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Temporal trend of total mercury levels in common minke, sei and Bryde′s whales in the western North Pacific in the period 1994–2014

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ABSTRACT

To examine yearly changes of total mercury (Hg) concentrations in common minke (*Balaenoptera acutorostrata*), sei (*B. borealis*) and Bryde′s (*B. edeni*) whales in the western North Pacific, total Hg concentrations were measured in muscle samples from whales collected between 1994 and 2014 by JARPN/JARPNII. Averages and standard deviations of total Hg concentrations in the samples of mature male common minke whales from coastal area off Kushiro and Sanriku were 0.22±0.05, 0.22±0.06, ppm wet wt, and from offshore sub-areas 7, 8 and 9 were 0.22±0.05, 0.22±0.06 and 0.24±0.10 ppm, respectively. The concentration in sei whales from sub-area 9 was 0.044±0.013 ppm, and that in Bryde′s whales from sub-areas 8 and 9 was 0.044±0.013 ppm. Multiple robust linear regression analysis was carried out considering several variables: sampling year, sampling location (longitude and latitude), sampling date, body length, blubber thickness and main prey item observed in their stomach. Results of the analyses can be summarized as follow: no significant yearly changes of total Hg concentrations in muscle of common minke whales off Kushiro, Sanriku and sub-area 8; no significant yearly changes of total Hg concentrations in muscle of Bryde′s whales in sub-areas 8 and 9; significant yearly changes of total Hg concentrations in muscle of minke whales from sub-areas 7 and 9, and significant yearly changes of total Hg concentrations in muscle of sei whales from sub-area 9. Temporal trends of total Hg concentrations have not been observed in environmental samples, lower trophic organisms and baleen whales, except for those cases mentioned above. Temporal changes in total Hg concentrations in common minke whales (sub-areas 7 and 9) and sei whales (sub-area 9) may reflect changes in their food habits rather than changes of background levels of total Hg in the marine environment. Consequently, it is concluded that the temporal trend of total Hg concentrations in the marine habitat of baleen whales in the western North Pacific remained stable in the research period.

INTRODUCTION

Mercury (Hg) is one of the most neurotoxic chemicals to human and wildlife in the environment. It is released into the ocean from a variety of sources such as volcanic emission, degassing from soil and combustion of coal from power plants. It is released in the form of elemental mercury, and is accumulated into top predators through the food chain in the marine ecosystem. There is a need to monitor Hg in the oceans.

Cetaceans have been used to monitor spatial and temporal trends of Hg in the oceans (Sanpera *et al.*, 1993; Borrell and Reijnders, 1999). Pollutants can be monitored in wide areas and integrated in some way over time by using cetacean as indicators because they are located at the top of the food chain in the marine ecosystem, and are mobile and long-lived animals.

The present study examines temporal changes of total Hg concentrations in common minke, sei and Bryde′s whales in the western North Pacific. To understand the pattern of accumulation of total Hg in whales it is important to consider some biological information such as sex and sexual maturity of the animals, and ecological information such as feeding habits of whales and indicators of body condition. The present study, which is based on samples collected by the Japanese Whale Research Program under Special Permit in the western North Pacific (JARPN) and its Second Phase, JARPNII in the period 1994–2014, considers such biological and ecological information to understand and interpret the pattern of accumulation of Hg in whales.

MATERIALS AND METHODS

Whale sampling

Common minke (1994–2014), sei (2002–2014) and Bryde′s (2002–2013) whales were sampled in sub-areas 7, 8 and 9 under the JARPN and JARPNII. In addition common minke whales were sampled in coastal areas off Sanriku (2003–2014) and off Kushiro (2002–2014) (Figure 1). Details of the sampling procedures are given in Tamura *et al.* (this TEREP-ICR issue).

For all sampled whales, biological sampling and measurements were conducted on the research base vessel, *Nisshin-maru* in the offshore component (JARPN/JARPNII), and at the land research stations in the case of the coastal component (JARPNII).

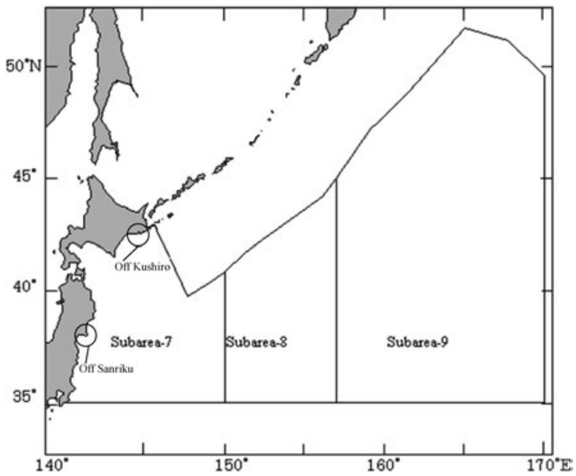

Figure 1. Sub-areas surveyed by the JARPN and the JARPNII surveys, excluding the EEZ of foreign countries.

Tissue sampling for Hg analysis

Figure 2 shows the overall process for Hg analysis from the tissue sampling at the field to the laboratory work. Muscle tissues were collected for total Hg analysis.

Biological information

The kind of biological information obtained from each sampled whale was described by Bando (this TEREP-ICR issue). In this study information on body length, blubber thickness and reproductive status of whales was used. Only mature male animals were used. Males of common minke, Bryde′s and sei whales were defined as sexually mature by testis weight of more than 290 g, 560 g and 1,090 g (heavier side), respectively. Only common minke whales from the Okhotsk Sea-West Pacific stock (O-stock) as identified by the microsatellite DNA analysis (Goto *et al.*, this TEREP-ICR issue), were used.

The forestomach contents have proved sufficient for determination of the common minke whale diet (see Konishi *et al.*, this TEREP-ICR issue). Data on prey composition and prey′s Hg concentrations used in the present study were based on contents from forestomach and analyses conducted by Yasunaga and Fujise (2009) and MHLW (2005).

Tables 1–3 show the number of samples by sub-area and year, and the biological information used for common minke, sei and Bryde′s whales in this study.

Measurement of total mercury concentration in muscle of whales

Total Hg analysis was conducted at the laboratory of the Institute of Cetacean Research (ICR) in Tokyo and also at the

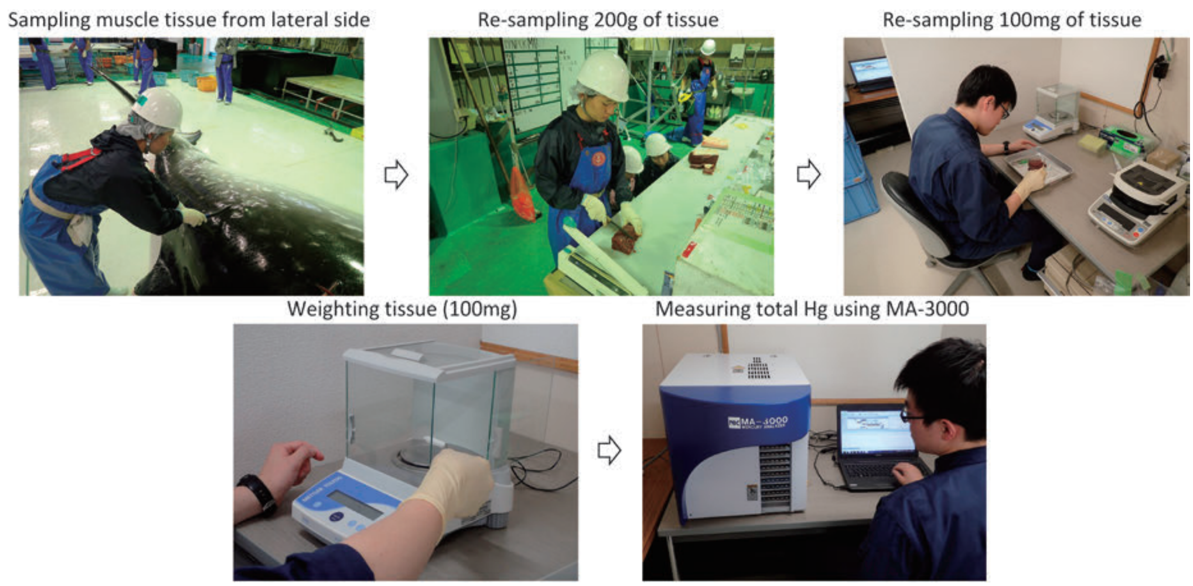

Figure 2. Schematic diagram of total Hg analysis in muscle tissue of whales.

Table 1

Biological data and total mercury concentrations in muscle of common minke whales (mature males) from the western North Pacific during 1994 and 2014.

Sub area	Year	*n*	Body length (m)	Blubber thickness (cm)	Muscular Hg (ppm wet wt.)
7	1996	18	(7.36±0.28)	(3.1±0.4)	(0.23±0.05)
	1998	35	(7.50±0.27)	(2.6±0.4)	(0.20±0.05)
	1999	31	(7.41±0.29)	(3.6±0.8)	(0.20±0.04)
	2000	6	(7.30±0.25)	(3.6±1.0)	(0.24±0.04)
	2001	27	(7.45±0.31)	(2.4±0.5)	(0.21±0.04)
	2002	33	(7.52±0.27)	(3.7±0.8)	(0.22±0.03)
	2003	11	(7.42±0.40)	(2.4±0.5)	(0.20±0.07)
	2004	6	(7.56±0.21)	(4.1±0.6)	(0.22±0.02)
	2005	17	(7.51±0.23)	(3.3±0.9)	(0.27±0.04)
	2006	16	(7.39±0.39)	(2.4±0.7)	(0.22±0.05)
	2007	41	(7.47±0.26)	(3.0±0.7)	(0.23±0.04)
	2009	11	(7.71±0.26)	(3.2±0.7)	(0.21±0.06)
	2011	23	(7.47±0.34)	(3.5±0.6)	(0.25±0.05)
	2012	19	(7.37±0.34)	(2.6±0.4)	(0.24±0.08)
	Total	294	(7.46±0.30)	(3.1±0.8)	(0.22±0.05)
Kushiro	2002	14	(7.22±0.34)	(4.3±1.0)	(0.21±0.06)
	2004	23	(7.43±0.24)	(4.2±0.6)	(0.20±0.03)
	2005	25	(7.44±0.32)	(3.5±0.6)	(0.25±0.05)
	2006	10	(7.52±0.29)	(4.4±0.8)	(0.22±0.03)
	2007	14	(7.33±0.59)	(4.1±0.8)	(0.23±0.06)
	2008	5	(7.26±0.21)	(4.3±1.0)	(0.25±0.01)
	2009	6	(7.54±0.37)	(4.3±0.4)	(0.21±0.07)
	2010	3	(7.49±0.21)	(3.8±0.4)	(0.23±0.02)
	2011 spring	4	(7.40±0.41)	(3.2±0.6)	(0.24±0.03)
	2011 autumn	10	(7.26±0.37)	(4.4±1.0)	(0.23±0.02)
	2012	5	(7.48±0.21)	(5.0±0.7)	(0.21±0.06)
	2013	23	(7.33±0.35)	(5.0±0.9)	(0.19±0.04)
	2014	10	(7.33±0.28)	(5.0±0.8)	(0.21±0.09)
	Total	152	(7.38±0.35)	(4.3±0.9)	(0.22±0.05)
Sanriku	2003	8	(7.10±0.35)	(2.9±0.5)	(0.18±0.04)
	2005	3	(7.27±0.13)	(2.5±0.3)	(0.29±0.02)
	2006	6	(7.24±0.32)	(2.8±0.2)	(0.19±0.05)
	2007	10	(7.50±0.30)	(2.5±0.4)	(0.25±0.08)
	2008	3	(7.49±0.32)	(3.2±0.3)	(0.19±0.03)
	2009	1	(6.85±)	(2.8±)	(0.21±)
	2010	5	(7.32±0.24)	(3.1±0.6)	(0.20±0.05)
	2012	2	(7.31±)	(3.4±)	(0.18±)
	2013	2	(7.52±)	(3.5±)	(0.30±)
	2014	2	(7.38±0.39)	(2.7±0.3)	(0.31±0.04)
	Total	42	(7.32±0.32)	(2.8±0.5)	(0.22±0.06)

field research stations of the coastal and offshore components. The muscle sample was stripped externally to avoid contamination before analysis, approximately 100 mg of tissue was weighed, and set on the total Hg analyser (Nippon Instruments Co., MA-3000) which applies a thermal decomposition system (Figure 2). To increase the accuracy of the determination, triplicate analyses were performed on each sample. Accuracy and precision of the present system were confirmed using standard reference materials, DORM-3 (NRCC, muscle of dogfish).

Table 1
Continued.

Sub area	Year	n	Body length (m)	Blubber thickness (cm)	Muscular Hg (ppm wet wt.)
8	1996	11	(7.44±0.33)	(2.6±0.5)	(0.25±0.04)
	1997	26	(7.44±0.36)	(3.5±0.6)	(0.27±0.06)
	1998	28	(7.54±0.25)	(2.6±0.4)	(0.23±0.05)
	2001	13	(7.78±0.34)	(2.3±0.4)	(0.21±0.05)
	2002	5	(7.71±0.21)	(3.2±0.6)	(0.20±0.11)
	2003	27	(7.50±0.24)	(2.4±0.4)	(0.18±0.06)
	2005	2	(7.54±)	(2.2±)	(0.16±)
	2006	24	(7.51±0.26)	(2.9±0.6)	(0.21±0.05)
	2007	10	(7.55±0.26)	(2.3±0.4)	(0.22±0.06)
	2008	3	(7.52±0.05)	(2.7±0.4)	(0.23±0.02)
	2009	6	(7.23±0.34)	(3.2±0.6)	(0.20±0.06)
	Total	155	(7.52±0.30)	(2.8±0.6)	(0.22±0.06)
9	1994	16	(7.42±0.27)	(3.5±0.7)	(0.36±0.16)
	1995	68	(7.45±0.31)	(3.1±0.5)	(0.27±0.06)
	1997	39	(7.41±0.32)	(3.1±0.5)	(0.25±0.11)
	2000	12	(7.51±0.23)	(2.6±0.5)	(0.16±0.03)
	2001	19	(7.69±0.29)	(2.5±0.4)	(0.19±0.05)
	2002	21	(7.55±0.21)	(2.9±0.6)	(0.20±0.05)
	2003	28	(7.50±0.32)	(2.9±0.6)	(0.18±0.05)
	2004	50	(7.47±0.21)	(3.9±0.7)	(0.20±0.07)
	2005	25	(7.49±0.29)	(3.5±0.6)	(0.17±0.05)
	2006	16	(7.56±0.30)	(3.4±0.6)	(0.28±0.08)
	2007	4	(7.56±0.20)	(2.2±0.3)	(0.18±0.09)
	2008	36	(7.45±0.26)	(3.1±0.7)	(0.30±0.15)
	2009	5	(7.41±0.41)	(3.0±0.8)	(0.19±0.06)
	2010	9	(7.66±0.23)	(3.2±0.5)	(0.22±0.03)
	2013	3	(7.59±0.22)	(4.0±1.3)	(0.19±0.06)
	Total	351	(7.49±0.28)	(3.2±0.7)	(0.24±0.10)

Table 2
Biological data and mercury concentrations in muscle of sei whales (mature males) from the western North Pacific during 2002 and 2014.

Sub area	Year	n	Body length (m)	Blubber thickness (cm)	Muscular Hg (ppm wet wt.)
9	2002	5	(13.60±0.16)	(4.7±0.5)	(0.050±0.012)
	2003	5	(13.80±0.43)	(4.7±0.7)	(0.057±0.007)
	2004	5	(13.61±0.04)	(4.1±0.6)	(0.050±0.009)
	2005	5	(13.54±0.38)	(4.8±0.6)	(0.049±0.011)
	2006	5	(13.84±0.51)	(4.9±0.6)	(0.052±0.006)
	2007	5	(13.92±0.08)	(5.8±0.7)	(0.058±0.010)
	2011	15	(13.82±0.42)	(4.8±0.8)	(0.039±0.009)
	2012	21	(13.74±0.45)	(5.0±0.5)	(0.030±0.011)
	2013	26	(13.76±0.50)	(5.6±0.8)	(0.040±0.009)
	2014	21	(13.80±0.36)	(4.8±0.5)	(0.053±0.009)
Total	2002–2014	113	(13.76±0.41)	(5.0±0.8)	(0.044±0.013)

Table 3
Biological data and mercury concentrations in muscle of Bryde's whales (mature males) from the western North Pacific during 2002 and 2013.

Sub area	Year	*n*	Body length (m)	Blubber thickness (cm)	Muscular Hg (ppm wet wt.)
8, 9	2002	5	(12.67±0.43)	(4.5±0.6)	(0.051±0.008)
	2004	5	(12.59±0.36)	(4.4±0.7)	(0.045±0.008)
	2006	5	(12.36±0.47)	(4.5±0.5)	(0.040±0.011)
	2007	5	(12.63±0.35)	(3.9±0.7)	(0.049±0.008)
	2011	3	(12.31±0.27)	(3.6±0.5)	(0.022±0.005)
	2012	6	(12.85±0.48)	(4.8±1.0)	(0.046±0.019)
	2013	9	(12.79±0.38)	(4.7±0.8)	(0.047±0.010)
Total	2002–2013	38	(12.64±0.41)	(4.4±0.8)	(0.044±0.013)

Statistical analysis
The yearly changes of total Hg concentrations in muscle of whales were assessed by multiple robust linear regression in the context of several variables (R Development Core Team, 2006). The following independent variables were considered: 'Year,' 'Date,' 'Latitude,' 'Longitude,' 'Body length,' 'Blubber thickness' and 'Main prey item'. All variables except the main prey item, were logarithmically transformed.

Categorical parameters of main prey items used in the analyses were the following: minke whale and sub-area 7 (Japanese anchovy: *Engraulis japonicus*, Euphausiids, Japanese flying squid: *Todarodes pacificus*, mackerel: *Scomber japonicus*, Japanese sardine: *Sardinops melanostictus*, Pacific saury: *Cololabis saira* and walleye pollock: *Theragra chalcogramma*); minke whale and sub-area 8 (anchovy, copepods, Euphausiids, Japanese flying squid, mackerel and Pacific saury); minke whale and sub-area 9 (anchovy, Atka mackerel: *Pleurogrammus monopterygius*, Copepods, Euphausiids, mackerel, minimal armhook squid: *Berryteuthis anonychus*, oceanic lightfish: *Vinciguerria nimbaria*, Pacific pomfret: *Brama japonica*, salmonids, Pacific saury); sei whale and sub-area 9 (Japanese anchovy, Copepods, Euphausiids, mackerel, minimal armhook squid, Japanese sardine and Pacific saury); Bryde's whale and sub-areas 8 and 9 (Japanese anchovy, Euphausiids and mackerel). Anchovy is the baseline prey item in sub-areas 7–9 so the effects of anchovy being the main prey item are included in the model intercepts. Categorical parameters of main prey items were not used in the case of Sanriku and Kushiro. In Sanriku the prey items of common minke whales were almost all sand lance. In Kushiro the diversity of prey items was too high in relation to the number of whale samples.

The cases of whales with empty stomach and damage by harpoon were excluded from the analysis. Furthermore, a generalized additive model (GAM) was used to examine the flexion point in the yearly changes of total Hg concentrations in muscle of whales. A *p* value of less than 0.05 was considered to indicate statistical significance in all tests. These statistical analyses were performed using the free software R, version 3.3.0.

RESULTS

Tables 1–3 show the total Hg concentrations in muscle of common minke, sei and Bryde's whales, respectively.

The results of multiple robust linear regression to examined yearly changes in the context of several variables are given in Tables 4–10. F statistics showed that the overall regression was statistically significant in all cases ($p<0.05$). Only in the cases of minke whales from sub-areas 7 and 9 (Tables 4, 8), and sei whales from sub-area 9 (Table 9), the total Hg concentrations were significantly associated with sampling year. In these cases the simple and GAM plots against research year are shown in Figures 3 and 4 for minke whales in sub-areas 7 and 9, respectively, and in Figure 5 for sei whale in sub-area 9.

Slight flexion points of yearly trends of muscular total Hg were observed in minke whales from sub-area 9 in 2008 and in sei whales from sub-area 9 in 2012.

DISCUSSION

Results of the analyses can be summarized as follows: no significant yearly changes of total Hg concentrations in muscle of common minke whales off Kushiro, Sanriku and sub-area 8; no significant yearly changes of total Hg concentrations in muscle of Bryde's whales in sub-areas 8 and 9; significant yearly changes of total Hg concentrations in muscle of minke whales from sub-areas 7 and 9, and significant yearly changes of total Hg concentrations in muscle of sei whales from sub-area 9.

It should be noted here that no significant trends of total Hg concentrations were found in prey species such as the krill, Japanese anchovy and Pacific saury from 1994

Table 4
Results of multiple robust linear regression analysis with ′total Hg levels in muscle of common minke whales from subarea 7′ as the dependent variable.

a) Analysis of Variance

Source	
Robust residual SE	0.20
R^2	0.135
Adjusted R^2	0.0969

b) Variables

Model	B	SE	T	*p* value
Intercept	−198.59771	53.16048	−3.736	***p*<0.05**
Year	26.054	6.788	3.84	***p*<0.05**
Body length	−0.138	0.237	−0.58	0.559
Blubber thickness	0.059	0.060	0.98	0.328
Latitude	−0.156	0.541	−0.29	0.773
Longitude	−0.064	0.568	−0.11	0.911
Date	0.038	0.017	2.21	***p*<0.05**
MainPrey_Euphausiids	0.076	0.045	1.70	0.089
MainPrey_JFSquid	0.062	0.054	1.15	0.250
MainPrey_Mackerel	0.372	0.026	14.53	***p*<0.05**
MainPrey_Sardine	−0.294	0.036	−8.25	***p*<0.05**
MainPrey_Saury	0.097	0.047	2.07	***p*<0.05**
MainPrey_WalleyePollock	0.138	0.049	2.83	***p*<0.05**

Table 5
Results of multiple robust linear regression analysis with ′total Hg levels in muscle of common minke whales from off Kushiro′ as the dependent variable.

a) Analysis of Variance

Source	
Robust residual SE	0.2834
R^2	0.3472
Adjusted R^2	0.3176

b) Variables

Model	B	SE	T	*p* value
Intercept	63.6	98.2	0.648	0.518
Year	−2.14	10.61	−0.20	0.840
Body length	0.904	0.843	1.07	0.285
Blubber thickness	−0.322	0.077	−4.15	***p*<0.05**
Latitude	5.384	6.941	0.78	0.439
Longitude	−14.215	13.618	−1.04	0.298
Date	0.119	0.149	0.80	0.424

Table 6
Results of multiple robust linear regression analysis with ′total Hg levels in muscle of common minke whales from off Sanriku′ as the dependent variable.

a) Analysis of Variance

Source	
Robust residual SE	0.2543
R^2	0.2374
Adjusted R^2	0.1067

b) Variables

Model	B	SE	T	*p* value
Intercept	−50.2	286.8	−0.175	0.862
Year	31.50	44.65	0.71	0.485
Body length	−0.029	0.025	−1.15	0.257
Blubber thickness	−0.400	0.274	−1.46	0.153
Latitude	23.792	17.674	1.35	0.187
Longitude	−56.288	43.990	−1.28	0.209
Date	1.079	0.569	1.90	0.066

Table 7
Results of multiple robust linear regression analysis with ′total Hg levels in muscle of common minke whales from subarea 8′ as the dependent variable.

a) Analysis of Variance

Source	
Robust residual SE	0.2439
R^2	0.3021
Adjusted R^2	0.2473

b) Variables

Model	B	SE	T	*p* value
Intercept	163.35009	95.210	1.716	0.088
Year	−17.288	13.636	−1.27	0.207
Body length	1.219	0.534	2.29	***p*<0.05**
Blubber thickness	0.288	0.108	2.67	***p*<0.05**
Latitude	−0.281	1.628	−0.17	0.863
Longitude	−7.181	2.778	−2.59	***p*<0.05**
Date	0.495	0.699	0.71	0.481
MainPrey_Copepods	−0.020	0.080	−0.25	0.805
MainPrey_Euphausiids	−0.104	0.144	−0.72	0.471
MainPrey_JFSquid	−0.137	0.101	−1.36	0.175
MainPrey_Mackerel	0.309	0.170	1.82	0.072
MainPrey_Saury	0.180	0.063	2.84	***p*<0.05**

to 2008 (Yasunaga and Fujise, 2009), and that total Hg concentrations in surface water of the North Pacific did not change from the 1980′s to 2000′s (Laurier *et al.*, 2004; Sunderland *et al.*, 2009).

Firstly those cases where significant yearly trend was observed, are discussed.

In sub-area 7, total Hg concentrations in muscle of common minke whales (period 1996–2012) were significantly associated with Intercept (−), Year (+), Date (+), Main prey items (mackerel, sardine, saury and Walleye pollock) (Table 4). A comparison of total Hg concentrations in muscle of common minke whale and in the whole

Table 8

Results of multiple robust linear regression analysis with 'total Hg levels in muscle of common minke whales from subarea 9' as the dependent variable.

a) Analysis of Variance

Source	
Robust residual SE	0.2834
R^2	0.3472
Adjusted R^2	0.3176

b) Variables

Model	B	SE	T	*p* value
Intercept	330.3	55.7	5.932	***p*<0.05**
Year	−43.74	7.31	−5.99	***p*<0.05**
Body length	0.150	0.441	0.34	0.735
Blubber thickness	0.164	0.092	1.78	0.076
Latitude	1.809	0.672	2.69	***p*<0.05**
Longitude	−0.784	0.899	−0.87	0.384
Date	−1.424	0.301	−4.73	***p*<0.05**
MainPrey_AtkaMackerel	−0.368	0.076	−4.86	***p*<0.05**
MainPrey_Copepods	0.044	0.224	0.20	0.843
MainPrey_Euphausiids	−0.177	0.159	−1.12	0.266
MainPrey_Mackerel	0.050	0.139	0.36	0.722
MainPrey_MAFSquid	−0.386	0.209	−1.84	0.066
MainPrey_OceanicLightfish	−0.439	0.060	−7.30	***p*<0.05**
MainPrey_PacificPomfret	0.930	0.335	2.78	***p*<0.05**
MainPrey_Salmonids	0.213	0.132	1.61	0.108
MainPrey_Saury	0.188	0.050	3.73	***p*<0.05**

body of the main prey species in the stomachs is shown in Table 11. Total Hg concentrations in minke whales having mackerel in the stomach were the highest while those having sardine in stomach was the lowest. The number of minke whales having mackerel and sardine in their stomach were only one and two whales, respectively. These observations indicate that total Hg concentrations of common minke whales from sub-area 7 may be less affected by total Hg in the prey species.

In sub-area 9, total Hg concentrations in muscle of common minke whales (period 1996–2012) were significantly associated with Intercept (+), Year (−), Latitude (+), Date (−) and Main prey items (Atka mackerel, oceanic lightfish, Pacific pomfret and saury) (Table 8). A comparison of total Hg concentrations in muscle of minke whale and in the whole body of the main prey species in the stomachs is shown in Table 12. Total Hg concentrations in common minke whales having Pacific pomfret in their stomach were the highest, and total Hg concentrations in Pacific pomfret were one or two orders of magnitude higher than those in the other prey items. Also total Hg concentrations in common minke whales having zooplankton such as copepods and euphausiids were lower than the others. Total Hg concentrations in the zooplankton were one or two orders of magnitude lower than those in the other prey items. Furthermore, yearly changes were observed in food items of the common minke whales in the same period (Konishi *et al.*, 2016).

Table 9

Results of multiple linear regression analysis with 'total Hg levels in muscle of sei whales from subarea 9' as the dependent variable.

a) Analysis of Variance

Source	
Robust residual SE	0.2526
R^2	0.3344
Adjusted R^2	0.2293

b) Variables

Model	B	SE	T	*p* value
Intercept	405.9	137.4	2.954	***p*<0.05**
Year	−54.46	18.35	−2.97	***p*<0.05**
Body length	3.579	1.029	3.48	***p*<0.05**
Blubber thickness	0.024	0.262	0.09	0.927
Latitude	0.910	1.188	0.77	0.446
Longitude	−1.233	1.431	−0.86	0.392
Date	−0.602	0.481	−1.25	0.215
MainPrey_Copepods	−0.182	0.096	−1.90	0.061
MainPrey_Euphausiids	−0.259	0.159	−1.63	0.107
MainPrey_Mackerel	−0.064	0.097	−0.66	0.510
MainPrey_Min.arm squid	−0.012	0.105	−0.12	0.906
MainPrey_Sardine	0.193	0.104	1.85	0.069
MainPrey_Saury	−0.136	0.096	−1.41	0.164

Table 10

Results of multiple robust linear regression analysis with 'total Hg levels in muscle of Bryde's whales from subareas 8 and 9' as the dependent variable.

a) Analysis of Variance

Source	
Robust residual SE	0.2025
R^2	0.3592
Adjusted R^2	0.1029

b) Variables

Model	B	SE	T	*p* value
Intercept	−101.1	162.8	−0.621	0.541
Year	9.93	22.02	0.45	0.657
Body length	2.431	1.453	1.67	0.110
Blubber thickness	−0.320	0.317	−1.01	0.325
Latitude	1.693	1.534	1.10	0.283
Longitude	1.933	2.810	0.69	0.499
Date	0.503	0.376	1.34	0.196
MainPrey_Euphausiids	−0.106	0.071	−1.51	0.148
MainPrey_Mackerel	−0.240	0.274	−0.88	0.391

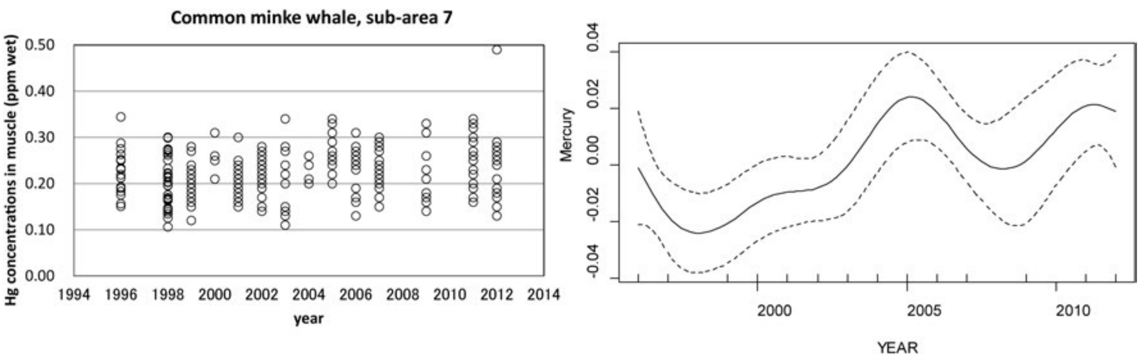

Figure 3. Simple plots and smoothing plots using the generalized additive model of total Hg concentrations in muscle of common minke whales (mature males, O-stock) in sub-area 7 against research years during the period 1996–2012.

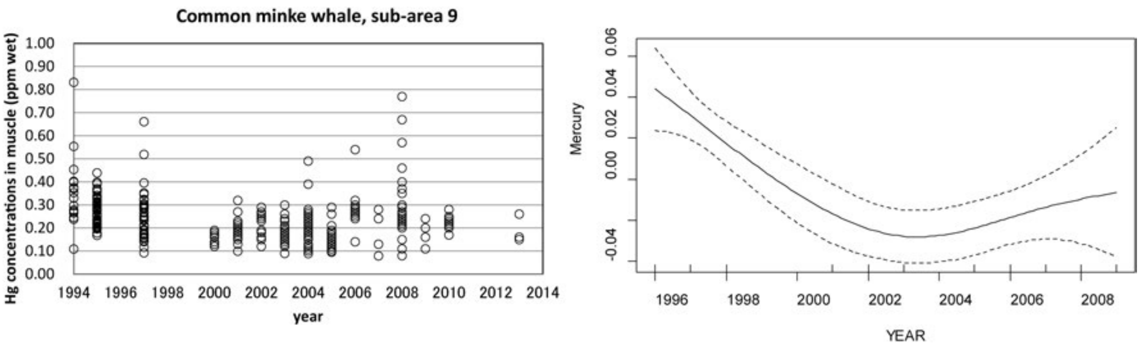

Figure 4. Simple plots and smoothing plots using the generalized additive model of total Hg concentrations in muscle of common minke whales (mature males, O-stock) in sub-area 9 against research years during the period 1994–2013.

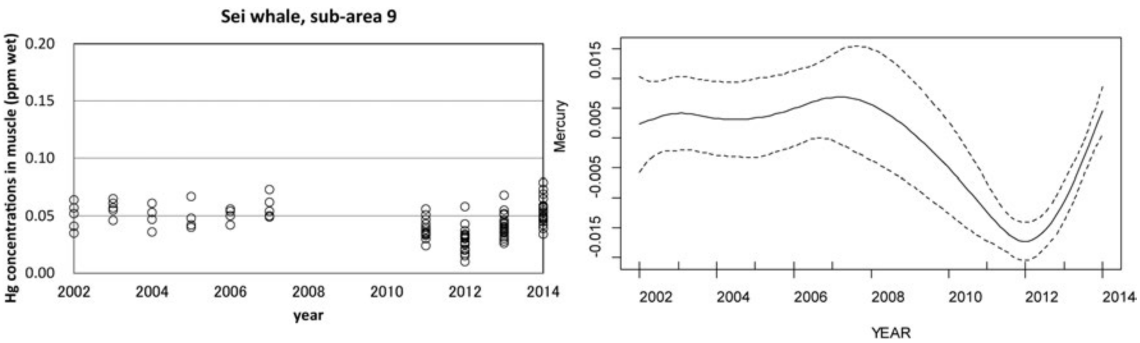

Figure 5. Simple plots and smoothing plots using the generalized additive model of total Hg concentrations in muscle of sei whales (mature males) in sub-area 9 against research years during the period 2002–2014.

A peak of total Hg concentration was observed in 2008 (Figure 4), and Pacific pomfret was observed in the stomach contents of common minke whales from sub-area 9 in that year (Tamura *et al.*, 2009). These results indicate that changes of total Hg concentrations in common minke whales in sub-area 9 reflect changes in food habits of this whale species rather than changes of background levels of total Hg in the marine environment.

In sub-area 9, total Hg concentrations in sei whales (period 2002–2014) were significantly associated with Intercept (+), Year (−) and Body length (+) (Table 9), whereas those in 2012 were lower than the others in the GAM plots (Figure 5). A comparison of total Hg concentrations in muscle of sei whale and in the whole body of the main prey species in the stomachs are shown in Table 13. Total Hg concentrations in sei whales having anchovy and sardine in the stomach were slightly higher than the other two whale species from sub-area 9. These results indicate that total Hg concentrations of sei whales from sub-area 9 may be less affected by total Hg in the food items.

Temporal trends of total Hg concentrations have not been observed in environmental samples, lower trophic

Table 11

Comparison between Hg concentrations in muscle of common minke whales and in the whole body of prey items in sub-area 7.

		Anchovy	Euphausiids	JFSquid	Mackerel	Sardine	Saury	Walleye Pollock
Muscle of whales	Ave.±SD	(0.21±0.051)	(0.22±0.049)	(0.22±0.03)	(0.33±)	(0.17±)	(0.23±0.043)	(0.24±0.056)
	n	238	33	8	1	2	26	28
Whole of prey spp.	Ave.±SD	(0.037±0.025)	(0.005±0.003)	(0.058±)	(0.020±0.002)	(0.018±)	(0.038±0.015)	(0.045±)
	n	20*	19*	57**	5*	66**	41*	2*

*: Yasunaga and Fujise (2009); **: Ministry of Health, Labour and Welfare (2005)

Table 12

Comparison between Hg concentrations in muscle of common minke whales and in the whole body of prey species in sub-area 9.

		Anchovy	Atka Mackerel	Copepods	Euphausiids	Mackerel	MAFSquid	Oceanic Lightfish	Pacific Pomfret	Salmonids	Saury
Muscle of whales	Ave.±SD	(0.22±0.10)	(0.13±)	(0.17±0.07)	(0.18±0.09)	(0.19±0.04)	(0.19±0.12)	(0.11±)	(0.44±0.26)	(0.32±0.08)	(0.24±0.09)
	n	83	1	6	15	3	5	1	6	5	257
Whole of prey spp.	Ave.±SD	(0.037±0.025)	(0.086±)	(0.005±0.003)	(0.005±0.003)	(0.020±0.002)			(0.23±0.03)	(0.027±)	(0.038±0.015)
	n	20*	61**	5*	19*	5*			3*	41**	41*

*: Yasunaga and Fujise (2009); **: Ministry of Health, Labour and Welfare (2005)

Table 13

Comparison between Hg concentrations in muscle of sei whales and in the whole body of prey species in sub-area 9.

		Anchovy	Copepods	Euphausiids	Mackerel	Min.arm squid	Sardine	Saury
Muscle of whales	Ave.±SD	(0.049±0.013)	(0.043±0.014)	(0.045±0.016)	(0.045±0.016)	(0.040±0.005)	(0.052±)	(0.041±0.015)
	n	11	48	9	9	3	2	7
Whole of prey spp.	Ave.±SD	(0.037±0.025)	(0.005±0.003)	(0.005±0.003)	(0.020±0.002)		(0.018±)	(0.038±0.015)
	n	20*	5*	19*	5*		66**	41*

*: Yasunaga and Fujise (2009); **: Ministry of Health, Labour and Welfare (2005)

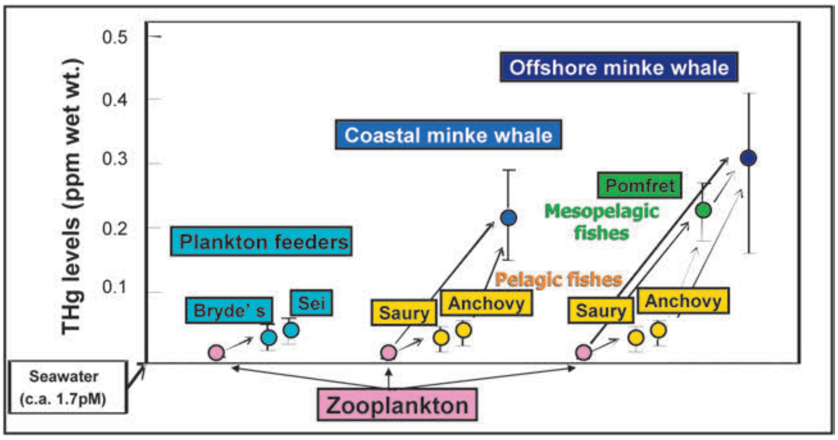

Figure 6. Schematic diagram showing total Hg flow in the western North Pacific food web.

organisms and baleen whales, except for common minke whales collected from sub-areas 7 and 9, and sei whales from sub-area 9 from 1990's to 2000's. Total Hg concentrations in these exceptions may reflect changes in food habits rather than changes of background levels of total Hg in the marine environment. This phenomenon is illustrated in Figure 6, which shows that differences in food habitat explain the pattern of Hg accumulation of baleen whales.

Consequently, it is concluded that temporal trend of total Hg concentrations in the marine habitat of baleen whales in the western North Pacific remained stable in the research period. In future, other variables such as age of the animals, should be included in the analyses to investigate yearly trend of Hg concentrations in baleen whales.

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