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Reproductive performance and organochlorine pollutants in an Antarctic marine top predator: The south polar skua

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Abstract

Despite low levels of organochlorine contaminants (OCs) in Antarctic biota, some compounds may exceed the levels in equivalent Arctic species, and previous studies have found biochemical evidence of pollutant exposure in south polar skuas (*Catharacta maccormicki*), a common marine top predator in the region. In this study we examined relationships between fitness components (fecundity and adult return rate between breeding seasons) and concentrations of OCs in this species. In 65 nests, both males and females were caught, and using principal component analyses (PCA) we produced composite measurements (PC1 and PC2) of six highly correlated OCs measured in blood samples. Although the concentrations of OC were below those documented to have reproductive effects in other aquatic birds, we found that the eggs of females with high levels of OCs in the blood hatched later, and their chicks were in poorer condition at hatching, than females with low OC levels. Thus OCs may delay reproduction and reduce foetal growth in the skuas. However, there was no relationship between the parents' OC residues and the occurrence of non-viable eggs, although the proportion of nests containing non-viable eggs was high (47%). Moreover, there were no significant relationships between OCs and reproductive variables in males, even if males had higher OC levels than females, and no associations between OCs and adult return rate between breeding seasons.

Keywords: Organochlorines; PCB; DDE; Mirex; HCB; Principal component analysis; Reproduction; Southern Hemisphere

1. Introduction

Many organochlorine contaminants (OCs) undergo long-range transport and may be found in relatively high concentrations in remote environments. In the 1960s and 1970s, OCs were discovered in Antarctica (Risebrough et al., 1976), but the levels of most compounds have been low compared to temperate and Arctic regions (Connell et al., 1999; Corsolini et al., 2002; Clarke and Harris, 2003; Bustnes et al., 2006a). Exceptions are some semi-volatile compounds, such as hexachlorobenzene (HCB) and some polychlorinated biphenyl (PCB) congeners, levels of which have been relatively high in Antarctic biota (Van den Brink, 1997; Weber and Goerke, 2003).

OCs may affect birds differently, including endocrine disruption and impaired immune function (Vos and Luster, 1989; Crews et al., 2000; Tanabe, 2002; Fairbrother et al., 2004), which in turn may affect reproduction and survival of individuals resulting in population declines. Moreover, since many OCs biomagnify in food chains, top predators are subject to the highest exposure and thus the most severe effects of OCs (Jones and de Voogt, 1999; Borgå et al., 2001).

This study focused on potential adverse effects of OCs on the south polar skua (*Catharacta maccormicki*), a common top predator in the Antarctic marine ecosystem (Furness, 1987). Compared to northern hemisphere seabirds, levels of OCs have been low in south polar skuas, but we recently documented blood levels of mirex, a formicide and fire retardant, in skuas breeding in Dronning Maud Land (at the Atlantic side of the Antarctic continent) similar to the highest concentrations

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Table 1
Correlation matrix and principal components for body size of males and females ($n=65$)

	Males				Females			
	Bill length	Bill height	Tarsus length	Wing length	Bill length	Bill height	Tarsus length	Wing length
Skull length	0.74	0.50	0.32	−0.20	0.76	0.52	0.59	0.08
Bill length		0.44	0.33	−0.13		0.38	0.39	0.06
Bill height			0.29	−0.14			0.24	0.17
Tarsus length				−0.06				0.13
	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
Importance of components								
Standard deviation	1.54	0.97	0.87	0.78	1.57	0.99	0.86	0.73
Proportion of variance	0.48	0.19	0.15	0.12	0.50	0.20	0.15	0.11
Cumulative proportion	0.48	0.67	0.83	0.95	0.50	0.70	0.85	0.96
Loadings								
Skull length	−0.56	0.00	0.29	0.25	−0.58	0.15	0.02	0.11
Bill length	−0.55	0.10	0.29	0.40	−0.52	0.20	−0.05	0.65
Bill height	−0.46	0.05	0.09	−0.88	−0.42	−0.17	−0.72	−0.49
Tarsus length	−0.36	0.29	−0.88	0.11	−0.44	0.02	0.68	−0.52
Wing length	0.19	0.95	0.24	−0.04	−0.14	−0.95	0.13	0.23

reported in blood and plasma of birds (Elliott and Shutt, 1993; Jarman et al., 1994; Bustnes et al., 2006a). In addition, mean HCB residues were 1.7 times higher than in sub-arctic great black-backed gulls (*Larus marinus*) from the Norwegian Coast (Bustnes et al., 2006a). South polar skuas are migrants and may cross the equator during the Antarctic winter (Furness, 1987), such that much of their OC burdens may be accumulated north of the Antarctic Convergence, especially compounds like PCB and *p,p′*-dichlorodiphenyldichloroethylene (*p,p′*-DDE) (Corsolini et al., 2002; Focadri et al., 1992; Court et al., 1997). However, by repeatedly sampling the same breeding individuals we found that little of the increase in mirex and HCB was explained by alterations in individual lipid pools, suggesting that the Antarctic is important for the accumulation of these compounds (Bustnes et al., 2006a). Furthermore, previous studies have found elevated levels of detoxification enzymes and TEQs (2378-tetrachlorordibenzo-*p*-dioxin equivalents) in south polar skua eggs and livers, raising concern about potential adverse effects (Focadri et al., 1992; Court et al., 1997; Kumar et al., 2002; Corsolini et al., 2002). Court et al. (1997) found high frequencies of non-viable eggs in skuas breeding at the Pacific part of Antarctica. However, the concentrations of OCs in south polar skuas have been much lower than the levels at which ecologically relevant reproductive effects have been documented in birds (Davidson et al., 1975; McArthur et al., 1983; Boersma et al., 1986; Hoffman et al., 1986; Fernie et al., 2001a,b; Elliott and Harris, 2001/2002; Bustnes et al., 2006a). In wildlife, however, OCs may cause adverse effects at lower levels than those in laboratory studies (Grue et al., 2002), for example due to combined effects of natural stress and pollutants (Keith and Mitchell, 1993; Gill and Elliott, 2003; Relyea and Mills, 2001; Sih et al., 2004; Bustnes et al., 2006b). Moreover, birds living under harsh polar conditions may be more stressed than those in temperate areas (Bonstra, 2004), making them more vulnerable to adverse effects of pollutants. For example, the south polar skuas experience very low temperatures during breeding (<-10 °C), and when they arrive in the nesting area food may be scarce since their main food source, eggs and young of the Antarctic petrel (*Thalassoica antarctica*), are not available (de Brooke et al., 1999). It is thus pertinent to ask whether OCs may have ecologically relevant effects on breeding south polar skuas. In this study we examined the relationships between blood concentrations of OCs and important fitness components including a set of reproductive parameters and adult return rate between breeding seasons.

2. Study area and methods

2.1. Field work

South polar skuas were studied at Svarthamaren (71° 53′ S, 05° 10′ E), Dronning Maud Land (Antarctica), in December 2001 and January 2002. Details of the study area are given in Mehlum et al. (1988). Svarthamaren is situated in the interior of Antarctica, approximately 200 km from the ice shelf, and has the largest breeding colony of Antarctic petrels in the world with about 250 000 pairs. The petrel colony supports a breeding population of 80–90 pairs (about 250 individuals including non-breeders) of south polar skuas. During the breeding season skuas feed almost exclusively on eggs and young of petrels (de Brooke et al., 1999).

All skua nests were marked shortly after our arrival in mid December. The adults were caught with a nest trap (Helberg et al., 2005) or by using a rod with a snare. Blood was sampled from the wing vein (ca 10 ml) with a syringe. The whole blood samples were frozen within 2–6 h. All individuals were marked with a letter-coded PVC band and a numbered steel band, and their bill length, bill height (±0.1 mm), skull length (head + bill), tarsus and wing length (±1 mm) and body mass (±5 g) were registered. We performed a principal component analysis on these measurements, and used the first principal component score as an index of body size (Table 1).

Eggs were laid in most nests at the time of our arrival, so laying dates could not be recorded directly. Egg length and width (±0.01 mm) were measured with sliding callipers and egg volume (ml) was estimated by the formula: $\text{Volume} = 0.000476 \times \text{Length} \times \text{Width}^2$ (Hoyt, 1979). The nests were checked daily to record hatching dates, and all eggs were monitored for cracks indicating that hatching had started. As cracks were discovered, the nests were checked at shorter intervals so the chicks could be weighed (to the nearest gram using a spring balance) as soon as possible after hatching. We estimated that all chicks were weighed within about 6 h of hatching. In nests with two hatching eggs, the

Table 2
Geometric mean [95% CI] and range of wet weight concentrations (ng/g) in the blood of female and male south polar skuas during breeding

	Females			Males		
	Mean	95% CI	Range	Mean	95% CI	Range
HCB	6.17	5.50–6.93	0.56–16.55	6.75	5.88–7.74	0.95–21.24
Oxychlordane	1.01	0.89–1.15	0.17–4.33	1.18	1.02–1.37	0.17–3.67
trans-nonachlor	0.21	0.18–0.24	0.03–1.62	0.20	0.17–0.23	0.03–1.01
DDE	4.87	4.19–5.65	0.59–22.83	5.94	4.91–7.18	0.45–40.88
Mirex	14.89	12.96–17.11	1.00–53.92	19.67	16.26–23.81	1.52–69.24
ΣPCB	6.94	5.96–8.08	1.03–50.89	8.19	6.96–9.64	1.14–36.27
ΣOC	35.40	31.06–40.34	3.39–115.97	43.57	36.87–51.49	4.52–158.69

Figures are based on males and females on a total of 65 nests (see Study area and methods). Data from Svarthamaren, Dronning Maud Land, Antarctica, 2001/2002.

chicks were weighed sequentially after they hatched. Since we did not know the laying sequence we used the mean weight of the chicks in the nest controlled for the mean of egg volume. Non-viable eggs were those not hatching or found to be addled during the incubation stage.

To record returning adults, the colony was visited in 2004. The colony was searched four times from 17 to 29 November and all colour banded individuals were recorded. We were thus able to record the individuals that had survived since 2001/2002, and returned to breed in 2004, with high probability. This means that we have data on return rate for one season three years after the birds were measured for OCs. In the following, we refer to this as adult return rate, assuming that it reflects the survival probability.

2.2. Laboratory analyses

All adults were sexed using the molecular method described by Sambrook et al. (1989) and Fridolfsson and Ellegren (1999). Of a total of 142 individuals there were 73 females and 69 males. In the analyses, we only used the 69 nests where both the male and the female were caught. This allowed us to test the effects of female and male OC levels simultaneously. The OC analyses were carried out at the Environmental Toxicology Laboratory at the Norwegian School of Veterinary Science/National Veterinary Institute. All details about the analyses, including gas chromatograph (GC) conditions, temperature program and quality assurance procedures are given in Andersen et al. (2001) and Bustnes et al. (2006a). Percent recoveries and coefficient of variance of individual OCs in spiked sheep blood varied from 77 to 127 and 0.04 to 14.09, respectively, which are in the acceptable range set by the laboratory quality control system. The following PCB-congeners were determined: -28, -52, -47, -74, -66, -101, -99, -110, -149, -118, -153, -105, -138, -187, -183, -128, -156, -157, -180, -170, -196, -189, -194, -206 (IUPAC-numbers; Ballschmiter and Zell, 1980). Other compounds analysed included HCB (hexachlorobenzene), the chlordane isomer *trans*-nonachlor and metabolite oxychlordane, *p,p′*-DDE (*p,p′*-dichlorodiphenyldichloroethylene), and mirex.

2.3. Statistical analyses

The levels of various OCs vary greatly, and extreme values lead to a skewed distribution. We therefore log transformed the OC levels to approximate the normal distribution, and standardized (mean 0, variance 1) them to facilitate the interpretation of the coefficients. The levels of various OC congeners obtained from the same individual are highly correlated (Jones and de Voogt, 1999; Bustnes et al., 2001). Accordingly, we tested the hypothesis that levels differ between males and females using a Multivariate Analysis of Variance (MANOVA). Due to the high colinearity among OCs, we did not attempt to separate the effect of individual components, but performed a principal component analysis on the OC levels. This allowed us to identify groups of highly correlated compounds and generate independent predictor variables that could be used in further analyses of the impact of OC on fitness components (reproductive performance and adult return rate) (see Everitt, 2005 for an outline to this analytical approach).

We performed a bivariate boxplot on the two first principal component scores to identify extreme observations in the data. This type of boxplot is useful in identifying outliers. Four observations stood well outside the “fence”, indicating potential troublesome outliers (see Everitt, 2005, page 25). These observations included one female with OC level less than half the average, and three females with OC levels that were 3–5 times higher than the other individuals. Such extreme values have high leverage, leading to a situation where the conclusion is likely to be drawn on the basis of a few extreme observations rather than the whole study population. Accordingly, we removed these outliers from our data.

The impact of OC on reproductive performance and adult return rate was analysed using Generalized Linear and Linear Models in the R system (R Development Core Team, 2005). We chose the most parsimonious statistical model based on Akaikes Information Criteria (AIC), corrected for small sample size (AICc) using the stepAIC function implemented in the MASS library of R (Venables and Ripley, 1999). In this procedure, the predictor variable explaining the least of the residual sums of squares are removed sequentially and the model refitted until the lowest AIC is obtained. Conceptually, this approach differs from the traditional elimination of predictor variables based on *P*-values in the sense that the scope is to identify the most parsimonious model explaining most of the variance, but avoiding over parameterization (i.e. including insignificant parameters) (Burnham and Anderson, 1998). For each nest, a life-history trait (egg size, hatching success, hatching dates, chick condition at hatching, and adult return rate) was the response variable and the female's and male's concentrations of OCs and a set of potentially confounding variables (female and male body mass, lipid content structural size [PC1], and the date of sampling) were predictor variables (see results). The AICs for all models are presented to facilitate comparison of competing models.

Table 3
Correlation matrix and principal components for OCs ($n=65$)

	Oxychlordane	*trans*-nonachlor	DDE	Mirex	ΣPCB
HCB	0.87	0.82	0.77	0.73	0.83
Oxychlordane		0.78	0.83	0.80	0.87
trans-nonachlor			0.82	0.76	0.83
DDE				0.78	0.92
Mirex					0.84
	PC1	PC2	PC3	PC4	PC5
Importance of components					
Standard deviation	2.12	0.52	0.38	0.33	0.31
Proportion of variance	0.87	0.05	0.03	0.02	0.02
Cumulative proportion	0.87	0.92	0.95	0.97	0.99
Loadings					
HCB	−0.41	0.32	0.33	0.70	−0.28
Oxychlordane	−0.42	0.41	0.03	−0.06	0.79
trans-nonachlor	−0.38	−0.49	0.71	−0.29	−0.03
DDE	−0.42	−0.32	−0.48	0.28	−0.17
Mirex	−0.41	0.47	−0.16	−0.59	−0.49
ΣPCB	−0.40	−0.42	−0.37	−0.05	0.17

3. Results

3.1. OC levels in males and females

Males had higher blood concentrations of OCs than females (MANOVA: $F_{1,127}=5.50$, $P<0.001$, Table 2). Mirex was the dominating compound making up about 45% of ΣOC, while PCB, p,p'-DDE and HCB made up 15–20% each (Table 2). There were no correlations between male and female blood concentrations of different OCs investigated in this study ($0.0047<R^2<0.03$). We therefore used the OC levels of males and females belonging to the same nest as independent predictor variables.

3.2. Patterns and correlation in OC levels

The first principal component score explained 87% of the variance in OC levels and correlated negatively to all individual components. This component thus gives a good measure of the overall OC level, but to facilitate the interpretation, we refer to the inverse of PC1; i.e. positive scores indicate high levels of contaminants. The second principal component score explained 5% of the variance and correlated positively to mirex, oxychlordane and HCB, and negatively to the other OCs thus making a contrast between these two groups of chemical compounds. Since the two first principal component scores explained 92% of the variance, we did not consider any other scores in our examination (Table 3).

3.3. OCs and egg size

A linear regression model including female body mass only gave the lowest AIC. Mean egg size in a clutch was positively related to the body mass of females (egg volume = 58.0 + 0.02 × female body mass, $R^2=0.07$, $P=0.03$). The parents' levels of OCs, as expressed through the principal components scores, did not explain any significant proportion of the variance in mean egg size (Table 4).

3.4. OCs and non-viable eggs

Of a total of 47 nests that could be tested for non-viable eggs, 22 (47%) contained such eggs. Concentrations of OCs in the parents were not related to the probability of having non-viable eggs, but the model with the lowest AICc included the lipid content of males and females

Table 4
Model selection for the analyses of egg volume, non-viable eggs, hatching date and predation in south polar skuas

	Egg volume	Hatching date	Males					Females					AICc	ΔAICc	K[a]	n
			Size	Body mass	PC1	PC2	Lipid	Size	Body mass	PC1	PC2	Lipid				
Egg volume	–	–			x	x	x		x	x	x	x	241.44	10.55	8	65
	–	–			x	x	x		x	x		x	238.84	7.95	7	65
	–	–			x		x		x	x		x	236.45	5.55	6	65
	–	–			x				x	x		x	234.12	3.22	5	65
	–	–							x	x		x	230.86	−0.04	4	65
	–	–							x			x	230.89	0.00	3	65
									x				230.69	−0.20	2	65
Non-viable eggs		–			x	x	x			x	x	x	73.88	8.70	7	47
		–				x	x			x	x	x	71.19	6.01	6	47
		–				x	x			x		x	68.65	3.48	5	47
		–					x			x		x	67.05	1.87	4	47
		–					x					x	65.18	0.00	3	47
		–										x	65.47	0.29	2	47
		–											66.16	0.69	1	47
Predation					x	x	x			x	x	x	70.23	9.47	7	64
					x		x			x	x	x	67.70	6.94	6	64
					x		x			x	x		65.30	4.54	5	64
							x			x	x		63.23	2.46	4	64
							x			x			61.73	0.97	3	64
							x						60.85	0.08	2	64
													60.76	0.00	1	64
Chick body mass	x	x			x	x	x			x	x	x	113.09	13.63	9	44
	x	x			x	x	x			x	x		109.95	10.49	8	44
	x	x			x	x	x			x			106.96	7.50	7	44
	x	x				x	x			x			104.13	4.66	6	44
	x	x				x				x			101.51	2.04	5	44
	x	x								x			99.47	0.00	4	44
	x	x											103.20	3.73	3	44
Hatching date		–			x	x	x		x	x	x	x	168.39	9.09	8	44
		–				x	x		x	x	x	x	165.47	6.17	7	44
		–				x	x		x	x		x	162.95	3.65	6	44
		–				x	x		x	x			161.93	2.63	5	44
	–						x		x	x			161.03	1.73	4	44
	–								x	x			159.30	0.00	3	44
	–								x				165.09	5.79	2	44

PC1 and PC2 are the principal component scores based on the analyses of OCs.
– Parameter not included in the analysis.
[a] $K=1$ is intercept only.

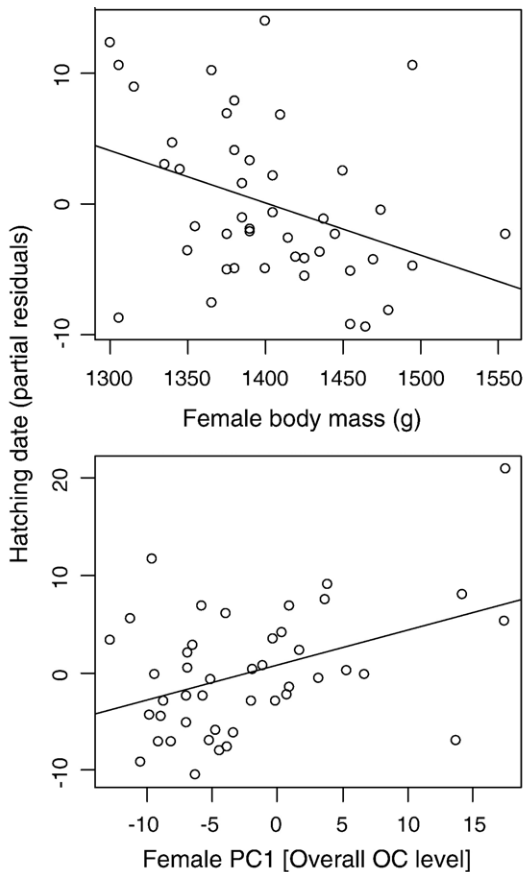

Fig. 1. The relationship between female body mass and blood concentrations of OCs (PC1 of 6 different compounds found in Table 2) and hatching date in south polar skuas from Svarthamaren, Antarctica. Note that the figure is of the partial residuals from the most parsimonious model in Table 4. In this way, the effect of female body mass on hatching date is controlled for when the effect of female blood concentrations of OCs on hatching date is examined.

(Table 4). However, compared to the null model (intercept only) the ΔAICc was <1. Following the principle of parsimony (Burnham and Anderson, 1998), these models thus did not out-compete the null model.

3.5. OCs and hatching dates

Forty-four nests had at least one egg that hatched. Hatching occurred earlier in nests where the female was heavy (hatching date [1=1 December]=104.2−0.05×female body mass, R^2=0.15, $P<0.01$). After controlling for female body mass there was a positive relationship between the first principal component for females and hatching date; i.e. females with high OC levels hatched later than those with low levels (Table 4, Fig. 1).

3.6. OCs and egg predation

Eleven of the 64 nests lost eggs due to predation by other skuas (17.2%). Neither size, nor body mass and OC levels of the parents could predict egg loss.

3.7. OCs and chick body mass at hatching

The chick's hatching body mass was negatively related to hatching date and positively related to egg size (chick hatching body mass=25.3+0.51×egg volume − 0.31×hatching date, $F_{3,41}$=28.3, $P<0.001$). After controlling for these confounders the OC levels in females improved the fit of the model indicating that overall OC levels of females negatively affected chick body mass at hatching (Table 4, Fig. 2). The estimated reduction in hatching body mass from the lowest to the highest OC levels was from 61.3 g to 56.2 g, i.e. an 8.2% reduction in hatching body mass.

3.8. OCs and adult return rate

There was no difference in return rates between males (25 of 65) and females (23 of 65), but structurally small individuals tended to have a higher probability of returning to the colony than large individuals (estimate=−0.22[95% CI: −0.44, 0.01]). There were no effects of OC levels on adult return rate (estimate=−0.02[−0.17, 0.13].

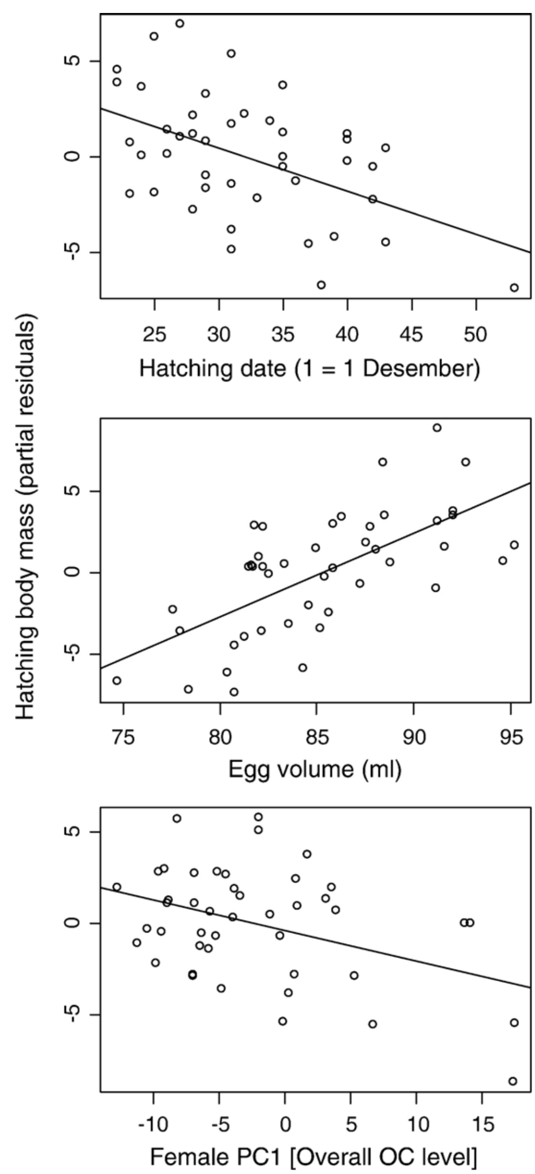

Fig. 2. The relationships between hatching date, egg volume and female blood concentrations of OCs (PC1 of 6 different compounds found in Table 2), and hatching mass of south polar skua chicks. Data from Svarthamaren, Antarctica. Note that the figure is based on the partial residuals from the most parsimonious model in Table 4. In this way, the effect of hatching date and egg volume on hatching mass is controlled for when the effect of female blood concentrations of OCs on hatching mass is examined.

4. Discussion

This study is the first to find associations between concentrations of OCs and fitness components in Antarctic birds; i.e. the timing of the reproduction and hatching mass of chicks were both adversely related to the mothers' blood residues of OCs. Such changes may affect population parameters in long-lived birds; i.e. late hatching may result in poor reproductive output (Klomp, 1970; Sydeman et al., 1991; DeForest and Gaston, 1996), and poor body condition of chicks at hatching may reduce their survival probability (Williams, 1994; Lindström, 1999). However, it is not known whether the effects found here are sufficient to affect the chick production in this skua population.

An important question in this study is whether OC levels in female blood is a suitable measure of the effect potential of the OCs: 1) in relation to factors affecting timing of reproduction, which is probably mostly related to OC levels in sensitive tissues of the females and, 2) in relation to chick hatching mass, which is probably mostly related to maternal transfer of OCs to the eggs. Several bird studies suggest that concentrations of OCs in blood are well correlated to levels in sensitive tissues (Friend et al., 1979; Marsili et al., 1996; Henriksen et al., 1998), and also a good measure of OCs sequestered into the seabird eggs (Verreault et al., 2006). However, some individuals may have eaten lipid-rich meals which temporarily increase blood lipids (up to 4%), with a corresponding increase in OC values. Similarly, temporarily low blood lipid levels will result in OC values that are poorly related to the body burden (Bustnes et al., 2005). In general the lipid values in seabird blood vary between 0.3 and 0.8%, and within this range the repeatability of OC measurements among individuals is high (Bustnes et al., 2001, 2005), and Bustnes et al. (2005) suggested that individuals with extreme lipid values should be removed as outliers in studies where potential effects are studied.

How OCs may influence the timing of reproduction is not known, but they can possibly cause stress which affects the females' ability to build up resources prior to egg-laying. This could be caused by behavioural modifications affecting courtship behaviour (McArthur et al., 1983; Fernie et al., 2001a), or by other factors related to the accumulation of body reserves, for example endocrine disruption (Burger et al., 2001; Crews et al., 2000; Fernie et al., 2001a; Tanabe, 2002), although endocrine effects of OCs in wild birds have been questioned (Dawson, 2000). There are few studies testing the relationship between OCs and reproductive timing. In great black-backed gulls in Norway, egg-laying was delayed in females with high OC levels, especially HCB (Helberg et al., 2005). In this context it is interesting to note that the mean female blood level of HCB in the skuas was higher (6.2 vs. 4.1 ng/g wet weight) than in the great black-backed gulls studied by Helberg et al. (2005). Such relationships were, however, not found in Arctic glaucous gulls (*Larus hyperboreus*) (Bustnes et al., 2003). In Dutch and Belgian common terns (*Sterna hirundo*), there was also evidence of delayed egg-laying with increasing pollutant levels in eggs (Murk et al., 1996), and in dosing experiments where females have been directly (McArthur et al., 1983; Fernie et al., 2001a), or in ovo (Fernie et al., 2001b) exposed to PCB, delayed egg-laying has also been documented.

Reduced embryonic weight may result from higher liver enzyme activity in the chick due to maternal transfer of OCs to the eggs (Kubiak et al., 1989). There are, however, few studies where the mothers' OC levels have been related to the hatching mass of their chicks, but, as in this study, both in great black-backed gulls and glaucous gulls chick hatching mass was negatively related to increasing blood concentration of OCs in the mothers (Bustnes et al., 2003; J. O. Bustnes et al. unpublished data). In other aquatic birds, such as Foster's terns (*Sterna fosteri*) and black-crowned night herons (*Nycticorax nycticorax*) reduced hatching mass of chicks has been found by comparing eggs from OC polluted and 'clean' sites (Hoffman et al., 1986; Kubiak et al., 1989). Hoffman et al. (1986) also showed that chick hatching mass was reduced with increasing PCB levels in sibling eggs collected from the same nests. Adverse effects of HCB on chick hatching mass have also been experimentally demonstrated in herring gulls (*Larus argentatus*) (Boersma et al., 1986).

In other studies where delayed egg-laying and low embryonic weight has been associated with OCs in wild birds, the OC levels have, however, been much higher than in the south polar skuas (Hoffman et al., 1986; Kubiak et al., 1989; Murk et al., 1996). It is thus pertinent to ask whether the relationships found here are real or results of confounding relationships; i.e. even if we controlled statistically for several potentially confounding variables, we cannot completely disregard the possibility that some unknown underlying factors explain the associations.

The results from different methods of measuring OCs may not be directly comparable, and it is not known whether the effects of OCs on embryonic weight start at a threshold or if there is a continuum of effects starting at very low OC levels. The latter would result in small effects in the skuas compared to more polluted species. In skuas there was an estimated 8% reduction in the chick hatching mass from the lowest to the highest OC levels in mothers. When comparing eggs from contaminated and 'clean' sites, Hoffman et al. (1986) and Kubiak et al. (1989) found that mean hatching mass was reduced by 15 and 17%, respectively. Moreover, the equation given by Hoffman et al. (1986) suggests a 30% decrease in chick hatching mass from the lowest to the highest PCB levels. Another problem with the comparisons is that the other studies have only measured PCB, which only makes up a minor fraction of the OCs in the skuas (20%; Bustnes et al., 2006a).

Even if the rate of non-viable eggs was high (47% of the nests where it could be checked), this parameter was not associated with OCs. Court et al. (1997) also found a high rate of non-viable eggs in south polar skuas from the Ross Sea, and concluded that residues of PCB and p,p'-DDE were too low to cause such effects. Unfortunately, we do not have any information regarding the levels of OCs in skua eggs, but mirex, the most common OC in skua blood (Bustnes et al., 2006a), is unlikely to cause embryo death since it is not very embryotoxic (Boersma et al., 1986). High rates of non-viable eggs have also been reported in great skuas (*Catharacta skua*) (Furness and Hutton, 1980; Furness, 1987), suggesting that large skuas may naturally have a high rate of non-viable eggs (Furness, 1987; Court et al., 1997). Moreover, at Svarthamaren temperatures are very low (−10 °C or below at night), and birds might suffer high egg mortality due to chilling.

The most sensitive parameter affecting population growth in long-lived birds is adult survival (Lebreton and Clobert, 1991). In south polar skuas, OCs had no effects on adult return rate, suggesting that survival was not affected. However, this study suggests that the OC levels in the skuas exert effects on fitness components in a manner that is expected from life-history theory (Stearns, 1992). That is, the first effects appear on the least sensitive fitness traits such as timing of egg-laying and hatching body mass of chicks. More serious effects such as lower adult survival may be expected in the future if the levels of emerging pollutants increase and/or the environmental conditions deteriorate since the effects of OCs may arise in combination with other stress factors; i.e. if food becomes scarce (Gill and Elliott, 2003; Gervais and Anthony, 2003; Bustnes et al., 2006b). This is a possible scenario since the natural stress on wildlife in extreme environments, such as the Antarctic, may be more severe than in temperate region, rendering such species more vulnerable to the effects of pollutants (Bonstra, 2004). In addition, skuas may experience stress during winter, which may result in poor condition at arrival in Antarctica. It should also be noted that in this study we only measured legacy OCs that have been in the ecosystems for several decades, and for which cessation of production and use have led to decreasing levels on a global scale (Loganathan and Kannan, 1994). However, there are several other groups of emerging contaminants, including perfluorinated and brominated contaminants that have recently been found in the Antarctic ecosystem (Corsolini et al., 2006; Tao et al., 2006). In the future, these compounds should be included in all pollution studies from this region.

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