 2).

All estimates of daily food consumption rate obtained from the three methods ranged from 3 to 4%. These values were similar to estimates by Lockyer (1981a) and Bushuev (1986).

If all of the stored body fat and meat is utilized during the austral summer as an energy source, minke whales obtain 73-86% of their food in the Antarctic and the rest in other regions. These values were similar to the estimate by Lockyer (1981a).

Armstrong and Siegfried (1991) estimated the mean daily food consumption rates from respiratory allometry methods of male and female minke whales during the austral summer to be 6.7% and 6.2%, respectively. Bushuev (1986) reported only a single feeding peak in the early morning (04:00-08:00 hrs) with relatively little feeding occurring during the rest of the day in areas with good feeding conditions. Since JARPA data indicate that the maximum forestomach content mass was 3.3%, Armstrong and Siegfried's food consumption rates appear to be overestimates.

Consumption of krill during austral summer by minke whales in Areas IV and V

We estimated the consumption of krill consumed by different maturity stages of minke whales in Areas IV and V based on the composition of maturity stages of minke whales sampled during JARPA research. Consumption of krill by minke whales in Areas IV and V was estimated to be $14.2\text{-}17.8\times10^5$t and $59.8\text{-}74.9\times10^5$t, respectively (Table 3, 4).

The total biomass of krill in and around Area IV was estimated to be about 66.7×10^5t (SC-CAMLR, 1996), so food consumption by minke whales amount to approximately one-fourth of the estimated biomass of krill during the austral summer.

There is little information about the total biomass of krill in Area V. Daily consumption of krill by adelie penguins (*Pygoscelis adeliae*) and crabeater seals (*Lobodon carcinophagus*) in the Ross Sea was estimated to be 2.1×10^3t and 0.6×10^3t, respectively (Ainley *et* *al.*, 1984; Ainley, 1985). Assuming that 51% of all minke whales in Ross Sea occurred in Area V (Nishiwaki *et al.*, 1992), the daily consumption of krill by minke whales in the Ross Sea was estimated to be 30.1-36.8$\times10^3$t. This value was about 14-18 times as large as that of the adelie penguins, and about 50-61 times as large as that of the crabeater seals.

This study indicates the importance of minke whales to the ecosystem in Areas IV and V of the Antarctic during the austral summer.

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Table 1 Number of samples of minke whales used in this study.

Area IV

	1989/90	1991/92	1993/94	1995/96	Combined
Male	184	165	200	272	821
Female	142	123	130	167	562
Total	326	288	330	439	1,383

Area V

	1990/91	1992/93	1994/95	Combined
Male	164	167	200	531
Female	159	160	130	449
Total	323	327	330	980

Table 2 Daily food consumption (kg and as % of *B.W.*) during summer by minke whale based on three different methods.

Sex	Maturity	B.W.(kg)	Method-1	Method-2	Method-3	Average
Male	Immmature	3,000	94.5-104.1(3.2-3.5%)	130.9(4.4%)	105.3(4.0%)	108.7(3.6%)
	Mature	6,900	217.4-239.4(3.2-3.5%)	237.7(3.5%)	228.1(3.3%)	223.0(3.2%)
Female	Immmature	3,900	122.9-135.3(3.2-3.5%)	158.5(4.1%)	152.0(3.9%)	137.2(3.5%)
	Mature	8,100	255.2-281.1(3.2-3.5%)	304.4(3.8%)	326.0(4.0%)	281.4(3.5%)

B.W.: Body weight

Table 3 Estimation total consumption of krill during summer by minke whales in Area IV.

Sex	Maturity	Population abundance	Daily consumption ($\times 10^3$ t)	Annual consumption ($\times 10^5$ t)
Male	Immmature	7,707	0.7- 1.0	0.7- 1.0
	Mature	36,189	7.2- 8.7	7.2- 8.7
Female	Immmature	11,727	1.4- 1.9	1.4- 1.9
	Mature	19,068	4.9- 6.2	4.9- 6.2
Sum		74,692	14.2-17.8	14.2-17.8

Table 4 Estimation total consumption of krill during summer by minke whales in Area V.

Sex	Maturity	Population abundance	Daily consumption ($\times 10^3$ t)	Annual consumption ($\times 10^5$ t)
Male	Immmature	21,950	2.1- 2.9	2.1- 2.9
	Mature	132,927	26.3-31.8	26.3-31.8
Female	Immmature	32,083	3.9- 5.1	3.9- 5.1
	Mature	107,650	27.5-35.1	27.5-35.1
Sum		294,610	59.8-74.9	59.8-74.9

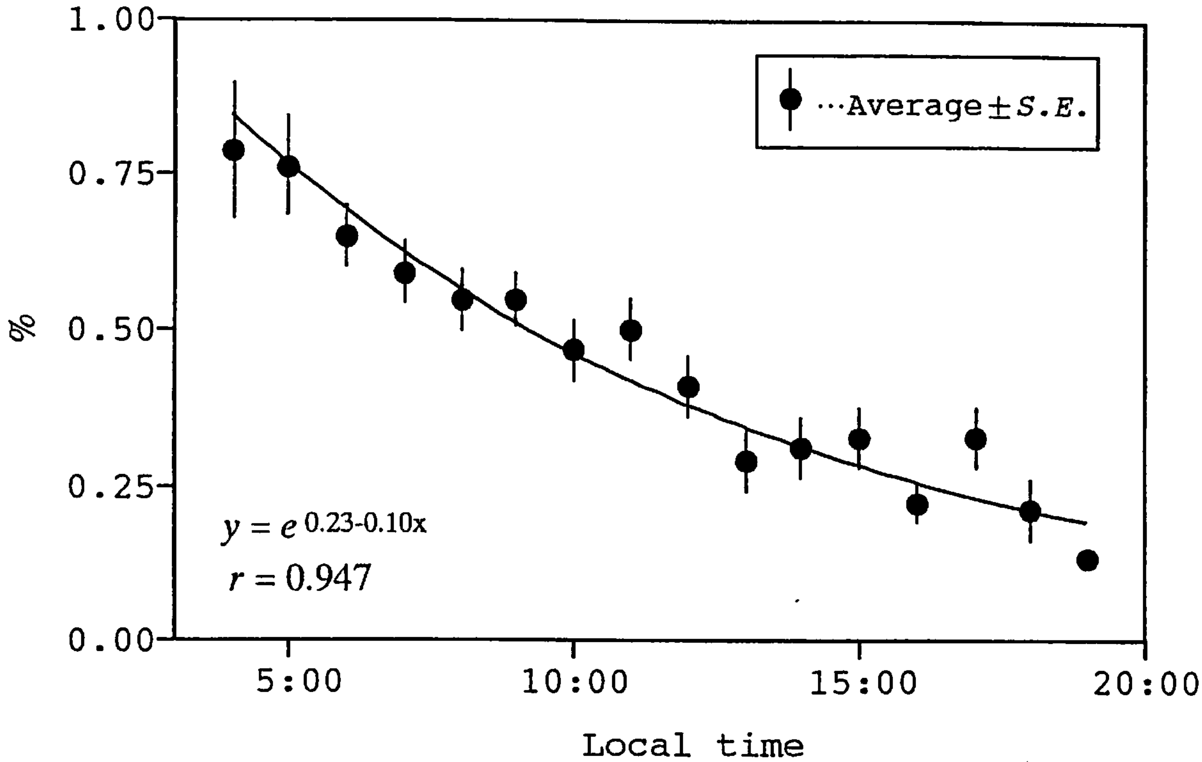

Fig. 1 Diurnal change in the mean forestmach content mass as % of body mass.