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Levels and patterns of persistent organochlorines in minke whale (*Balaenoptera acutorostrata*) stocks from the North Atlantic and European Arctic

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The authors would like to dedicate this paper to the memory of Dr. Stuart Innes who died in a tragic accident while conducting marine mammal research in the Canadian Arctic in May 2000. His work using organochlorine patterns to identify stocks of beluga inspired this study.

"Capsule": *Minke whales appear to be quite mobile and have multiple feeding areas in the NE Atlantic Ocean.*

Abstract

Regional variation in PCBs and organochlorine (OC) pesticide concentrations was examined using the blubber of 155 minke whales (*Balaenoptera acutorostrata*) sampled in seven regions in the North Atlantic and European Arctic, including western and southeastern Greenland, the Norwegian Sea, the North Sea and the Barents Sea. The levels and relative proportions of OCs were also used to examine the boundaries for North Atlantic minke whale stocks previously defined by the International Whaling Commission (IWC). Concentrations of major OC groups (ΣPCB, 89.1–22 800 ng/g lipid; ΣDDT, 65.3–6280 ng/g lipid; ΣCHL, 33.3–2110 ng/g lipid) generally increased from west to east, while HCH concentrations (ΣHCH, <1–497 ng/g lipid) showed the opposite trend. Statistical comparison between six regions using sex-adjusted least squared mean concentrations showed that minke whales from the Barents Sea had significantly higher concentrations of ΣPCBs than those from the Vestfjorden/Lofoten, the North Sea, and west Svalbard, as well as significantly higher ΣDDT concentrations compared to west Greenland animals. The differences in concentrations suggest that west and southeast Greenland minkes may represent one group of whales, which are distinct from both the Jan Mayen minkes and those from other IWC defined stocks in northern European waters. Principal components analysis using proportions of 71 PCB congeners and 20 OC pesticides (of total OCs) did not reveal any major differences among groups although minkes from the North Sea were distinguished from those from Greenland waters by higher loadings of more highly chlorinated PCBs and recalcitrant OC pesticides. The general similarity in mean levels of ΣPCBs, ΣDDT and ΣCHL, as well as mean principal components analysis scores, among minkes sampled at Jan Mayen, Svalbard, Vestfjorden/Lofoten, the North Sea and the Barents Sea suggests that the whales are quite mobile and may feed in multiple areas within the northeastern Atlantic.

Keywords: North Atlantic; Minke whales; PCBs; Organochlorine pesticides; Stock delineation

1. Introduction

Minke whales (*Balaenoptera acutorostrata*) are found throughout the North Atlantic from the east coast of Canada to the North Sea, Svalbard and as far east as the Novaya Zemlya region of the western Russian arctic during the summer. Although the distribution of minkes is relatively continuous across this range, the International Whaling Commission (IWC) has defined four management units for the North Atlantic minke whales (Canadian East Coast, West Greenland, Central and Northeastern) because of the apparent occurrence of

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population substructuring. Nonetheless, there has been disagreement as to whether these management units represent meaningful biological groupings. For example, sex ratio data from catch records and genetic studies suggest that there is no biological basis for the division between east and west Greenland (e.g. Larsen and Øien, 1988; Palsbøll et al., 1997), however, results were not sufficient to unequivocally define new, more meaningful groupings. To elucidate the population substructure of North Atlantic minke whales, samples have been analysed for regional differences in signatures of elemental and stable isotopes (Born et al., 2001), fatty acids (Møller et al., 2001), and genetics (Andersen et al., 2001), as well as PCB and OC pesticide levels (present study).

A number of studies have used differences in concentrations of OC contaminants to identify separate stocks or groups of marine mammals. For example, Aguilar et al. (1993) were able to identify different schools of long-finned pilot whales (*Globocephala melas*) using differences in ΣPCB and ΣDDT concentrations, ΣDDE/ΣDDT and ΣDDT/ΣPCB ratios. In some cases multivariate analyses using proportions of individual PCB congeners and OC pesticides can also be used to successfully identify animals from separate regions. For example, using canonical discriminant analysis, Innes et al. (2001) identified seven groups of beluga whales from the eastern Canadian Arctic and western Greenland, each of which had highly distinct patterns of PCBs and OC pesticides. Weis and Muir (1997) were able to distinguish ringed seals in western and high Arctic locations from those in Hudson Bay, using principal components analysis to identify chlorobenzenes as major contributors to this separation. With the same technique Westgate and Tolley (1999) could also distinguish harbour porpoises (*Phocoena phocoena*) from three different regions of the western North Atlantic (Newfoundland, Bay of Fundy, Gulf of Maine) based on levels and patterns of OC pesticides and PCB congeners.

A comparison of PCBs and persistent organochlorine (OC) pesticide levels from eastern and western North Atlantic has not previously been carried out for minkes, nor for any other cetaceans. Previous studies using samples from minkes in the early 1990s found relatively high levels of PCBs (mean 5770 ng/g) in blubber of adult males from northern Norway and the Barents Sea area (Kleivane and Skaare, 1998; Skaare, 1995) and in blubber of males and females from the western north Atlantic (Gulf of St Lawrence, mean 2670 ng/g) (Gauthier et al., 1997). However, due to the overall paucity of such data for these whales across their summer range, it has not previously been possible to use contaminants to help elucidate any population substructure. The availability of samples as part of a stock assessment program on minke whales (Born et al., 2001) provided an opportunity to examine this question. In this study we present the levels of OC contamination in the blubber of minke whales sampled from seven management units (IWC small areas) in the North Atlantic, ranging from west Greenland to the Barents Sea, in order to assess spatial trends in contamination and to help determine biologically appropriate stock boundaries.

2. Materials and methods

2.1. Sample collection

Blubber samples were obtained from 155 minke whales (females and males) sampled in 1998, from seven different management units (i.e. IWC "small areas") in the North Atlantic: west Greenland (WG), which is representative of the West Greenland management unit, southeast Greenland (SEG) and Jan Mayen (JM), which represent the Central management unit, as well as the North Sea (NS), Vestfjorden/Lofoten (V/L), west Svalbard (WS), and the Barents Sea (BS), which represent the Northeastern management unit (Fig. 1). No samples were available for males from SEG, and there were more samples from females than from male whales for most other management units. In Greenland, local hunters collected samples whereas in the other areas trained staff on board the catcher boats collected the samples. Whenever possible, each whale's standard body length and sex were determined in the field and sex was confirmed genetically from skin samples. Blubber samples were stored at −20 °C and the epidermis was separated from the blubber prior to the analysis of each blubber sample.

2.2. Chemical analysis

Samples taken from North Atlantic minke whales were analysed in the Trace Organics Analytical Laboratory of the Environmental Resources Studies, at Trent University, for PCBs and OC pesticides as described in Metcalfe and Metcalfe (1997), with minor modifications. Briefly, blubber samples were ground with sodium sulfate and extracted in a Soxhlet apparatus with hexane–dichloromethane (1:1) for 4 h. Blubber extracts were concentrated by rotary evaporation and lipids were separated from analytes by gel permeation chromatography using hexane–dichloromethane (55:45). Lipid content was determined gravimetrically using a subsample of the extract. The remaining extract was further cleaned-up and fractionated on Silica columns to separate PCBs and some pesticides (e.g. *p,p′*-DDE) (fraction 1; hexane) from most OC pesticides (fraction 2; dichloromethane: hexane, 1:1). Final extracts were analysed by high resolution gas chromatography (HRGC) using a Varian model 3500 GC with a 60-m

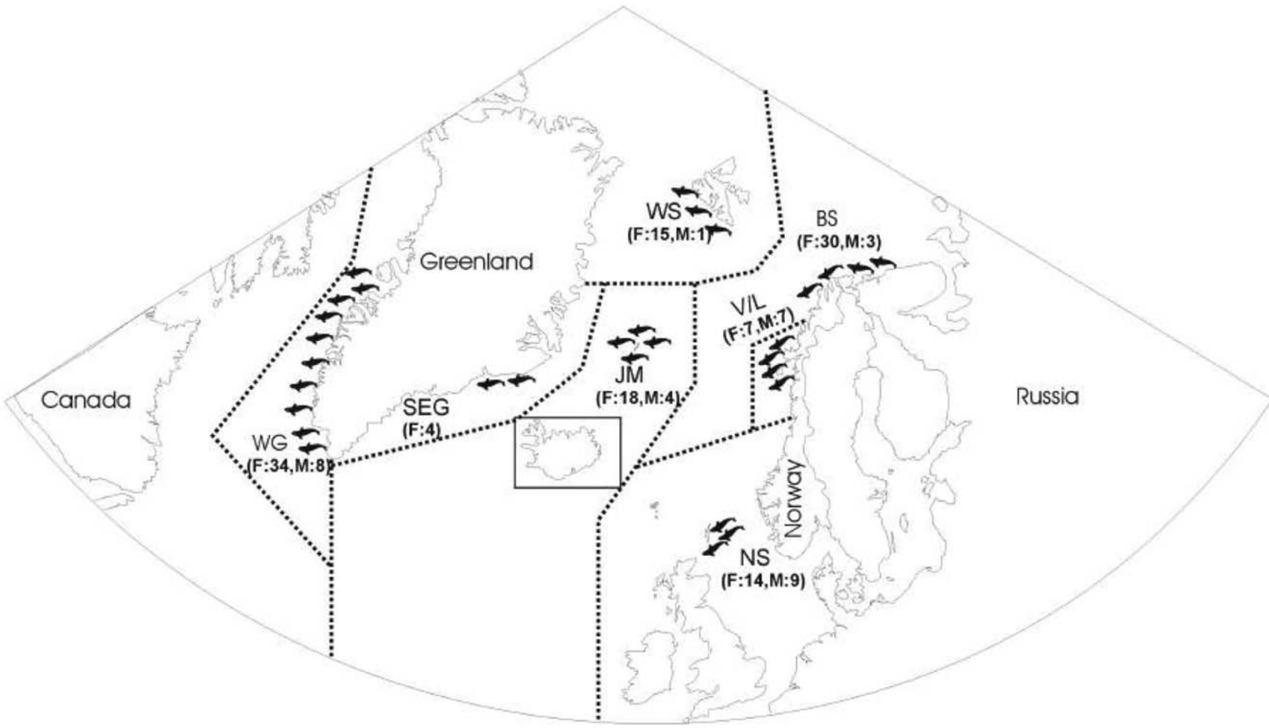

Fig. 1. Regions in the North Atlantic region where tissue samples of minke whales were collected in 1998. Acronyms and boundaries of relevant IWC "small areas" are indicated with whale symbols. Number and sex of samples included in the OC analyses are given for each area. Whales from western Greenland (WG) are representative of the West Greenland management unit, while those from southeast Greenland (SEG) and Jan Mayen (JM) are representative of the Central management unit, and whales from the North Sea (NS), Vestfjorden/Lofoten (V/L), west Svalbard (WS), and the Barents Sea (BS) are representative of the Northeastern management unit.

DB-5 (J&W) column (0.25 mm i.d.) and an electron capture (^{63}Ni) detector. A total of 102 PCB congeners (including co-eluting congeners[1]) were quantified. Sum PCB (ΣPCB) was the sum of these congeners. Sum chlordane (ΣCHL) was the sum of *cis*- and *trans*-chlordane, oxychlordane, *cis*- and *trans*-nonachlor, heptachlor and heptachlor epoxide. Sum DDT (ΣDDT) was the sum of *o,p′* and *p,p′*-DDE,-DDD and -DDT. Sum HCH (ΣHCH) was the sum of α-HCH, β-HCH and γ-HCH.

Quality assurance included analysis of procedural blanks, duplicate samples and cod liver oil standard reference material (NIST 1588a; National Institute of Standards and Technology, Gaithersburg, MD). Results for three samples analysed in duplicate indicated that the relative percent differences of major contaminants (ΣPCB, ΣDDT, ΣCHL, ΣHCH, endrin, dieldrin, mirex and HCB) were generally less than 20%. Results for ΣPCB and ΣDDT in NIST 1588a ($n=6$) were within 8% of certified values and average deviation for 32 certified PCB and OC pesticides analytes was 19%. Blank values for all analytes were uniformly low and no blank correction was necessary.

2.3. Statistical analysis

OC concentrations in minke whale blubber samples were lipid normalized to bring all results to the equivalent of 100% lipid, because percent lipid content ranged from about 10–90%. Mean values were used where a sample was analysed in duplicate.

Principal components analysis (PCA) was conducted on results for all whales to examine patterns, similarities and differences between whales from the different IWC regions, age classes and sex using 71 PCBs (including co-eluting congeners) and 20 OC pesticides. For PCA, compounds having concentrations below the detection limits for more than 10% of the samples were excluded from the analysis. Concentrations of each compound were normalized to total organochlorines. ANCOVA was also performed using $\log_{10}$ transformed data for immature and mature animals to investigate the effects of region, sex and length on major OC groups and selected individual OC pesticides. The ANCOVA model was of the form: Log 10 concentration $= \mu +$ region $+$ sex $+$ length $+$ region* length $+$ sex*region $+ \varepsilon$, where μ is

[1] 4/10, 7/9, 6, 8/5, 19, 30, 12/13, 18, 15/17, 24/27, 16/32, 54/29, 26, 25, 50/31, 28, 20/53/33, 51, 22, 45, 46, 52, 43, 49, 48, 47, 44, 59, 42, 64/41/71, 40, 100, 63, 74, 70, 76/98, 66/95, 91, 55, 56/60, 92, 84, 101, 99, 119, 83, 97, 87/81, 85, 136, 110, 82, 151, 135/144, 147/107, 149, 118, 133, 114/134, 131, 146, 153, 132, 105, 141, 179, 137, 176/130, 138/163, 158, 129, 178, 175, 187/182, 183, 128, 167, 185, 174, 177, 202/171/156, 157/200/173, 204, 172, 197, 180, 193, 191, 199, 170, 190, 198, 201, 203/196, 189, 208, 195, 207, 194, 205, 206, 209.

a constant and ϵ is an error term. The ANCOVA was successively reduced for factors not significant at the 5% level according to Type III Sums of Squares Test. Prior to running PCA and ANCOVA, zeros (where concentrations below detection limits) were substituted with random values between one-tenth and one-half of the detection limit for all compounds with undetectable concentrations. All statistical comparisons referred to as significant are based on $P \leqslant 0.05$ while those referred to as marginally significant represent $P > 0.05$ and < 0.10. All statistical analyses were performed using SYSTAT 9.0 (SPSS Inc., 1998).

3. Results

Although age estimates were not available for whales examined in the present study, their sexual maturity was assessed based on measurements of standard body length. Ninety-nine of the minke whales examined were judged to be sexually mature (females >730 cm, males >670 cm; Johnsgård, 1951; Christensen, 1981; Larsen, 1984). Fifty-two animals sampled likely had not yet reached sexual maturity, and the length (and maturity) of the remaining four whales was not known. Mean concentrations and ranges of major contaminants are summarised in Table 1, by sex, for all 155 whales taken from the seven sampling regions.

The ANCOVA model was applied to the data in order to investigate the effects of region, sex and length on comparisons of major OC groups and selected individual OC pesticides. Length and sex*region interactions were not significant and were excluded from the model. However, sex was a significant covariate for ΣPCB, ΣDDT, *p,p′*-DDE and *p,p′*-DDT (Table 2), and thus sex-adjusted least square means were calculated for the six regions for which data was available for both sexes (all but SE Greenland, $n = 151$; Fig. 2). Sex-adjusted ΣPCB concentrations were significantly higher in Barents Sea minkes ($P < 0.05$), than those from Vestfjorden/Lofoten, and were marginally higher than in minkes from the North Sea and Svalbard ($P = 0.056$ and $P = 0.058$, respectively). Sex-adjusted ΣDDT concentrations were significantly higher in minkes from the Barents Sea than those from west Greenland. Sex-adjusted *p,p′*-DDE concentrations were significantly higher in whales from the Barents Sea and the North Sea than those from west Greenland, and were marginally higher in whales from Jan Mayen compared to whales from west Greenland. Similarly, sex-adjusted *p,p′*-DDT was higher in whales from the North Sea than in whales from west Greenland. The ΣDDT/ΣPCB ratio in minke whales from Vestfjorden/Lofoten was significantly higher than in minkes from the Barents Sea, Svalbard and west Greenland, and was marginally higher than North Sea whales ($P = 0.051$; Fig. 3). No regional differences were detected in mean DDE/ΣDDT ratios (Fig. 3). No other significant differences in contaminant concentrations were detectable for sex-adjusted values from the six regions examined.

Since sex was not a significant covariate for any other compounds, a simple ANOVA was run on region, using the full data set ($n = 155$; Table 2). Significant geographical trends were found for *o,p′*-DDD, *p,p′*-DDD, γ-HCH, *trans*-chlordane, *cis*-nonachlor, *trans*-nonachlor, oxychlordane, heptachlor epoxide, α-endosulfan and mirex (Fig. 4). Levels of *p,p′*-DDD were lower in west Greenland whales than those from the Barents Sea, and marginally lower than North Sea ($P = 0.051$) and Jan Mayen whales ($P = 0.076$), while, *o,p′*-DDD was higher in minkes from Jan Mayen than west Greenland. γ-HCH (lindane) concentrations were significantly higher in whales from the North Sea than those from Svalbard and west Greenland. *cis*- and *trans*-Nonachlor were present at lower concentrations in West Greenland whales than those from Jan Mayen, Vestfjorden/Lofoten or the North Sea, and marginally lower than whales from the Barents Sea. *trans*-Nonachlor was also present in marginally higher concentrations in North Sea whales than those from Svalbard and SE Greenland. *trans*-Chlordane levels were lower in West Greenland whales than in Jan Mayen, Vestfjorden/Lofoten, Barents Sea or North Sea whales, and marginally higher in Vestfjorden/Lofoten whales than those from Svalbard. Oxychlordane levels were lower in West Greenland and SE Greenland minkes than Jan Mayen and west Greenland minkes, and marginally lower than in Barents Sea ($P = 0.078$) and Vestfjorden/Lofoten minkes ($P = 0.052$). Mirex levels were also marginally lower in minkes from west Greenland than those from Jan Mayen (0.050) and the Barents Sea ($P = 0.051$). Heptachlor epoxide levels were higher in minkes from west Greenland compared to minkes from Jan Mayen. α-Endosulfan was significantly higher in whales from the North Sea than those from all other locations and minkes from the Barents Sea had higher α-endosulfan than those from Jan Mayen and west Greenland. Barents Sea and North Sea minkes had marginally lower concentrations of α-HCH than west Greenland. No significant effect of region was found for ΣHCH, ΣCHL, dieldrin, endrin, HCB, *o,p′*-DDT, β-HCH or *cis*-chlordane (Table 2).

Multivariate analysis of the PCB and OC pesticide data using PCA, yielded four factors, which explained 59.7% of the variance, but did not yield any very distinct groupings of animals based on variation in contaminant patterns by region, sex or sexual maturity. However, PCA plots (Figs. 5 and 6) provide additional support for the geographical trends observed with univariate analyses of selected compounds. For example, minke whales from the North Sea had higher loadings of many of the more chlorinated and recalcitrant organochlorines examined (e.g. PCB 180, 170, 191, mirex

Table 1
Summary of OC pesticide concentrations (ng/g lipid) in the blubber of mature North Atlantic minke whales

		W. Green land (WG)		E. Greenland (SEG)	Jan Mayen (JM)		North Sea (NS)		Vestfjorden/Lofoten (V/L)		W. Svalbard (WS)		Barents Sea (BS)	
		female	male	female	female	male	female	male	female	male	female	male	female	male
	n	34	8	4	19	4	14	9	7	7	15	1	30	3
Body length	Mean	683[a]	663[b]	795[c]	775	645	786	755	719	624	768	700	757	764
	Range	500–850[a]	495–800[b]	670–965[c]	676–858	564–686	550–905	605–825	512–870	420–810	670–820	–	633–870	710–815
ΣPCB[d]	Mean	3190	3490	1170	2250	4570	1840	6120	1360	3610	2480	1770	3630	7140
	Range	384–22 800	89.1–10 200	710–1880	518–5640	1250–8630	224–4160	1120–14 800	422–3530	492–8070	1130–5250	–	1020–8160	4530–11 900
ΣDDT[e]	Mean	903	999	329	1100	1760	964	3190	667	2450	891	683	1070	2710
	Range	65.3–3340	197–1930	92.7–680	476–4690	1206–2620	214–2130	321–7770	248–1290	389–6280	430–1960	–	310–2210	1300–5310
ΣCHL[f]	Mean	432	485	556	379	653	383	855	386	679	364	159	528	703
	Range	33.3–1730	177–1180	87.7–1420	120–670	325–1060	81.5–733	116–1490	162–922	236–1260	115–678	–	104–2110	483–944
Σ HCH[g]	Mean	94.3	99.9	95.4	49.6	55	68.9	114.0	49.2	78.9	66.4	49.5	57.6	125
	Range	< 1–497	60.7–172	43.4–202	7.17–85.4	50.7–64.8	24.5–134	43.3–204	29.9–108	44.8–99.4	15.1–126	–	< 1–153	74.5–198
HCB	Mean	114	114	56.9	98.1	169	66.6	362	87.4	131	117	34.6	138	260
	Range	< 1–544	< 1–264	6.16–112	4.11–205	128–215	2.09–234	3.15–2060	56.6–213	62.0–199	2.50–250	–	25.6–334	190–351
Dieldrin	Mean	383	357	175	284	435	491	886	303	714	395	285	366	589
	Range	52.0–1390	181–490	55.6–358	117–486	285–772	121–1060	< 1–2340	160–700	270–1480	222–701	–	129–960	300–806
Endrin	Mean	7.62	11.6	13.6	21.5	16.4	13.5	37.1	16.6	16.2	14.2	15.4	16.6	24.6
	Range	< 1–40.3	< 1–27.6	< 1–42.1	< 1–35.9	< 1–28.5	< 1–43.0	< 1–135	< 1–58.4	< 1–32.1	< 1–31.3	–	< 1–119	18.0–36.8
Mirex	Mean	9.01	7.77	2.81	8.84	15.8	6.87	54.6	7.71	11.0	10.0	7.93	9.79	12.0
	Range	< 1–71.2	< 1–19.1	< 1–5.24	0.86–19.7	9.14–23.5	< 1–21.2	2.54–398	< 1–35.4	< 1–29.0	4.27–26.0	–	< 1–27.5	6.85–20.1
α-Endosulfan	Mean	1.31	1.76	5.1	0.62	< 1	34.0	43.0	4.51	9.17	2.63	< 1	7.74	9.99
	Range	< 1–18.4	< 1–7.93	< 1–20.4	< 1–11.7	–	< 1–100	1–166	< 1–22.6	< 1–23.5	< 1–22.6	–	< 1–33.6	< 1–30.0
Lindane	Mean	15.3	16.4	18.2	9.68	11.7	31.8	55.9	16.9	25.9	11.2	14.0	15.3	28.8
	Range	< 1–86.6	12.2–24.3	6.99–43.8	< 1–16.5	9.40–16.6	9.64–57.6	13.0–108	10.7–26.6	18.7–36.1	< 1–20.8	–	< 1–44.7	23.5–33.4

[a] *n* = 32 for mean body length and range.
[b] *n* = 7 for mean body length and range.
[c] *n* = 3 for mean body length and range.
[d] ΣPCB, sum of 102 congeners peaks (includes co-eluters).
[e] ΣDDT, sum of *o,p*- and *p,p′*-DDE,-DDD,-DDT.
[f] ΣCHL, sum of *cis*- and *trans*-chlordane, oxychlordane, *cis*- and *trans*-nonachlor, heptachlor, heptachlor epoxide and methoxychlor.
[g] ΣHCH, sum of α-,β-,γ-HCH.

and most DDT isomers) on principal component (PC) 1 than minkes from the more westerly regions (especially SE Greenland). Conversely, west Greenland minkes had higher loadings of many less chlorinated PCB congeners on PC2, in comparison to minkes from more easterly regions, the distinction being greatest compared to whales from the Vestfjorden/Lofoten region of Norway and the North Sea (Fig. 5). Minkes from the North Sea and Barents Sea had higher loadings of OC pesticide components such as *cis*-nonachlor, oxychlordane, *o,p*-DDD, dieldrin, endrin, and current use pesticides lindane and α-endosulfan on PC4. Minkes from the Barents Sea, Jan Mayen and west Greenland also had higher loadings of several of the less chlorinated PCB congeners on PC3 than minkes from other regions (Fig. 6).

Table 2
Results of ANCOVA of major organochlorines in North Atlantic minke whales

Contaminants	Factor	
	Region	Sex[a]
ΣPCB	**[b]	**
ΣDDT	*	**
ΣHCH	NS	NS
ΣCHL	NS	NS
p,p′-DDE	*	**
o,p′-DDD	*	NS
p,p′-DDD	*	NS
o,p′-DDT	NS	NS
p,p′-DDT	*	*
α-HCH	*	NS
β-HCH	NS	NS
γ-HCH (lindane)	*	NS
cis-Chlordane	NS	NS
trans-Chlordane	**	NS
cis-Nonachlor	**	NS
trans-nonachlor	**	NS
Oxychlordane	**	NS
Heptachlor epoxide	*	NS
α-Endosulfan	**	NS
Dieldrin	NS	NS
Endrin	NS	NS
Mirex	**	NS
HCB	NS	NS
ΣDDT/ΣPCB	**	NS
DDE/ΣDDT	NS	NS

[a] Using the model: $\log_{10}$concentration = μ + region + sex + ε.
[b] **$P<0.01$, *$P \leqslant 0.05 > 0.01$, NS (not significant) $P>0.05$.
Body length was not a significant co-variate.
No significant sex*region interaction occurred for any compound.

4. Discussion

4.1. Using PCBs and OC pesticides to identify stocks of marine mammals

Contaminants in minke whales from the seven IWC small areas we examined differ extensively enough to indicate that some revisions to the IWC's management divisions for North Atlantic minke whales may be appropriate. Lower concentrations of *o,p′*-DDD, mirex, *cis*- and *trans*-nonachlor, oxychlordane, *trans*-chlordane, as well as higher heptachlor epoxide and marginally lower *p,p′*-DDE concentrations in west Greenland whales, compared to those from Jan Mayen, all suggest that whales from these small areas represent distinct groups. Fig. 4 shows clear trends toward lower concentrations of all of these compounds in both west and SE Greenland whales, compared to Jan Mayen whales, suggesting that west and SE Greenland minkes intermingle and should be grouped together, and that they are distinct from the Jan Mayen whales. This is corroborated by the significantly higher concentrations of *cis*-nonachlor and oxychlordane in Jan Mayen whales compared to SE Greenland whales. However, given the absence of samples from males and the small sample size ($n=4$) for this region, it is difficult to draw further

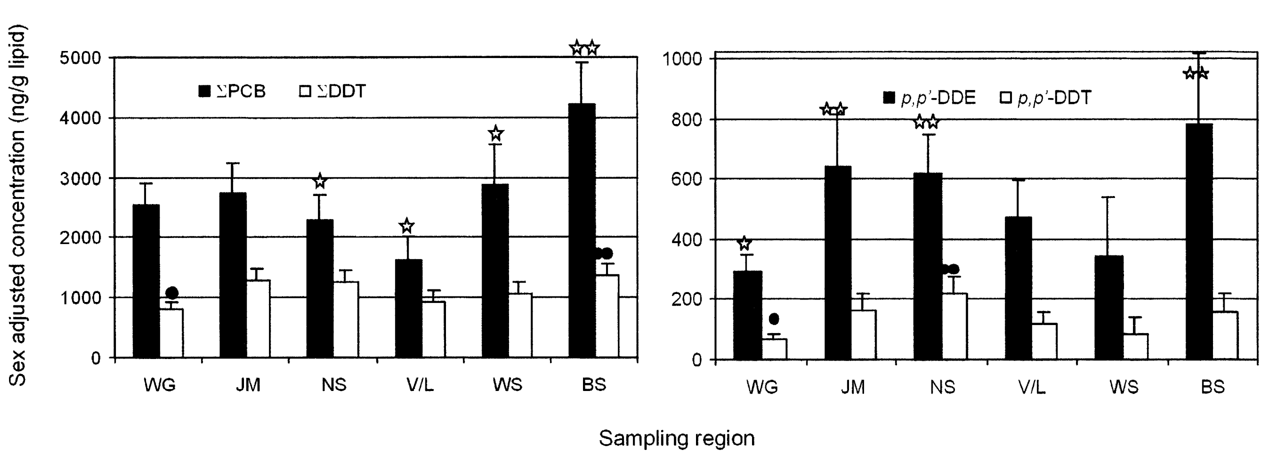

Fig. 2. Sex-adjusted geometric mean concentrations (±standard error) of ΣPCB, ΣDDT, *p,p′*-DDE and *p,p′*-DDT in minke whales from each region, in geographical order from west to east. Regions marked with different numbers of one type of symbol have significantly different levels of that compound.

conclusions about the grouping of minkes from west and southeast Greenland. Major differences in OC concentrations were seen between West Greenland and northeast Greenland (Scoresbysund) in blubber of less mobile marine mammals such as ringed seals and walrus (Cleeman et al., 2000; Muir et al., 2000a,b). The lack of distinct differences in OC concentrations in minkes from Greenland waters would not be surprising if minkes move back and forth around the southern end of Greenland when feeding, thus blending the differing contaminant levels from the two regions. The differences seen between levels in other marine mammals from east and west Greenland may also be more pronounced because sampling locations in eastern Greenland were further north than where the minkes were sampled for the present study.

Regardless of the possible regrouping of western Atlantic minkes, the lower *cis*- and *trans*-nonachlor and oxychlordane concentrations in west and SE Greenland whales compared to those from all areas in the Northeastern stock (Svalbard, Vestfjorden/Lofoten, North Sea, Barents Sea) are in agreement with the IWC's present division between these regions. The significantly lower concentrations of α-endosulfan, in Jan Mayen whales relative to whales from Barents Sea and North Sea also suggest that the Jan Mayen minkes are relatively distinct from whales in these regions. However, overall PCB and OC pesticide concentrations in Jan Mayen whales were most similar to whales from the Northeast Atlantic management unit (Figs. 2 and 4), which is consistent with the west to east increase in OC levels in harp seal blubber, and higher concentrations of PCBs and DDTs in ringed seals from northeastern Greenland, Svalbard and northern Norway than those from western Greenland and the Canadian arctic (de March et al., 1998; Muir et al., 2000a).

The IWC's grouping of minkes from the North Sea, Vestfjorden/Lofoten, Svalbard and the Barents Sea into one management unit (Northeast Atlantic region) could

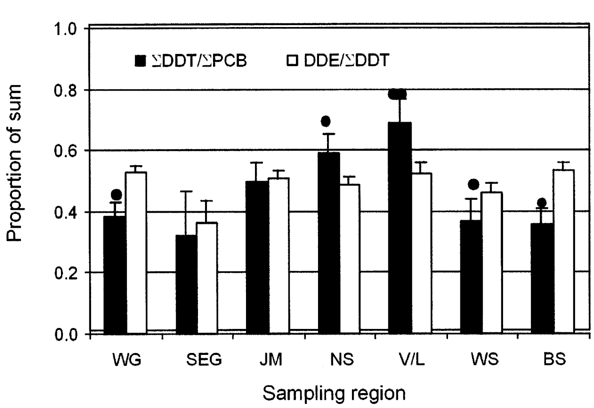

Fig. 3. Mean ratios (±standard deviation) of DDE/ΣDDT and ΣDDT/ΣPCB for each region, in geographical order from west to east. Regions marked with different numbers of one type of symbol have significantly different levels of that compound.

also be assessed using contaminant concentrations and PCA scores. The higher concentrations of the current use pesticides, lindane and α-endosulfan, and marginally higher concentrations of *trans*-nonachlor, in North Sea minkes compared to Svalbard whales, as well as the differences identified with the multivariate analysis (Figs. 5 and 6), are consistent with the view that North Sea minkes are distinct based on genetics (Andersen et al., 2001), fatty acid profiles (Møller et al., 2001) and elemental and stable isotopic signatures (Born et al., 2001) in the same individuals. Higher levels of PCBs have also been found in adult female minke whales from the North Sea, compared to Spitsbergen (Skaare et al., 2002), as well as in harbour seals, grey seals and harbour porpoises from the North Sea than from northern Norway (Skaare, 1995). The higher concentrations of ΣPCB, and lower ΣDDT/ΣPCB ratio in Barents Sea minkes compared to those from Vestfjorden/Lofoten, North Sea and Svalbard whales, indicate that minkes from the Barents Sea may also be relatively separate from whales in other small areas within the IWC Northeastern region. These results are in general agreement with higher levels of PCBs and DDTs in ringed seals from the Yenisey Gulf (south Kara Sea) than those from northern Norway and higher levels of OCs in harbour porpoises from the Barents Sea compared to those from west Greenland (de March et al., 1998). Furthermore, Vestfjorden/Lofoten whales seem to be relatively separate from Svalbard whales, based on their higher ΣDDT/ΣPCB ratio, and marginally higher *trans*-chlordane concentrations.

4.2. Inferring regional differences OC levels in seawater and food web organisms

The use of levels and patterns of persistent OCs to distinguish marine mammal stocks ultimately depends on the hypothesis that the levels and patterns of contaminants in their tissues will reflect those in the waters they inhabit and the prey they consume. In general, this is well demonstrated with nearly 30 years of PCB and OC pesticide measurements, although rarely has it been demonstrated with actual measurements in seawater or marine food webs. In Arctic ringed seals and, to a lesser extent, polar bears, recent work has shown that geographic variation among populations is consistent with known trends of the contaminants in the circumpolar Arctic (Muir and Norstrom, 2000; Muir et al., 2000a). Levels of PCBs and persistent OC pesticides in polar bears and ringed seals vary longitudinally, with higher levels of PCBs in the European Arctic (including northeastern Greenland) and higher levels of some pesticides, especially ΣHCH, in the Canadian Arctic and western Greenland (Norstrom et al., 1998; Weis and Muir, 1997; Muir et al., 2000a). In the case of HCH this variation is quite consistent with the spatial trends in levels in Arctic

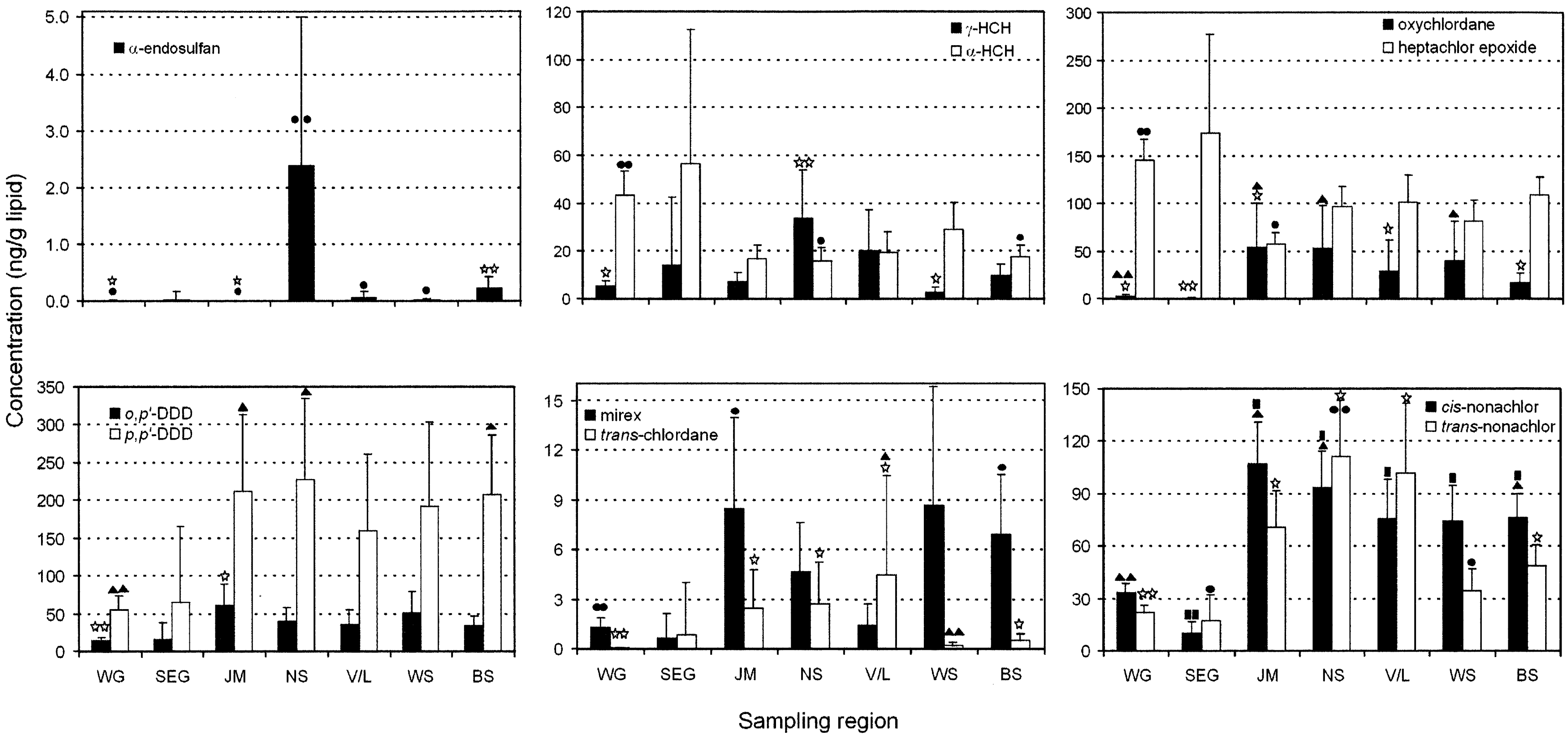

Fig. 4. Geometric mean concentrations (±standard deviation) of OC pesticides for which geographic differences were detected in minke whales from the seven regions, listed in geographical order from west to east. Regions marked with different numbers of one type of symbol have significantly different levels of that compound.

Ocean waters where higher HCH levels are found in the Alaskan and Western Canadian arctic than elsewhere (Macdonald et al., 2000). Hoekstra et al. (2002) showed that proportions of βHCH in blubber of the bowhead whale (*Balaena mysticetus*) fluctuated with seasonal migration of this species between the Bering, Chukchi, and Beaufort Seas. The higher proportions of β-HCH in bowheads migrating from the Bering Sea overwintering

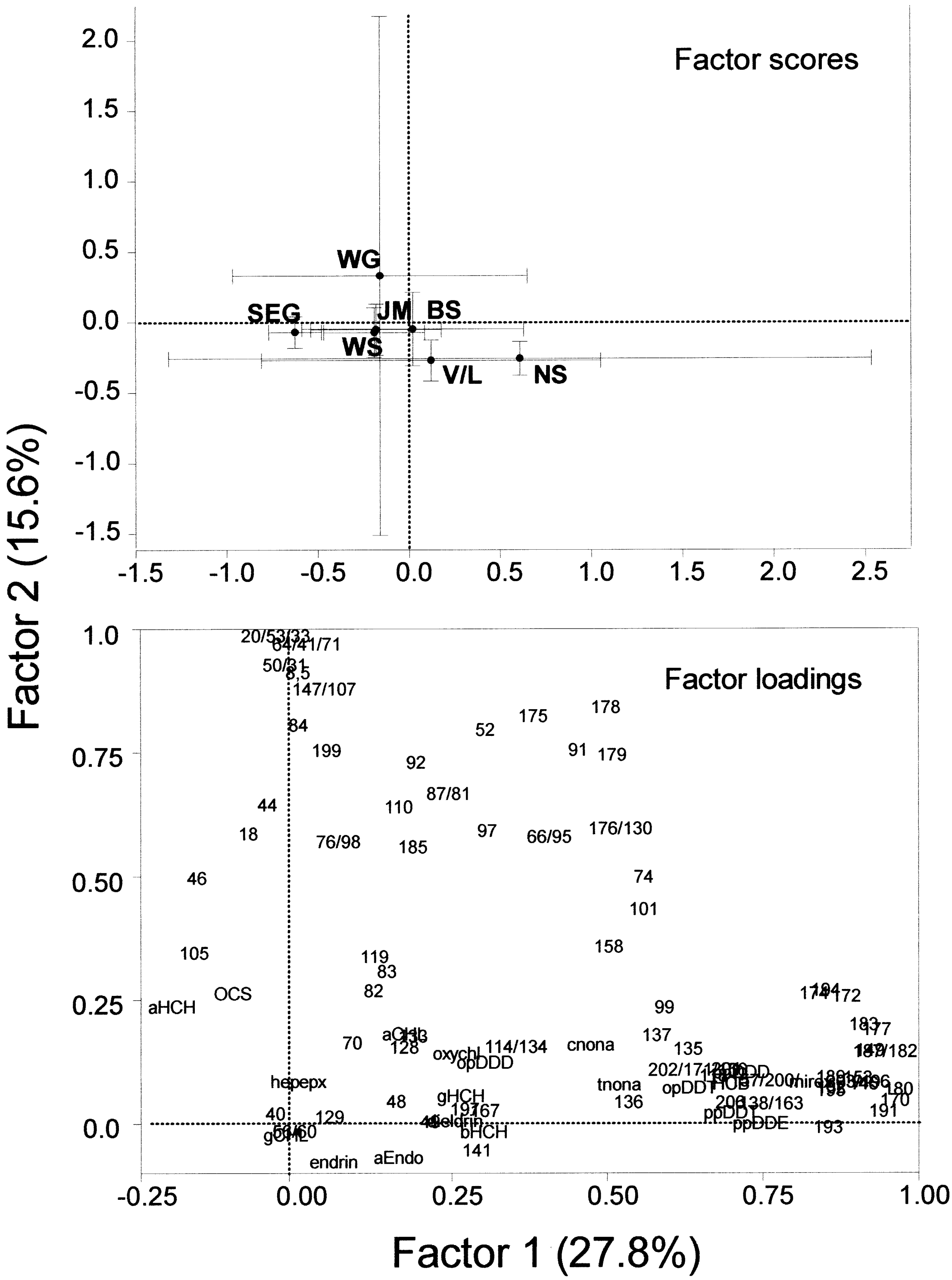

Fig. 5. Results of principal components analysis showing mean (±standard deviation) scores for minke whales from different regions in the North Atlantic Ocean and European Arctic, and loadings of individual PCB/OC pesticide compounds on PC 1 and 2. Values in brackets represent percent variance explained by that PC. Abbreviations: WG = west Greenland, SEG = southeast Greenland, JM = Jan Mayen, NS = North Sea, V/L = Vestfjorden/Lofoten, WS = west Svalbard, and BS = Barents Sea.

area coincides with elevated levels of β-HCH in seawater from the Bering Sea compared to the Chukchi/Beaufort Seas (Li et al., 2002).

There are fewer reliable data for PCBs in the Arctic Ocean and North Atlantic Ocean waters. In any case, because of the greater biomagnification of PCBs, relative to HCHs, and their association with particles, levels in the water column may be less relevant for comparison of spatial trends of contaminants in cetaceans. However, ΣPCB levels in prey species (e.g. arctic cod in case of seals and seals in case of polar bear) are reported to be significantly higher in the Barents Sea (Svalbard) area, in the White Sea and in the south Kara Sea, compared to west Greenland (de Wit et al., 2000; de

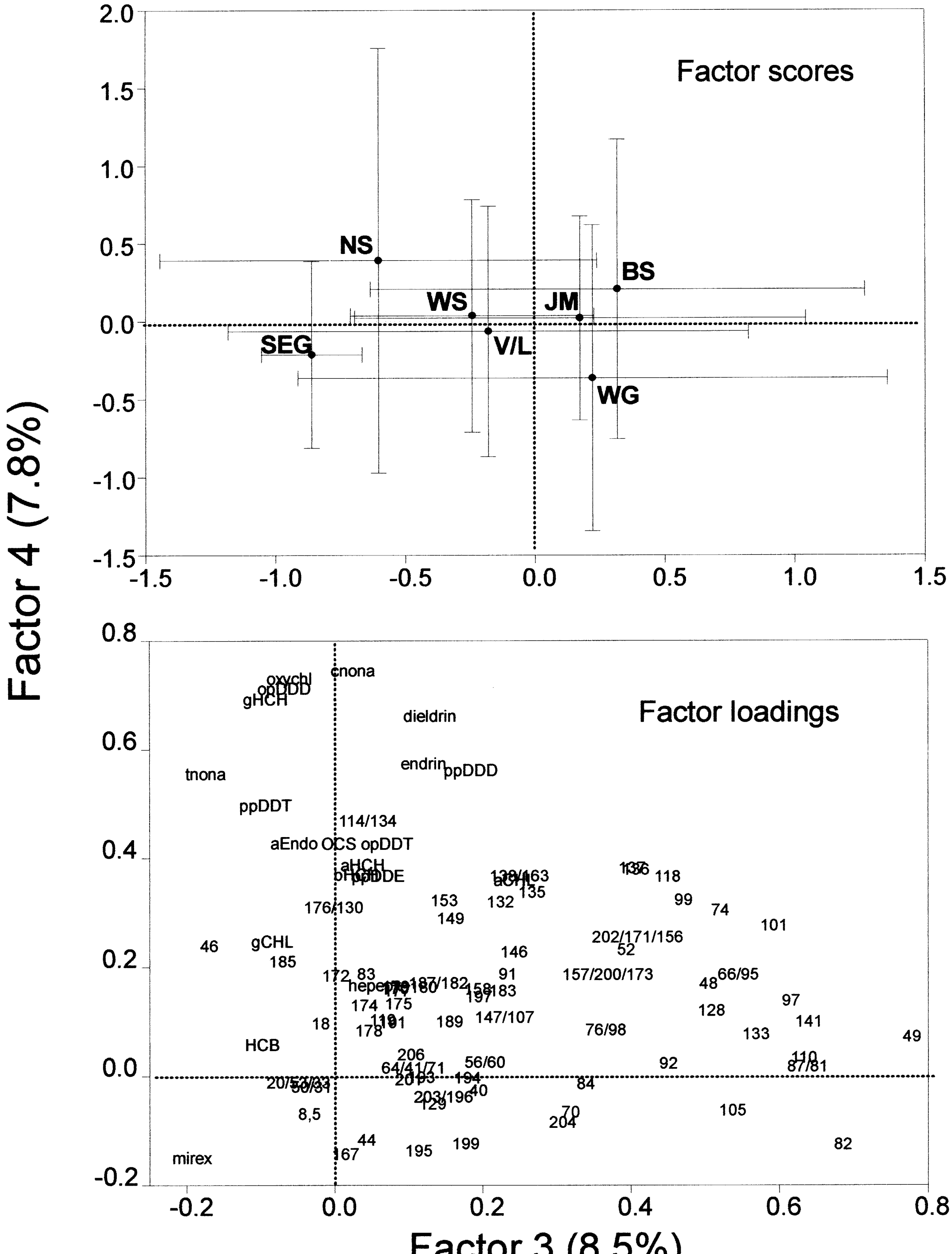

Fig. 6. Results of principal components analysis showing mean (±standard deviation) scores for minke whales from different regions in the North Atlantic Ocean and European Arctic, and loadings of individual PCB/OC pesticide compounds on PC 3 and 4. Abbreviations: WG = west Greenland, SEG = southeast Greenland, JM = Jan Mayen, NS = North Sea, V/L = Vestfjorden/Lofoten, WS = west Svalbard, and BS = Barents Sea.

Table 3
Organochlorine concentrations previously reported in northern hemisphere minke whales during the 1990's

	NW Atlantic, 1991–1992			NE Atlantic, 1992						N Pacific, 1994
	Gulf of St. Lawrence[a] *ng/g lipid weight*	N.Norway & Barents Sea[b] *ng/g wet weight*		Norway, NW Spitzbergen, Bear Isl. & Kola Peninsula[c] *ng/g lipid weight*				North Sea[d] Spitzbergen[d] *ng/g wet weight*		N Pacific[e] *ng/g wet weight*
Sex	m and f	m	f	m (juvenile)	f (juvenile)	m (adult)	f (adult)	f (adult)	f (adult)	m
n	21	31	30	15	13	22	22	5	5	18
% Lipid	60	Unknown	Unknown	90	86	89	87	72	63	74
	mean (S.D.)	mean (range)	mean (range)	mean (range)	mean (range)	mean (range)	mean (range)	mean (range)	Mean (range)	mean (range)
ΣPCB	2700 (1500)	3700 (540–8280)	2000 (1130–4050)	2980 (600–5820)	3770 (1380–10 370)	5770 (2280–20 760)	2270 (1250–3940)	2190 (876–3640)	461 (162–595)	2300 (620–3100)
ΣDDT	1570 (861)	2400 (460–4860)	1400 (570–2880)	1940 (520–4520)	2770 (940–6560)	3860 (1270–14 760)	1510 (700–3370)	–	–	1700 (230–2600)
ΣCHL	639 (245)	–	–	910 (300–1960)	1280 (460–3190)	1630 (480–5070)	750 (280–1880)	–	–	440 (98–640)
ΣHCH	163 (35)	–	–	90 (40–180)	150 (60–580)	150 (60–390)	80 (40–180)	–	–	330 (140–660)
HCB	101 (35)	–	–	230 (140–470)	360 (170–1080)	260 (120–380)	190 (80–430)	–	–	140 (66–320)

no data.

[a] Gauthier et al. (1997); ΣPCB, sum of 19 congeners; ΣDDT, *p,p'*-DDD,-DDE,-DDT; ΣCHL, sum of *cis*- and trans-chlordane, *cis*-nonachlor, oxychlordafle; ΣHCH, α-, β-,γ-,δ-HCH.

[b] Skaare (1995); ΣPCB, sum of 22 congeners; ΣDDT, *p,p'*-DDD, DDE, DDT and *o,p'*-DDD and-DDT; ΣCHL, sum of heptachlor, oxychlordane, heptachlor epoxide and *trans*-nonachlor; ΣHCH, sum α-,β-,γ-HCH.

[c] Klievane and Skaare (1998); ΣPCB, sum of 18 congeners; ΣDDT, sum of *p,p'*-DDD,-DDE,-DDT and *o,p'*-DDD and -DDT; ΣCHL, sum of oxychlordafle *cis*- and *trans*-chlordane, *cis*- and *trans*-nonachlor; ΣHCH, sum of α-,β-, γ-HCH.

[d] Skaare et al. (in preparation); ΣPCB, sum of 35 congeners.

[e] Aono et al. (1997); ΣPCB, sum of 94 congeners; ΣDDT, sum of *p,p'*-DDE,-DDD & -DDT; ΣCHL, sum of oxychlordane, *trans*-chlordane, *cis*-chlordane, *cis*-nonachlor; ΣHCH sum of α-,β-,γ-HCH.

March et al., 1998; Savinova et al., 2000). Higher levels of PCBs and DDT have also been found in Atlantic cod from the North Sea compared to those from Iceland (Stange and Klungsøyr, 1997). Taken together all this information suggests that there is a gradient of PCB and persistent OCs across the North Atlantic from the North Sea to Greenland, and from the Barents Sea to Greenland, which could influence levels in minke tissues. Therefore, it would be reasonable to hypothesize that minke whales feeding in the eastern portion of the North Atlantic minkes summer range could differ significantly in levels and patterns of PCB congeners compared to those feeding in western Greenland. The generally higher levels of PCBs in Svalbard and Barents Sea minkes, as well as the low levels of *o,p′*- and *p,p′*-DDD, *cis*- and *trans*-nonachlor and oxychlordane in Greenland minkes compared to those from more easterly locations in the North Atlantic and European Arctic are consistent with trends for these compounds in other marine species (de March et al., 1998). Similarly, the higher levels of α-HCH in the Greenland minkes, compared to other locations to the east coincides well with the general trends for a west to east decrease from the Canadian arctic archipelago to the Barents Sea of this compound in seawater (Macdonald et al., 2000). Animals that move between feeding areas with relatively different degrees of contamination on an annual basis, as is the case with minkes (Stewart and Leatherwood, 1985), might be expected to have blended the different regions contaminant signals. This would particularly affect the levels of those OCs that are more rapidly eliminated because of greater polarity and/or metabolism in mammals, e.g. HCH, chlorobenzenes and lower chlorinated PCBs. This may explain why mean ΣPCB and ΣDDT levels showed much less regional variation than more rapidly degraded compounds such as endosulfan and lindane.

Minkes feed at a lower trophic level than polar bears, odontocetes and some seals. Stomach contents surveys show that they feed primarily on capelin (*Mallotus villosus*), herring (*Clupea harengus*), Atlantic cod (*Gadus morhua*), and krill (*Thysanoessa spp.*) (Larsen and Kapel, 1981; Nordøy and Blix, 1992; Haug et al., 1995; Skaug et al., 1997). Regional differences in availability of prey items might therefore influence concentrations especially of highly biomagnified OCs found in minkes.

Although little detail is known about their migrations, minkes found from Greenland to Atlantic Canada in the summer months are believed to undertake a largely offshore migration southward to more temperate waters in the winter (Stewart and Leatherwood, 1985). The eastern North Atlantic minkes are believed to migrate southward along the European coast in the autumn and have been observed in waters around areas such as Holland, the Mediterranean and the Italian coast (Stewart and Leatherwood, 1985). These large-scale movements will also influence their exposure to contaminants.

4.3. Comparison with other studies of minke whales from the North Atlantic and North Pacific

Data from the present study were compared to other studies conducted on northern hemisphere minke whales, including three for whales from both sides of the North Atlantic during the 1990's (Table 3; Skaare, 1995; Gauthier et al., 1997; Kleivane and Skaare, 1998), northeast Atlantic minkes in 2001 (Skaare et al., 2002), and North Pacific minkes in sampled in 1994 (Aono et al., 1997). To maximize the comparability of data from the present study and these other studies, concentrations of "sum" OC and PCB groups quantified in the present study were recalculated (data not shown) so that they only included the individual compounds incorporated in each major compound group examined in the other studies. Nevertheless, given differences in factors such as age and sex distribution, and sampling dates, only general comparisons were possible.

Mean ΣPCB, ΣDDT, ΣCHL and ΣHCH concentrations in minkes (pooled sexes) from the western Atlantic (NW Gulf of St Lawrence) in 1991–1992 (Gauthier et al., 1997), were roughly 2–3 fold higher than levels reported in whales from west Greenland, and roughly 6–9 fold higher than in the four female whales from SE Greenland (present study). The greater difference for SE Greenland whales may be influenced by their longer average length, which suggests that they are older than the Gulf of St Lawrence whales, and thus presumably have had greater opportunity to eliminate contaminants during gestation and lactation, assuming they are reproductively active. HCB concentrations (101 ± 35.5 ng/g) in the Gulf whales were comparable to those in minkes from western Greenland (present study). These differences may also be influenced by variations in sex distributions, seasonal sampling dates and maturities of the whales. Mean ΣPCB, ΣDDT, ΣCHL, ΣHCH and HCB concentrations reported in minke whales from the N.E. Atlantic (W. Spitzbergen, Lofoten/Vesteralen, Finmark, Bear Island, and the Kola Peninsula) in 1992 (Kleivane and Skaare, 1998), were about 2–3 fold higher than mean levels reported in the same regions in the present study (sites pooled). Mean ΣPCB and ΣDDT levels reported by Skaare (1995) for minkes sampled from the northern Norwegian coast and in the Barents Sea in 1992 were also generally higher than in whales from the same areas in present study, a difference apparently driven by levels in minkes from Bear Island and Svalbard, which were roughly 2–5 fold higher than in Svalbard whales from the present study. The lower contaminant levels in minkes from the present study, compared to 1992 levels, may be partly attributable to changes in the availability of N.E. Atlantic minke whale prey species. For example, in 1992 the diet of Svalbard minke whales was dominated by capelin, while in subsequent years, following the collapse of the capelin stocks in 1992/1993, their diet was almost 100% krill (Haug et al., 2002). A general decline in PCB levels in the marine food web of the southern Barents Sea during the 1990s may also be reflected in differences between samples from 1992 and 1999. Henriksen et al. (2001) found a significant decline (approximately 2-fold) in levels of PCB153 in plasma of polar bears from Svalbard from 1991 to 1999.

Mean ΣPCB and ΣDDT levels in minkes from the Kola Peninsula reported by Skaare (1995) were comparable to levels in whales from the Kola region of the Barents Sea in the present study. The notably higher concentrations of ΣPCB in minkes sampled from the southern North Sea, in comparison to levels in minkes from Spitsbergen (Skaare et al., 2002) are consistent with the results in this study and support the view that the North Sea minkes are distinct from minkes in other regions of the North Atlantic and European Arctic. Mean ΣPCB and ΣDDT levels of male minke whales from the North Pacific (Aono et al., 1997) are generally lower than in minkes from the eastern North Atlantic (present study and Skaare et al., 2002). Only west Greenland and west Svalbard males had lower ΣDDT and HCB concentrations than the North Pacific males. However, average ΣHCH concentrations were higher in the North Pacific minkes than mean concentrations in minkes from all regions in the North Atlantic in the present study. This general trend is consistent with observations of much higher HCH levels in seawater in the North Pacific compared to the North Atlantic Ocean (Iwata et al., 1993; Lakaschus et al., 2002; Li et al., 2002).

5. Conclusions

Concentrations of PCBs, DDT- and chlordane related compounds in blubber of minke whales from Greenland, the North Atlantic, and the European arctic generally increased from west to east, while HCH concentrations showed the opposite trend, which is consistent with known trends in seawater, fishes, seals and polar bears. Concentrations and patterns of PCB and OC pesticide in North Atlantic minke whales suggest that west and southeast Greenland minkes may represent one group of whales, which are quite distinct from those sampled at Jan Mayen, and those from other more easterly IWC small areas. This distinction between west Greenland minkes and those from other sites is in agreement with findings for genetics (Andersen et al., 2001), fatty acids (Møller et al., 2001) and elemental and stable isotopes (Born et al., 2001) studies on the same animals. However, no firm conclusions can be drawn for the southeast Greenland whales due to small sample sizes. Although some mixing probably occurs between whales from the Barents Sea and Svalbard small areas, and between whales from North Sea and Vestfjorden/Lofoten, there appears to be some separation between these two sets of regions based on distinct differences in more readily metabolizable OC compounds such as endosulfan and lindane. The general similarity in mean levels of ΣPCBs, ΣDDT and ΣCHL,?as well as mean principal components analysis scores, among minkes sampled at Jan Mayen, Svalbard, Vestfjorden/Lofoten, the North Sea and the Barents Sea suggests that the whales are quite mobile and may feed in multiple areas within the northeastern Atlantic.

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