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An update of the study on age at sexual maturity trends in the Antarctic minke whale

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ABSTRACT

An update of the analysis of age at sexual maturity in the Antarctic minke whale based on the transition phase was carried out by using all samples available from former Japanese whale research programs under special permit in the Antarctic (JARPA, JARPAII, NEWREP-A) from the 1987/88 to the 2018/19 austral summer seasons. These research programs and surveys, designed and implemented by the Institute of Cetacean Research, were conducted in the Indo-Pacific sector of the Antarctic (0°–120°W, south of 60°S). The updated analyses confirmed that the age at sexual maturity of this species declined from 10–12 years old in the mid-1940s year classes to 7–8 years old in the early 1970s year classes. The age at sexual maturity remained stable at that level until the 2000s year classes. Although some significant statistical trends were found for the recent year classes (from the 1970s), the extent of such changes, when confirmed, is very small in comparison with the extent of the changes observed in the middle of the past century. These results for the age at sexual maturity are interpreted and discussed in conjunction with changes observed in other ecological and biological parameters of the Antarctic minke whale, in the context of some established hypotheses on changes of the Antarctic ecosystem.

INTRODUCTION

Since the moratorium on commercial whaling was implemented in 1988, the Institute of Cetacean Research (ICR) undertook different whale research programs in the Antarctic Ocean under Article VIII of the International Convention for the Regulation of Whaling (ICRW). The Japanese Whale Research Program under Special Permit in the Antarctic (JARPA) was conducted in the austral summers from 1987/88 to 2004/05 and in a second phase (JARPAII) from 2005/06 to 2013/14. The New Scientific Whale Research Program in the Antarctic Ocean (NEWREP-A) was conducted from 2015/16 to 2018/19. These programs carried out systematic surveys in the Indo-Pacific sector (0°–120°W, south of 60°S) of the Antarctic using both lethal (biological sampling of a limited number of Antarctic minke whales [*Balaenoptera bonaerensis*]) and non-lethal (biopsy sampling and photo-identification of several whale species, oceanographic and marine debris surveys, dedicated sighting surveys) approaches.

Data and samples obtained from the Antarctic minke whales were analyzed in regard to several objectives of the research programs related to both assessment (e.g. stock structure, biological parameters, abundance estimates) and ecological (e.g. feeding ecology, environmental pollutants) aspects of this species (see Tamura *et al.*, 2017). The long time series of data allowed scientists to investigate and interpret the temporal trend in several biological and demographic parameters of the Antarctic minke whale in the context of some established hypotheses on changes in the Antarctic ecosystem. Fujise and Pastene (2021) discussed the historical and current ecosystem changes in the Indo-Pacific sector of the Antarctic through the examination of the information on biological and demographical parameters of mainly Antarctic minke whales and other whales, which are sea-based predators.

Regarding historical changes, Fujise and Pastene (2021) concluded that the increased krill availability in the middle of the past century as a result of the heavy harvesting of the larger baleen whale species could have translated into better nutritional conditions for the Antarctic minke whale, resulting in a decreasing trend in the age at sexual maturity and an increasing trend in recruitment rate and hence total population size between approximately 1940 and 1970. Regarding current changes, Fujise and Pastene (2021) concluded that the nutritional conditions of the Antarctic minke whale have deteriorated more recently, as confirmed by a decrease in energy storage and stomach content weight observed since the 1980′s. These changes coincide with appreciable increases in the abundance of humpback (*Megaptera novaeangliae*) and fin (*B. physalus*) whales, which are also krill-eaters and were heavily harvested in the first half of the past century.

Fujise and Pastene (2021) suggested that the historical changes were consistent with the pattern to be expected under the krill surplus hypothesis and that the most recent scenario shows the Antarctic minke whale again competing with other (recovering) baleen whale species for krill. Furthermore, these authors suggested that Antarctic minke whales could be using alternative feeding areas (e.g. polynyas within the pack-ice) in response to the increase in abundance and geographical expansion of other large whale species.

One of the biological parameters discussed in the review by Fujise and Pastene (2021) was the age at sexual maturity, which is considered a good indicator of changes in the environment of whales. Previous studies used data

Table 1

Number of Antarctic minke whales sampled by Japanese surveys in the Antarctic during 1987/88 to 2018/19, and number of whales examined for age at transition phase (TP).

Survey year	Female		Male		Total	
	n	Number of TP* determined	*n*	Number of TP* determined	*n*	Number of TP* determined
1987/88	119	41	153	81	272	122
1988/89	151	48	85	18	236	66
1989/90	142	34	184	76	326	110
1990/91	159	56	164	51	323	107
1991/92	123	31	165	52	288	83
1992/93	160	69	167	87	327	156
1993/94	130	32	200	81	330	113
1994/95	130	51	200	106	330	157
1995/96	167	59	273	137	440	196
1996/97	234	137	206	124	440	261
1997/98	159	27	279	119	438	146
1998/99	142	46	247	114	389	160
1999/00	206	77	233	112	439	189
2000/01	182	64	258	136	440	200
2001/02	239	76	201	88	440	164
2002/03	205	80	235	104	440	184
2003/04	240	96	200	68	440	164
2004/05	263	131	177	89	440	220
2005/06	391	156	462	225	853	381
2006/07	351	152	154	75	505	227
2007/08	278	114	273	100	551	214
2008/09	304	129	375	148	679	277
2009/10	269	104	237	87	506	191
2010/11	108	52	62	32	170	84
2011/12	167	82	99	50	266	132
2012/13	53	13	50	16	103	29
2013/14	125	26	125	35	250	61
2015/16	230	103	103	45	333	148
2016/17	178	79	155	69	333	148
2017/18	181	54	152	40	333	94
2018/19	147	44	186	93	333	137
total	5,933	2,263	6,060	2,658	11,993	4,921

*TP: age at which transition phase layer was formed in the earplug.

and samples collected from 1987/88 to 2010/11 surveys (Bando *et al.*, 2014). Additional samples and data are available up to the 2018/19 season.

The objective of this study was to update the analyses of the age at sexual maturity of Antarctic minke whale by using all the available samples and data. The results of these analyses will contribute further to the interpretation of current changes in the ecosystem of the Indo-Pacific sector of the Antarctic.

SAMPLES

Biological samples were collected under the surveys of JARPA (1987/88–2004/05), JARPAII (2005/06–2013/14) and the New Scientific Whale Research Program in the Antarctic Ocean (NEWREP-A) (2015/16–2018/19). A total of 11,993 Antarctic minke whales were sampled in the whole period. Previous analyses included samples from 1987/88 to 2010/11. The present study included samples collected from 1987/88 to 2018/19, which incorporates new samples collected by NEWREP-A surveys. Table 1 shows the number of Antarctic minke whales sampled and the number of whales examined for age at transition phase, which is considered as the age at sexual maturity (see Bando, 2017 and the next section).

ANALYTICAL PROCEDURES

Age at sexual maturity by transition phase

The age of baleen whales was estimated by counting growth layers accumulated in the earplug (Lockyer, 1984). The layer at which the spacing changed abruptly from irregular early younger layers in the earplug is called the transition phase (Lockyer, 1972). It is generally known that the transition phase in earplugs of baleen whales indicates the age at sexual maturity (Lockyer, 1972). Therefore, the age at the transition layer was recorded, if it was present, when observing the earplug.

Year of birth

The year of birth (=year class) in each individual was defined as: (starting year of an austral survey season, e.g. 1987 in the case of 1987/88 season)−(age at capture).

Evaluation of age data reading

Age and transition phase in earplugs were read by three different readers during the period of study. A test to evaluate the consistency and comparability of reading among readers was required. Results of the test indicated that the data from different readers were consistent and comparable (see details of the test in Bando *et al.*, 2014). Therefore, the whole data set for the whole period was used in the present analysis.

Truncation bias

It is known that the age at sexual maturity in recent age classes will be underestimated when using the transition phase analysis, due to the under-representation of late maturing individuals (Figure 1). This is known as the truncation effect. This can be addressed by combining samples from different year classes (Kato, 1985; Zenitani, 2011). Furthermore, in consideration of the information in Figure 2, only transition phase data for individuals older than certain ages were used as shown below:

Year classes 1971–1975: 15 years
Year classes 1976–1980: 12 years
Year classes 1981–1985: 12 years
Year classes 1986–1990: 12 years
Year classes 1991–1995: 12 years
Year classes 1996–2000: 12 years
Year classes 2001–2010: 12 years

Data for these age values and older should therefore be free of truncation bias, however the sample size will be reduced.

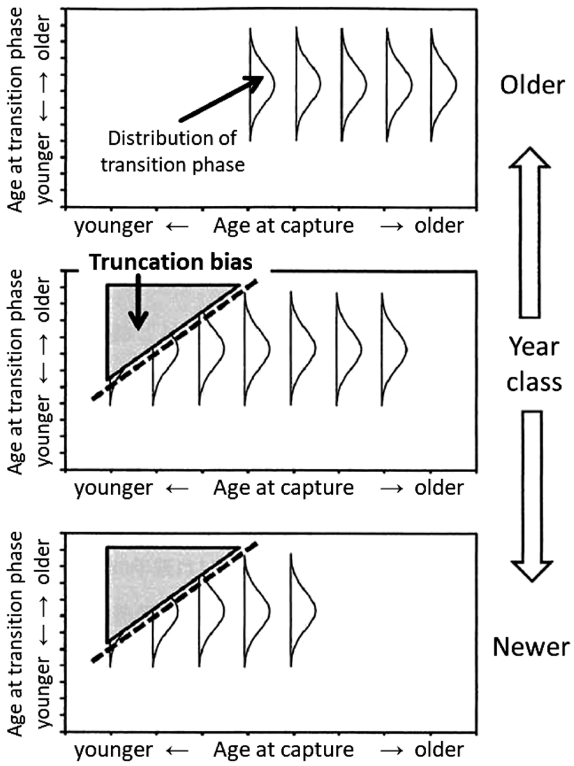

Figure 1. Schematic illustration of the relationship between distribution of age at transition phase and age at capture in certain year classes with truncation bias (after Zenitani, 2011).

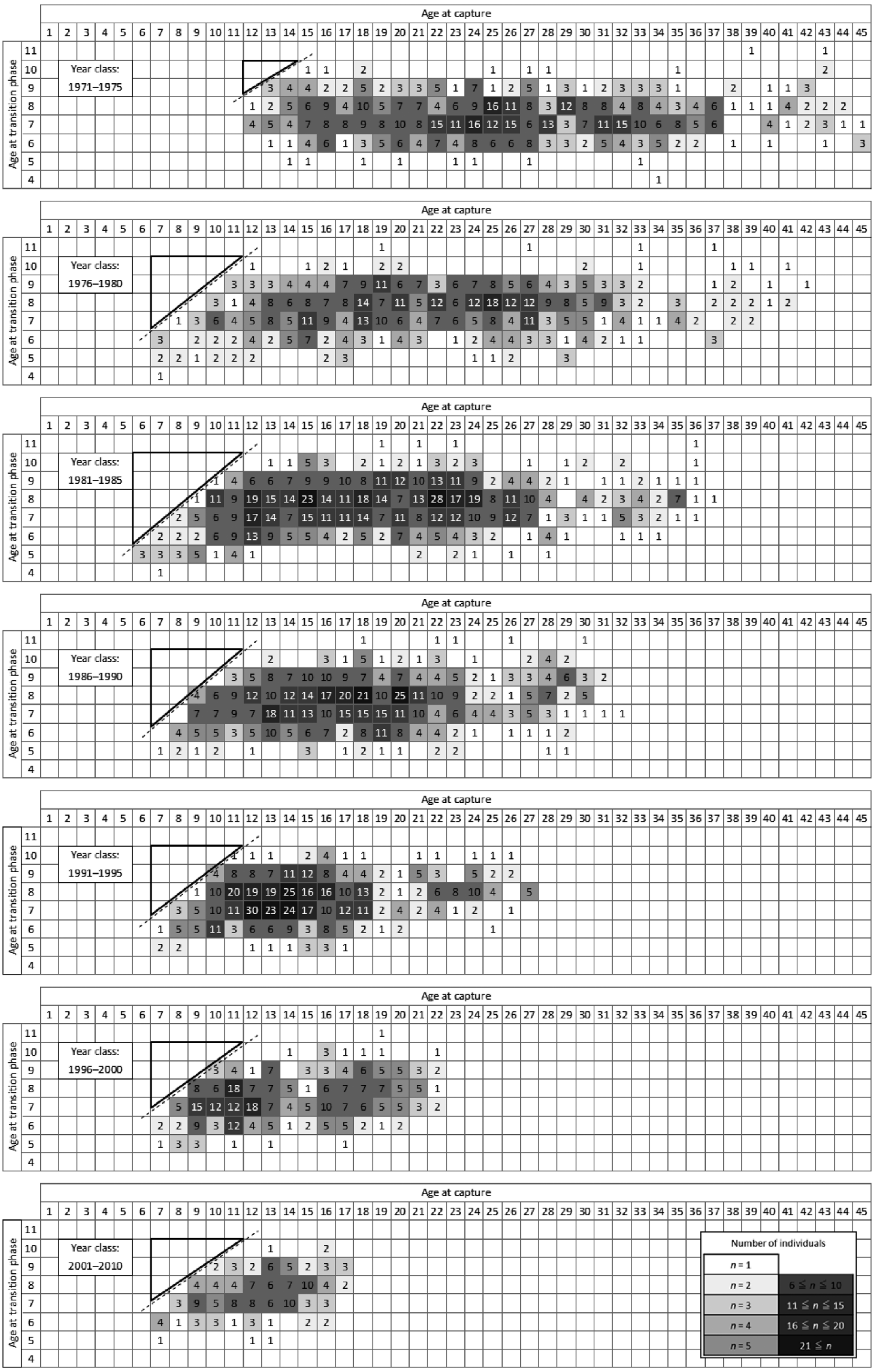

Figure 2. Distribution of age at transition phase against age at capture in each year class group. The triangle corresponds to truncation bias. Maximum age for truncation bias is indicated by the corner of the triangle.

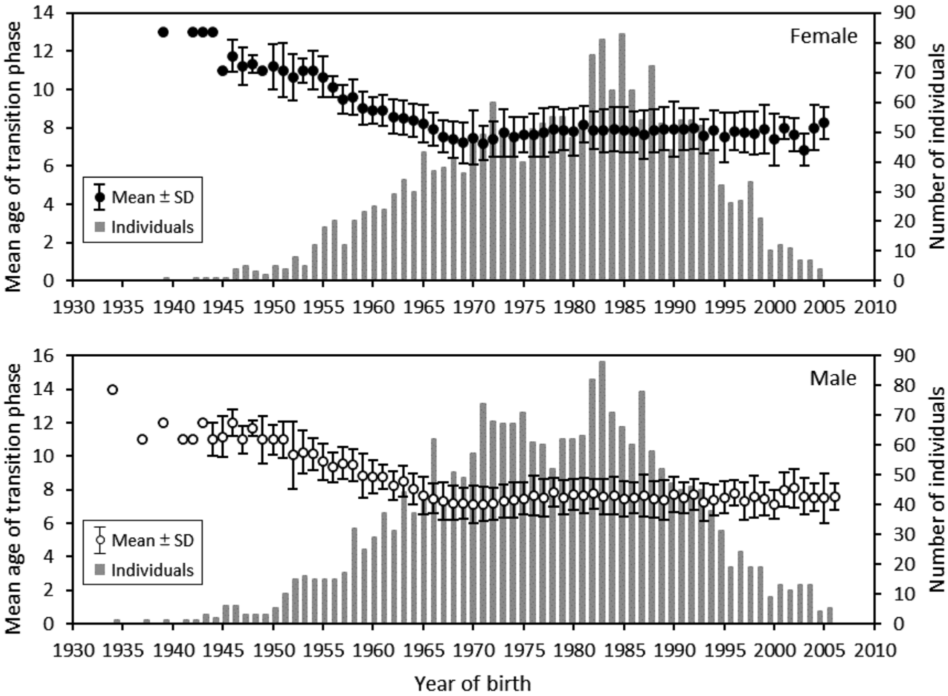

Figure 3. Temporal trend of mean age at sexual maturity by a transition phase of Antarctic minke whales by year class and sex, for the whole area.

After considering truncation bias, this study used a total of 4,417 (2,078 females and 2,339 males) age and transition phase data for temporal trend analysis.

Statistical analysis

Linear regression analysis was applied to examine long-term trends in the age at sexual maturity from the year in which the trend had stabilized, e.g. 1970′s (Bando *et al.*, 2014). For the statistical test on trend, p values < 0.05 were considered to be statistically significant.

RESULTS

Temporal trend of age at sexual maturity for the whole area

The analysis involved samples from 4,417 Antarctic minke whales (2,078 females and 2,339 males) taken from 0°–120°W of the Indo-Pacific region, south of 60°S. The mean age at sexual maturity by year class and sex is shown in Figure 3, and detailed values are available in Table 2. Age at sexual maturity in the most recent year class was estimated to be about 7–9 years old in 2005 for females and about 7–9 years old in 2006 for males.

The statistical examination of the trend of age at sexual maturity from 1970 to 2005 in females and from 1970 to 2006 in males (e.g. recent changes) revealed results of interest. The age at sexual maturity increased slightly for year class after the 1970s in both sexes. The regression equations were $y=0.0084x-8.8299$ for females, and $y=0.0085x-9.3362$ in males (y is mean age at sexual maturity and x is year of birth). In both cases the trend was statistically significant ($p<0.05$).

Temporal trend of sexual maturity by stocks

At least two stocks of Antarctic minke whales occur in the Indo-Pacific sector of the Antarctic (I- and P-stocks) (Pastene and Goto, 2016; Murase *et al.*, 2020). The boundary between these two stocks is variable and changes by year and sex (Kitakado *et al.*, 2014). Figure 4 shows the temporal trend of age at sexual maturity for the main areas occupied by the two stocks, 0°–130°E for the I-stock and 165°E–120°W for the P-stock. Table 2 shows the data on age at sexual maturity by year class, sex and stock.

The regression equations for the recent trend for each case in Figure 4 were:

I-stock, female: $y=0.0051x-2.3859$

I-stock, male: $y=0.0113x-14.8503$

P-stock, female: $y=0.0082x-8.5696$

P-stock, Male: $y=0.0019x+3.7597$

The statistical test for temporal trend indicated that only the age at sexual maturity for males of the I-stock was significant ($p<0.05$).

Table 2

Age at sexual maturity of Antarctic minke whales derived from a transition phase in earplugs by year class, sex and stock.

Year of class	0°–120°W as "All area"								0°–130°E as "Indian sector"								165°E–120°W as "Pacific sector"							
	Female				Male				Female				Male				Female				Male			
	Mean	SD	Range	n	Mean	SD	Range	n	Mean	SD	Range	n	Mean	SD	Range	n	Mean	SD	Range	n	Mean	SD	Range	n
1934	—	—	—	—	14.00	—	—	1	—	—	—	—	14.00	—	—	1	—	—	—	—	—	—	—	—
1935	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1936	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1937	—	—	—	—	11.00	—	—	1	—	—	—	—	11.00	—	—	1	—	—	—	—	—	—	—	—
1938	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1939	13.00	—	—	1	12.00	—	—	1	13.00	—	—	1	12.00	—	—	1	—	—	—	—	—	—	—	—
1940	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1941	—	—	—	—	11.00	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1942	13.00	—	—	1	11.00	—	—	1	—	—	—	—	11.00	—	—	1	—	—	—	—	—	—	—	—
1943	13.00	—	—	1	12.00	0.00	12–12	3	13.00	—	—	1	12.00	—	—	1	—	—	—	—	—	—	—	—
1944	13.00	—	—	1	11.00	1.00	10–12	2	—	—	—	—	11.00	1.00	10–12	2	13.00	—	—	1	—	—	—	—
1945	11.00	—	—	1	11.17	1.21	9–13	6	—	—	—	—	10.67	1.25	9–12	3	11.00	—	—	1	11.00	—	—	1
1946	11.75	0.83	11–13	4	12.00	0.82	11–13	6	—	—	—	—	12.00	0.89	11–13	5	13.00	—	—	1	12.00	—	—	1
1947	11.20	0.98	10–12	5	11.00	0.82	10–12	3	12.00	—	—	1	10.00	—	—	1	12.00	—	—	1	11.00	—	—	1
1948	11.33	0.47	11–12	3	11.67	0.47	11–12	3	11.33	0.47	11–12	3	12.00	—	—	1	—	—	—	—	—	—	—	—
1949	11.00	0.00	11–11	2	11.00	1.41	9–12	3	11.00	—	—	1	11.00	1.41	9–12	3	11.00	—	—	1	—	—	—	—
1950	11.20	1.17	10–13	5	11.00	0.89	10–12	5	10.50	0.50	10–11	2	11.00	1.00	10–12	2	11.67	1.25	10–13	3	10.00	—	—	1
1951	11.00	1.41	9–13	4	11.00	1.10	10–13	10	12.00	1.00	11–13	2	10.80	1.17	10–13	5	10.00	1.00	9–11	2	10.67	0.94	10–12	3
1952	10.63	1.22	8–12	8	10.07	2.02	7–15	15	10.25	1.48	8–12	4	9.89	2.18	7–15	9	10.50	0.50	10–11	2	9.75	1.48	8–12	4
1953	11.00	0.63	10–12	5	10.25	1.30	8–12	16	11.33	0.47	11–12	3	10.00	1.13	8–12	11	11.00	—	—	1	12.00	—	—	1
1954	11.00	1.00	9–13	12	10.13	0.96	9–12	15	10.75	0.43	10–11	4	10.40	0.92	9–12	10	11.00	0.71	10–12	4	10.00	0.82	9–11	3
1955	10.67	1.05	8–12	18	9.67	1.07	7–11	15	9.80	1.17	8–11	5	9.60	1.02	8–11	5	11.13	0.78	10–12	8	9.88	0.60	9–11	8
1956	10.15	0.57	9–11	20	9.33	0.87	8–11	15	10.29	0.45	10–11	7	9.33	0.94	8–11	9	10.50	0.50	10–11	4	9.00	0.82	8–10	3
1957	9.50	0.76	8–11	12	9.59	0.97	8–12	17	10.00	0.82	9–11	3	9.40	0.66	8–10	10	9.50	0.50	9–10	6	9.67	1.70	8–12	3
1958	9.60	0.92	8–12	20	9.47	0.93	7–12	32	9.60	0.49	9–10	5	9.37	1.04	7–12	19	9.11	0.74	8–10	9	9.20	0.75	8–10	5
1959	9.04	0.86	7–11	23	8.84	1.32	6–11	25	8.57	0.90	7–10	7	8.92	1.33	6–11	13	9.18	0.72	8–10	11	8.43	1.50	6–11	7
1960	8.92	0.69	8–10	25	8.76	0.97	6–10	29	9.09	0.79	8–10	11	8.59	1.14	6–10	17	9.00	0.47	8–10	9	8.83	0.69	8–10	6
1961	8.92	0.81	7–10	24	8.76	0.71	8–10	37	8.92	0.86	7–10	12	8.72	0.72	8–10	25	8.86	0.83	8–10	7	8.67	0.75	8–10	6
1962	8.59	0.89	7–10	29	8.26	0.84	6–10	31	8.73	0.93	7–10	15	8.06	0.85	6–9	18	8.33	0.75	7–9	6	8.67	0.47	8–9	6
1963	8.53	0.92	6–10	34	8.50	0.92	7–10	44	8.56	1.00	6–10	16	8.65	0.96	7–10	23	8.36	0.77	7–9	11	8.08	0.86	7–9	12
1964	8.40	0.88	6–10	30	8.03	0.91	6–10	37	8.42	0.86	7–10	12	7.94	0.97	6–9	16	8.36	1.07	6–10	11	8.25	0.66	7–9	8
1965	8.23	0.98	5–10	43	7.67	1.11	5–10	42	8.48	1.14	5–10	21	7.96	0.89	6–10	24	8.00	0.69	7–9	17	7.33	1.25	5–9	9
1966	7.95	0.87	6–10	37	7.48	0.91	6–10	62	8.06	0.87	7–10	17	7.55	0.94	6–10	31	7.81	0.73	6–9	16	7.53	0.88	6–9	15
1967	7.55	0.85	6–10	38	7.32	1.11	5–10	41	7.53	1.09	6–10	17	7.30	1.19	5–10	20	7.63	0.60	7–9	16	7.50	1.12	6–9	14
1968	7.39	0.93	6–9	41	7.22	1.00	5–10	51	7.21	1.01	6–9	14	7.21	1.05	5–10	28	7.55	0.89	6–9	22	7.33	1.11	6–10	12
1969	7.22	1.06	5–10	36	7.18	0.92	5–9	49	7.11	0.94	5–9	18	6.86	0.74	6–8	14	7.21	1.26	5–10	14	7.17	0.90	5–9	18
1970	7.49	1.40	4–11	49	7.14	1.12	5–10	57	7.53	1.61	4–10	17	7.00	1.15	5–9	27	7.56	1.26	6–11	27	7.65	1.13	6–10	17
1971	7.20	0.90	5–9	49	7.15	1.02	5–10	74	7.22	0.97	5–9	18	7.12	1.02	6–10	43	7.26	0.85	6–9	23	7.05	0.97	5–9	20
1972	7.42	0.94	6–11	60	7.16	0.95	5–9	68	7.45	0.80	6–9	20	7.27	0.93	5–9	33	7.52	1.01	6–11	31	7.26	0.96	6–9	19
1973	7.73	1.24	6–10	49	7.33	0.98	4–10	67	7.59	1.24	6–10	17	7.20	1.23	4–10	25	7.79	1.21	6–10	28	7.53	0.72	6–9	30
1974	7.52	1.02	6–10	48	7.39	1.08	5–11	67	7.53	1.20	6–10	15	7.29	0.98	5–9	21	7.46	0.89	6–9	26	7.36	1.11	6–11	28
1975	7.63	0.91	6–9	40	7.48	0.95	5–9	71	7.67	0.79	6–9	15	7.38	1.03	5–9	34	7.64	1.02	6–9	22	7.67	0.77	6–9	27
1976	7.63	1.14	6–10	51	7.62	1.19	5–10	61	7.80	1.11	6–9	15	7.81	1.33	5–10	26	7.55	1.19	6–10	31	7.42	0.95	6–9	24
1977	7.77	1.27	5–10	53	7.53	1.13	5–10	60	8.25	1.30	6–10	16	7.69	1.05	5–10	29	7.52	1.16	5–10	31	7.56	1.12	5–10	18
1978	7.91	1.18	5–11	55	7.85	0.84	6–9	52	7.86	0.91	6–9	14	8.10	0.77	7–9	20	7.94	1.32	5–11	33	7.59	0.84	6–9	17
1979	7.89	1.07	5–11	55	7.55	1.04	5–9	62	7.84	1.23	5–11	19	7.48	1.06	5–9	23	7.80	1.02	6–10	25	7.57	0.94	6–9	28
1980	7.79	1.26	5–11	48	7.73	0.94	5–9	62	7.95	1.43	5–11	20	7.65	0.90	6–9	31	7.74	1.25	5–10	19	8.00	0.62	7–9	21
1981	8.19	0.95	6–11	53	7.63	1.06	6–11	63	8.05	0.64	7–9	22	7.48	0.93	6–9	29	8.35	1.13	6–11	23	7.81	1.26	6–11	21
1982	7.88	1.00	5–10	76	7.77	0.90	6–10	82	8.03	1.02	5–10	30	7.88	0.90	6–10	34	7.91	0.95	6–10	34	7.84	0.83	6–10	32
1983	7.86	1.12	5–11	81	7.60	1.06	5–10	88	7.85	1.00	6–10	39	7.70	1.00	5–10	40	7.91	1.11	6–10	33	7.68	1.07	6–10	28
1984	7.92	1.14	5–10	64	7.65	1.14	5–11	71	8.00	1.02	5–10	21	7.96	0.98	7–11	24	7.82	1.17	6–10	34	7.34	1.21	5–9	29
1985	7.89	1.18	5–10	83	7.45	1.03	6–10	66	8.00	1.05	6–10	36	7.46	1.18	6–10	28	7.84	1.18	5–10	38	7.48	0.94	6–9	25
1986	7.80	1.08	5–10	64	7.52	0.92	5–9	60	7.81	0.96	6–10	21	7.38	0.90	5–9	24	7.63	1.07	5–10	35	7.85	0.79	6–9	20
1987	7.63	1.27	5–10	54	7.64	1.26	5–11	78	7.74	1.29	5–10	27	7.61	1.28	5–11	33	7.40	1.32	5–10	20	7.57	1.12	5–11	30
1988	7.86	1.13	6–11	72	7.43	1.10	5–10	58	7.75	0.97	6–10	40	7.57	1.28	5–10	23	7.96	1.34	6–11	26	7.38	0.90	6–9	21
1989	7.94	1.12	6–10	53	7.38	1.20	5–10	52	8.21	0.89	7–10	19	7.48	1.13	5–10	27	7.83	1.34	6–10	23	7.11	1.15	5–9	18
1990	7.91	1.44	5–11	44	7.70	1.05	6–11	47	7.53	1.53	5–11	19	7.53	0.92	6–9	30	8.14	1.36	6–10	21	8.07	1.24	6–11	15
1991	7.93	1.09	6–10	54	7.53	0.93	6–10	45	8.08	1.15	6–10	24	7.33	0.90	6–9	24	7.84	1.05	6–10	25	8.07	0.85	7–10	15
1992	7.96	1.07	5–10	54	7.72	0.90	5–10	46	7.83	0.90	7–9	12	7.83	1.07	5–10	24	8.06	1.20	5–10	32	7.63	0.70	6–9	16
1993	7.56	0.89	5–9	52	7.27	1.12	5–9	45	7.27	1.01	5–9	22	7.38	1.11	5–9	24	7.88	0.65	6–9	25	7.08	1.14	5–9	13
1994	7.89	1.05	5–10	44	7.37	0.93	6–9	38	7.68	1.13	5–10	19	7.31	0.85	6–9	16	8.18	0.92	7–10	17	7.25	0.90	6–9	16
1995	7.50	1.27	5–10	32	7.55	0.94	6–10	31	7.36	0.81	6–9	14	7.57	0.73	6–9	14	7.56	1.46	5–10	16	7.78	1.23	6–10	9
1996	7.81	0.96	6–10	26	7.79	0.77	7–9	19	7.85	1.10	6–10	13	7.83	0.90	7–9	6	7.73	0.86	7–9	11	7.75	0.72	7–9	12
1997	7.78	1.07	6–11	27	7.33	1.11	6–10	24	8.50	1.20	7–11	10	7.64	0.88	6–9	11	7.38	0.70	6–8	16	7.17	1.21	6–10	12
1998	7.73	1.11	6–10	33	7.58	1.23	5–10	19	8.11	0.87	7–9	9	8.50	1.12	7–10	4	7.58	1.15	6–10	24	7.36	0.98	6–9	11
1999	7.90	1.27	6–10	21	7.47	0.99	5–9	19	7.22	1.13	6–9	9	7.22	1.13	5–9	9	8.42	1.11	6–10	12	7.78	0.79	7–9	9
2000	7.40	1.36	6–10	10	7.11	0.87	6–9	9	7.20	1.47	6–10	5	7.25	0.83	6–9	8	7.60	1.20	6–9	5	6.00	—	—	1
2001	8.00	0.58	7–9	12	8.00	1.04	6–9	13	8.00	0.00	8–8	5	8.17	1.07	6–9	6	8.00	0.76	7–9	7	7.86	0.99	6–9	7
2002	7.64	0.88	6–9	11	8.09	1.16	6–10	11	8.00	—	—	1	8.11	1.29	6–10	9	7.56	0.96	6–9	9	8.00	0.00	8–8	2
2003	6.86	0.83	5–8	7	7.62	1.08	6–10	13	7.50	0.50	7–8	2	8.00	1.00	7–10	8	6.60	0.80	5–7	5	7.00	0.89	6–8	5
2004	8.00	1.20	6–9	7	7.54	0.84	6–9	13	8.00	1.00	7–9	4	7.54	0.84	6–9	13	8.00	1.41	6–9	3	—	—	—	—
2005	8.25	0.83	7–9	4	7.50	1.50	5–9	4	8.33	0.94	7–9	3	7.50	1.50	5–9	4	8.00	—	—	1	—	—	—	—
2006	—	—	—	—	7.6	0.80	7–9	5	—	—	—	—	7.60	0.80	7–9	5	—	—	—	—	—	—	—	—
total	8.00	1.31	4–13	2,078	7.78	1.30	4–15	2,339	8.01	1.29	4–13	814	7.85	1.35	4–15	1,118	7.93	1.27	5–13	975	7.69	1.15	5–12	763

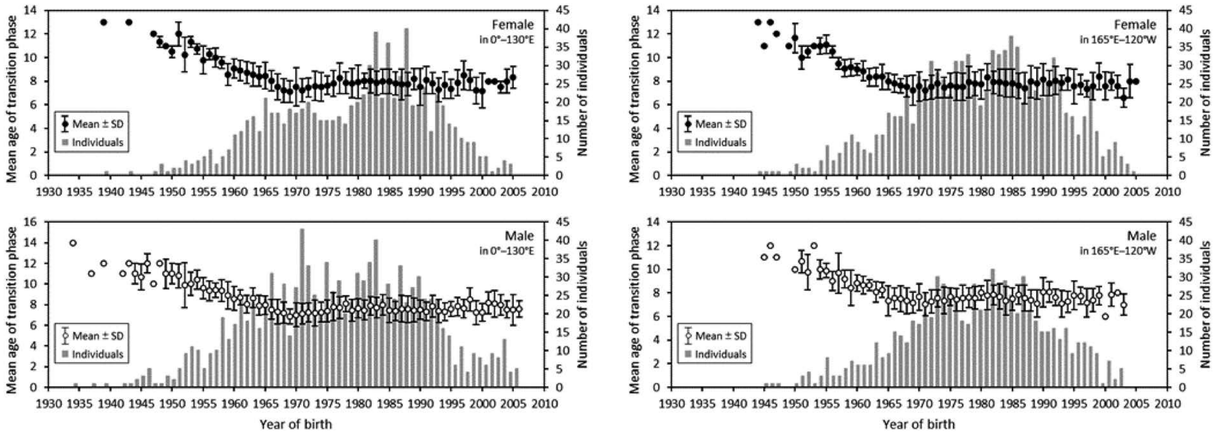

Figure 4. Temporal trend of sexual maturity by transition phase of Antarctic minke whales by year class, sex and stock (left: I-stock; right: P-stock).

SUMMAY AND INTERPRETATION OF RESULTS

The previous study by Bando *et al.* (2014) examined the age at sexual maturity (based on a transition phase) until the 1998′s year class. This study updated the analyses by examining seven additional year classes (1999–2006). The updated analyses confirmed that the age at sexual maturity of this species declined from 10–12 years old in the mid-1940s year classes to 7–8 years old in the early 1970s year classes, and that has remained stable at that level till the 2000s year classes. There were no substantial differences when the analyses were conducted by stock.

Although some significant statistical trends were found for the recent year classes (from the 1970′s), the extent of such changes, when confirmed, is very small in comparison with the extent of the changes observed in the middle of the past century. In general, the age at sexual maturity in recent year classes (from the 1970′s) has remained stable at around 7–9 years old.

The results of stable age at sexual maturity in this study should be examined in conjunction with the information on recent trends in other biological and ecological aspects. In recent years the Antarctic minke whale has maintained a high apparent pregnancy rate of over 90% (Bando *et al.*, 2006); the recruitment estimated by Statistical Catch-At-Age (SCAA) analysis has not increased and has remained somewhat constant at a level that is not as high as that observed between 1940 and 1970 (Punt *et al.*, 2014); and a decrease in blubber thickness and average stomach contents weight has been reported (blubber thickness: Konishi *et al.*, 2008; stomach contents: Konishi *et al.*, 2014). In addition, Antarctic minke whales have been observed in polynyas in recent years while an increase in the abundance of other large whale species has been reported (e.g. humpback whale: Hakamada and Matsuoka, 2014; fin whale: Matsuoka and Hakamada, 2014). These results are consistent with the following two hypotheses:

Hypothesis 1: interspecific competition for krill resources

Under this hypothesis, the deteriorating nutritional conditions of the Antarctic minke whale are a consequence of limited krill availability, which in turn is due to the increase in the abundance of other krill-eater whale species. The distribution of Antarctic minke whales in polynyas is part of this hypothesis as the increasing abundance (and expanded distribution) of other large whale species has pushed the Antarctic minke whale to find other areas for feeding. The observations that the recruitment has not increased in recent years and remaining somewhat constant at a level but not as high as that observed between 1940 and 1970, and that the abundance of Antarctic minke whale has remained constant/slightly decreased are consistent with this hypothesis. The apparent contradiction between low age at sexual maturity/high pregnancy rates and current recruitment rates are due to a temporal phenomenon in which the response of biological parameters to environmental changes (food limitation) may be subjected to time lags (Bjerke and Walløe, in press).

Hypothesis 2: the environmental conditions for Antarctic minke whale remain optimal

Low age at sexual maturity and high pregnancy rates are consistent with this hypothesis. Although the nutritional conditions have deteriorated slightly, such conditions are not critical for the population. The observations that the recruitment has not increased and has remained somewhat constant at a level but not as high as that observed between 1940 and 1970, and that the abundance trends have remained constant are a reflection of the constraints of the surveys, which cannot cover new areas of distribution of the Antarctic minke whale such as the polynyas. Colonizing of new areas by the Antarctic minke whale has been facilitated by environmental changes such as the increase of surface temperature, which are opening new routes into the pack ice.

Further monitoring of biological and ecological parameters of the Antarctic minke whale is required to discern between the two proposed hypotheses. Also, additional analytical procedures are required. For example, in the case of the age at sexual maturity based on transition phase, model-based analysis (e.g. Thomson *et al.*, 1999), should be used in the future to further address the truncation bias and the fringe effect of age data at the transition phase in earplugs.

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