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Effects of sheens associated with offshore oil and gas development on the feather microstructure of pelagic seabirds

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ABSTRACT

Operational discharges of hydrocarbons from maritime activities can have major cumulative impacts on marine ecosystems. Small quantities of oil (i.e., 10 ml) results in often lethally reduced thermoregulation in seabirds. Thin sheens of oil and drilling fluids form around offshore petroleum production structures from currently permissible operational discharges of hydrocarbons. Methodology was developed to measure feather microstructure impacts (amalgamation index or AI) associated with sheen exposure. We collected feather samples from two common North Atlantic species of seabirds; Common Murres (*Uria aalge*) and Dovekies (*Alle alle*). Impacts were compared after feather exposure to crude oil and synthetic lubricant sheens of varying thicknesses. Feather weight and microstructure changed significantly for both species after exposure to thin sheens of crude oil and synthetic drilling fluids. Thus, seabirds may be impacted by thin sheens forming around offshore petroleum production facilities from discharged produced water containing currently admissible concentrations of hydrocarbons.

1. Introduction

Discharges of hydrocarbons into the marine environment at either or both low-volumes and low-concentrations are commonly referred to as "chronic oil pollution" because these discharges typically are not reported or do not trigger a mitigation response. Chronic oil pollution discharges can be either legal or illegal, and can occur intentionally or accidentally. Although small in volume or low in concentration, these discharges constitute over half of the estimated input of oil pollution into the marine environment associated with maritime human activities (NRC, 2003; GESAMP, 2007) yet, it remains difficult to attribute environmental costs associated with this category of oil pollution. Nevertheless, there is a growing recognition that impacts from oil pollution from low-volume discharges and often unreported maritime spills ("chronic oil pollution") can be cumulative, and there is evidence that in some areas chronic oil pollution is a major cause of seabird mortality (Camphuysen, 1989; Burger and Fry, 1993; Wiese and Ryan, 2003).

The intentional (i.e., operational) discharge of low-volume and low-concentration hydrocarbons is a common practice associated with offshore oil and gas production. Periodically, due to the effects of interactions with several factors that are not clearly understood, hydrocarbons from these discharges rise to the surface and concentrate to produce thin, visible sheens around offshore oil and gas operations (ERIN and OCL, 2003). These types of discharges are permissible and regulated; however, our understanding of environmental impacts from sheens and other activities associated with offshore oil and gas production is still developing and further research is necessary (Wiese et al., 2001; Fraser et al., 2006).

Most marine avifauna rely on feathers for flight and insulation, and many species also rely on feathers for buoyancy. Generally, it is accepted that feather fouling from oil is the primary cause of mortality in seabirds exposed to oil pollution (Leighton, 1991). The capacity of a feather to repel water is dependent on the ratio of barb thickness and distances between barbs and the surface tension of the water (Stephenson, 1997). Oil disrupts feather microstructure, causing the collapse of hooks, barbs and barbules (Hartung, 1967; Jenssen and Ekker, 1988; Jenssen, 1994), changing the ratio of barb thickness and distances between barbs enough that the surface tension of the water no longer prevents water penetration. Feather fouling from as little as 10 ml of heavy oil can significantly reduce thermoregulation in marine and aquatic avifauna and may be lethal, especially in colder climates (Hartung, 1967; McEwan and Koelink, 1973; Levy, 1980; Lambert et al., 1982; Jenssen and Ekker, 1989; Burger and Fry, 1993).

Pelagic seabirds are particularly vulnerable to chronic oil pollution because of their biology and foraging behaviour. Seabird indi-

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viduals are exposed to a high risk of encountering maritime oil pollution because they spend most of their annual cycle at-sea, returning to land during breeding only. During these protracted periods at-sea even small quantities of feathers contaminated by oil can be lethal, causing hypothermia and reduced buoyancy (Tuck, 1960 as cited in Hartung, 1967; Levy, 1980). Breeding success can also be impacted because oil-fouled adults may transfer oil directly to their eggs or chicks during brooding (King and Lefever, 1979). Risk of exposure to oil pollution likely varies among pelagic species with different foraging modes (King and Sanger, 1979; Camphuysen, 1989; Williams et al., 1995) – for example, species that feed by diving below or feeding at the ocean surface are at greater risk of plumage fouling than species that pluck prey from the surface while in-flight. Furthermore, attraction to offshore drilling and production structures increases the risk of exposure to oil from operational discharges for many species of seabirds (Tasker et al., 1986; Baird, 1990; Wiese and Montevecchi, 2000; Wiese et al., 2001).

Populations of seabirds are vulnerable to impacts from oil exposure because of life history characteristics that are remarkably consistent among species. Although quite diverse morphologically, most seabirds exhibit high adult survival rates, low-reproductive rates, and deferred onset of sexual maturity (Ricklefs, 1990). These characteristics make seabird populations sensitive to small increases in adult mortality, and because of their low-reproductive rates and delayed maturity, populations tend to take a long time to recover from perturbations (Wiese and Robertson, 2004).

Although seabirds are exposed to slicks and sheens formed from operational hydrocarbon discharges associated with offshore oil and gas production, it is unclear if there is any impact from this exposure. Slicks and sheens associated with offshore drilling operations tend to be thin and in many cases invisible to the human eye. The purpose of these experiments was to determine if exposure of pelagic seabird feathers to thin oil sheens results in oil transfer to feathers and/or measurable disruption of feather microstructure. We collected feathers from two species of seabird that are common in the Atlantic Canada region, the Common Murre (*Uria aalge*) and Dovekie (*Alle alle*), and we examined impacts on feather structure from exposure to sheens of various thicknesses that we produced in laboratory setting using crude oil and synthetic based drilling fluid. Both the crude oil and synthetic based drilling fluid samples were donated from oil and gas production facilities found in the Atlantic Canada region, and sheen thicknesses produced in the lab were appropriate for those associated with operational discharges in this region.

2. Materials and methods

Approximately 30 upper breast and lower neck contour feathers were sampled from Canadian Atlantic pelagic seabirds, Common Murres (*U. aalge*) and Dovekies (*A. alle*). Crude oil was obtained from Hibernia and synthetic based drilling fluid from Petro-Canada (PureDrill IA-35LV, Mississauga, Ontario). Laboratory experiments were conducted at the University of Victoria in Victoria, BC. Sheens were created from crude oil at thicknesses that can occur from discharges of produced water or disposal of cuttings around oil production or drilling platforms. Produced water was not used in the experiments due to difficulty in creating standard sheens of various thicknesses on ocean water in the scaled-down "environment" of a Petri-dish.

Sheen thickness treatments were chosen to range from thin to thick corresponding to pre-established categories based on aerial observation of oil sheens and include (1) control – no oil added, (2) barely visible sheen – 0.04 μm thick, (3) trace colour sheen – 0.1 μm thick, (4) dark colour or thick sheen – 3.0 μm thick, and (5) slick – 25 μm thick (HAZMAT, 1996). Because it was not known whether sheens would have an appreciable effect on feather microstructure, the positive control (25 μm), simulating an oil slick, was used. Note that an oil film equal or less than 3 μm is referred to as a 'sheen' and an oil film greater that 3 μm is referred to as a 'slick', as defined in ERIN and OCL (2003) (see Table 1). Sheens and slicks of appropriate thickness were created by calculating the amount of oil required to create the designated thickness given the surface area of the Petri-dish using the standard formula for calculating the volume of a cylinder: volume of oil added (ml or cm^3) = πr^2 (cm^2) × oil thickness (cm).

Seawater and oil were cooled in an ice bath to approximately 5 °C to simulate typical winter seawater surface temperatures in Atlantic Canada. Petri-dishes were filled with cooled seawater to a depth of 5 mm. One treatment level was prepared at a time with two replicate Petri-dishes. Cooled seawater was measured into two Petri-dishes and appropriate volumes of oil were pipetted onto the surface using a calibrated micropipetter. Oil was gently stirred with the tip of the pipette. Before being exposed to the oil sheen, feathers were weighed on a Scaltec SBC 22 analytical balance (Heilingenstadt, Germany), accuracy class I to 0.0001 g. Using tweezers, one feather was picked up by the calamus (Fig. 1) and placed on the oil sheen for 15 s. The feather was then swiped three times across the surface and then left stationary on the sheen surface for an additional 15 s. The feather was then placed onto a large glass slide, convex surface up, with a smaller glass slide laid across the end of the calamus to hold the feather in place, leaving feather surface untouched. The feather was then immediately photographed using a microscope at 60× magnification. Two images were taken on each side of the rachis for a total of four images for each feather. Image locations were chosen semi-randomly, in areas that did not contain large anomalies such as pre-oiling splits between rami (Fig. 2). Unfortunately we did not assess feathers for anomalies prior to treatment and assumed that variation in anomalies pre-treatment was randomly distributed among treatment groups. After the feather was photographed, it was weighed a second time.

The above procedure was repeated with the same treatment in a new Petri-dish, with a new feather. Once both feathers were assessed from one treatment, two new Petri-dishes were prepared in the next treatment. In order to randomize treatment order, the "RAND" function in Microsoft Excel was used to generate the experimental sequence. Only two Petri-dishes were prepared at any one time to minimize evaporation of volatile components prior to feather testing. Note that each feather was tested in a new Petri-dish with a freshly created sheen, and that each feather was only tested once. Ten feathers were tested from each treatment (1–5), and four images were taken on each feather for a total of 40 images per treatment.

Changes in feather weight were compared among treatments using an ANOVA (SAS, 1999) with treatment as the effect and change in weight as the response. A barbule amalgamation index (AI) was calculated for each image to quantify clumping of barbules resulting from exposure to oil. We developed this measure following preliminary experiments that suggested exposure to oil could cause adjacent barbules to 'clump'. This may be similar to the feather microstructure 'derangement' described by Hartung (1967) following feather immersion in oil slicks. On each image, we measured a 0.8 mm section of a ramus and counted the number of barbules with hooks (from herein referred to as barbules) originating from this section. We then counted the number of barbules in each clump and calculated an AI for each section as mean barbules per clump (Fig. 3 and Table 2). AI was compared among treatments using a mixed model ANOVA (SAS, 1999) with feather, and each image nested within feather as random factors, and treatment as the fixed effect. Data were transformed when necessary to re-

Table 1
Experimental treatments used for crude oil and drilling fluid.

Code	Number of feathers	Oil thickness (μm)	Petri-dish diameter (mm)	Volume of oil (μl)	Volume of seawater (ml)
1	10	0.00	86	0	29
2	10	0.04	86	0.6	29
3	10	0.10	86	1.5	29
4	10	3.00	140	17.4	77
5	10	25.0	140	145.2	77

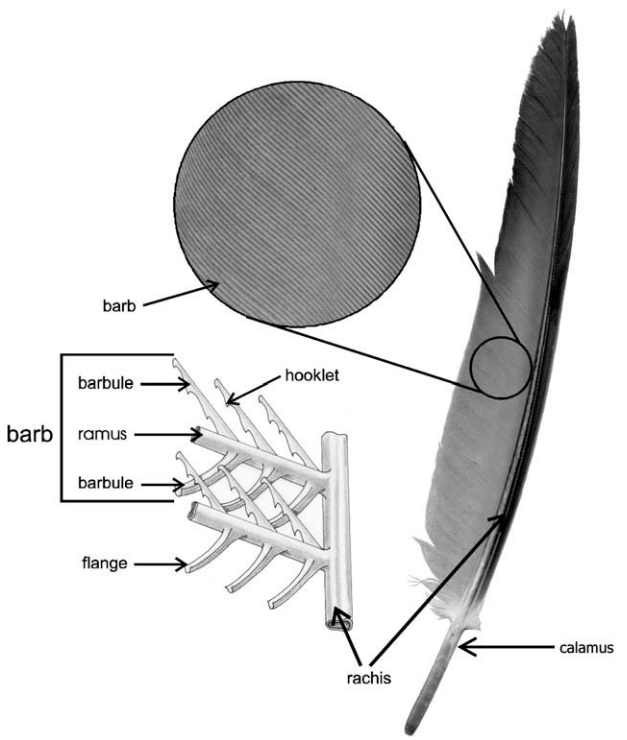

Fig. 1. Feather microstructure (diagram created by and used with permission of J. Clowater).

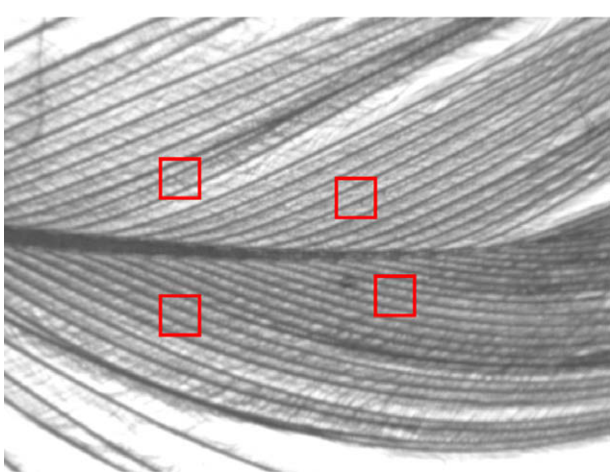

Fig. 2. A Common Murre feather exposed to seawater. The box represents four possible semi-randomly chosen locations on the feather for photographs.

duce the relationship between the mean and variance and to improve normalcy. All reported means and graphs are from non-transformed data. Means were compared orthogonally (a priori) using Least-Squares Means controlling for feather, and species and treatment ('LS-Means': SAS, 1999).

3. Results

Crude oil placed on the water surface appeared to distribute evenly over the surface whereas synthetic drilling fluid remained dispersed unevenly in clumps rather than forming a uniform sheen or slick. Feathers exposed to thin oil sheens (0.04 and 0.1 μm) (crude oil and drilling fluid) had oil/fluid droplets visible under 60× magnification. Barbules from these feathers generally appeared to be clumped together more so than control feathers. For both crude oil and drilling fluid, feathers exposed to 3 μm sheens contained large areas affected by the oil/fluid, visible under 60× magnification, and often had many barbules stuck together. See Fig. 3 for examples of images from different treatments levels.

Feather weight gain following exposure to crude oil varied among thickness treatment levels for both Common Murres ($F_{4,44} = 45.87$, $P < 0.0001$) and Dovekies ($F_{4,45} = 46.26$, $P < 0.0001$; Fig. 4). Weight increases differed significantly between Common Murre feathers exposed to 25 μm slicks of crude oil and other thicknesses but there was no difference in weight change among the other treatment levels (Fig. 4). Weight changed more consistently for Dovekie feathers among treatment with differences among slicks, thick sheens (3 μm) and the rest of the treatment levels. There was no difference among sheen thickness of 0.10 μm and less (Fig. 4). As well, feather weight change following exposure to synthetic drilling fluid varied among treatment levels for both Common Murres ($F_{4,45} = 11.11$, $P < 0.0001$) and Dovekies ($F_{4,45} = 20.87$, $P < 0.0001$). Only exposure to slicks (25 μm) resulted in a weight gain that was significantly different from other levels of exposure to drilling fluids for both species (Fig. 5).

Feathers exposed to crude oil and drilling fluid slicks (25 μm) were completely coated with oil/fluid and we were unable to distinguish barbules and calculate an AI (see Section 2). Therefore, data collected from the 25 μm thickness treatments were excluded from AI analyses. Otherwise, AI varied significantly among the remaining treatment levels of feathers exposed to crude oil sheens for both Common Murres ($F_{3,36} = 22.01$, $P < 0.0001$; Fig. 6) and Dovekies ($F_{3,36} = 22.01$, $P < 0.0001$), however, AI differed only between thick sheens (3 μm) and other treatment levels for Dovekies (Fig. 6). AI differed for Common Murres between thick sheens and other treatments and also between trace colour sheens (0.1 μm) and the control group. Following exposure to synthetic drilling fluids, Common Murre feathers showed no difference in AI among treatments ($F_{3,34.9} = 2.12$, $P = 0.115$). For Dovekie feathers exposed to synthetic drilling fluids, AI did vary among treatments ($F_{3,21} = 16.92$, $P < 0.0001$), but only between thick sheens (0.3 μm) and other levels of exposure (Fig. 7).

4. Discussion

Exposure to crude oil sheens (⩾0.10 μm – trace colour or higher visibility) and slicks resulted in a measurable oil transfer to feathers and caused impacts to microstructure for feathers collected

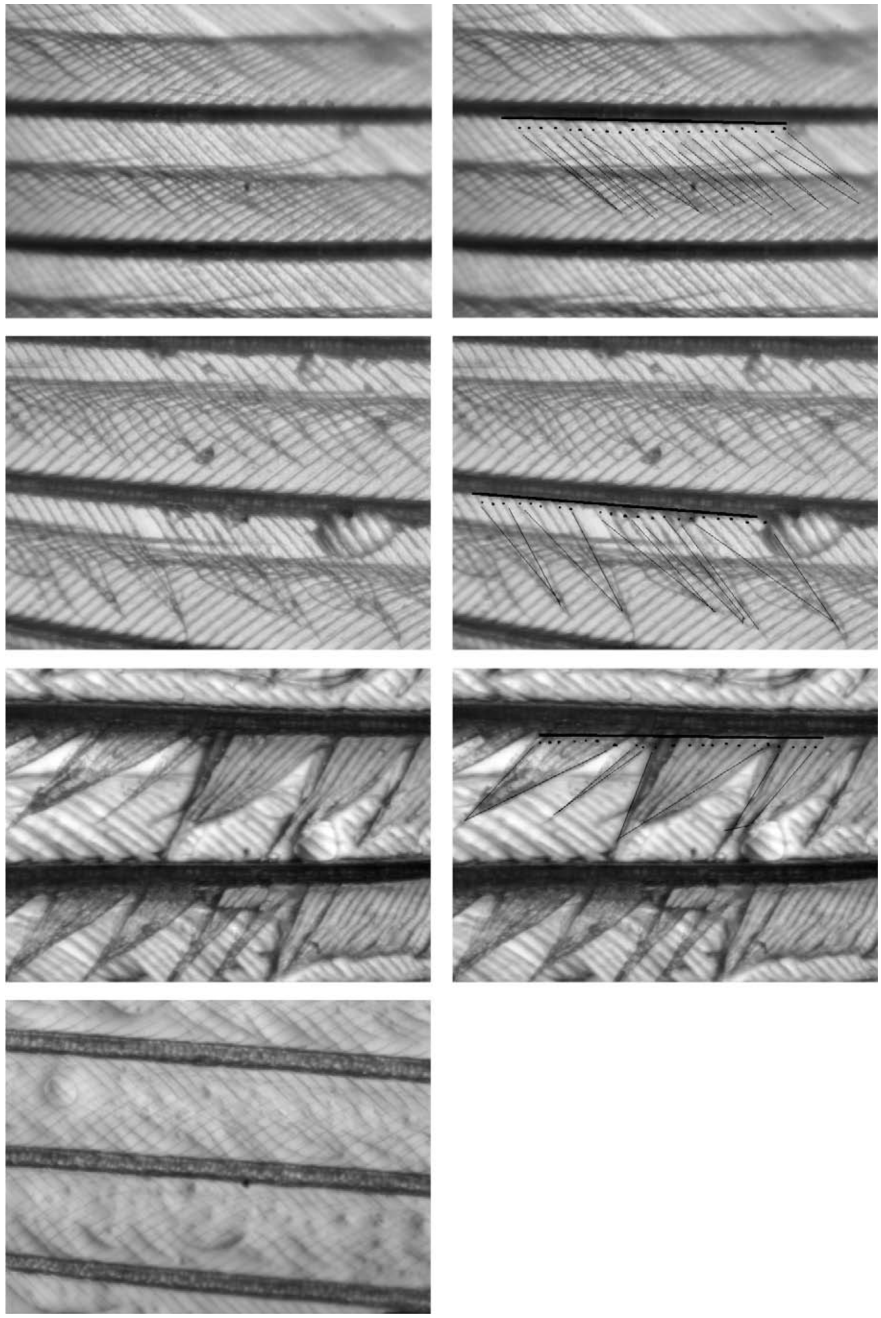

Fig. 3. Images of Common Murre feathers, at 60× magnification showing barbs (thick, horizontal black lines) and barbules (thinner, vertical lines), after treatment in different thicknesses of Hibernia crude oil. Images on the left are untouched and images on the right are marked for analysis of amalgamation index (AI). Because of extensive oil on feathers we were unable to calculate AI for the 25 μg treatment.

Table 2
Amalgamation index (AI) example results from Dovekie feather images a, b, and c, Trt = treatment thickness of crude oil on seawater.

Trt (μm)	Feather	Image	Number of barbules	Amalgamation														AI
0.00	69	1	21	2	1	1	1	4	1	1	1	1	1	1	3	1	2	1.5
0.10	73	2	21	3	5	3	3	1	6									3.5
3.00	89	3	22	7	2	9	4											5.5

from both species of seabird. Exposure of feathers to very thin crude oil sheens (0.04 μm) did not impact feather microstructure significantly or result in measurable oil transfer for either species of seabird. Common Murre feathers did not pick up a measurable amount of crude oil when exposed to sheens, but did when exposed to the 25 μm oil slick treatment. Dovekie feathers showed measurable crude oil transfer on single feathers from the 3.0 and 25 μm treatments, and had lower weight change than Common

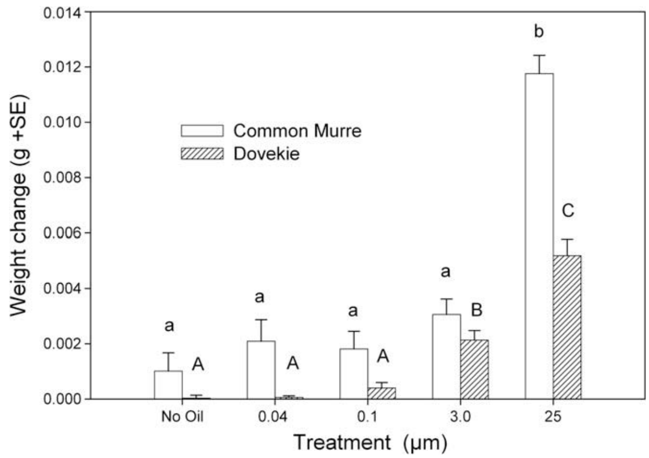

Fig. 4. Weight change of Common Murre and Dovekie feathers exposed to five crude oil (Hibernia) sheen and slick thicknesses on seawater. Bars with the different letters within bird species are significantly different ($P < 0.05$).

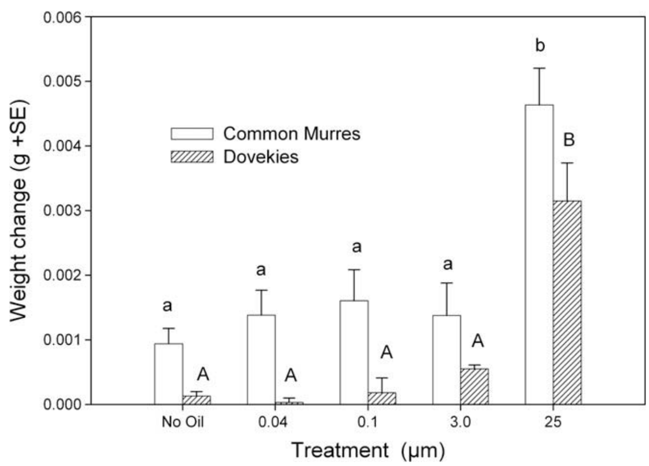

Fig. 5. Weight change of Common Murre and Dovekie feathers exposed to five drilling fluid (PureDrill IA-35LV, Petro-Canada) sheen and slick thicknesses on seawater. Bars with the different letters within bird species are significantly different ($P < 0.05$).

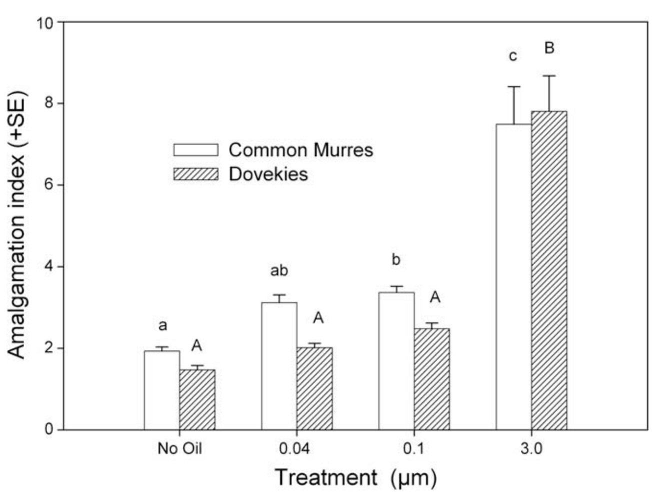

Fig. 6. Amalgamation index from feathers exposed to four thicknesses of crude oil (Hibernia) sheens on seawater. Bars with the different letters within bird species are significantly different ($P < 0.05$).

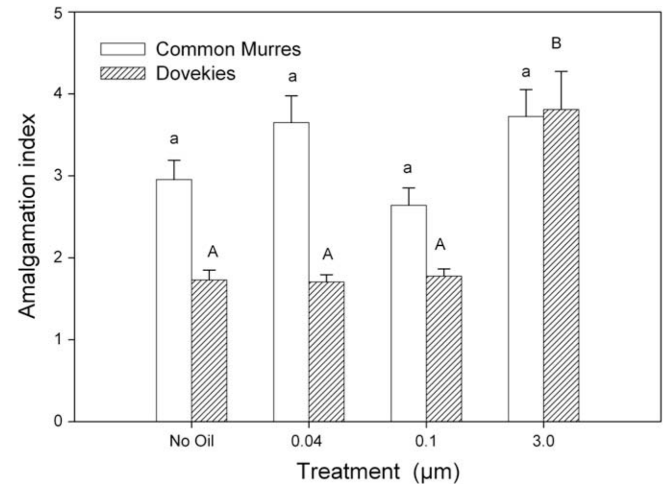

Fig. 7. Amalgamation index from feathers exposed to four thicknesses of synthetic oil drilling fluid sheens on seawater. Bars with the different letters within bird species are significantly different ($P < 0.05$).

Murre feathers after treatment, likely because of their smaller size. For drilling fluid, weight change was only measurable for the 25 μm treatment for feathers from both bird species.

Microstructure alterations were measurable with our amalgamation index (AI) after exposure to 0.1 and 3.0 μm crude oil sheens for Common Murre feathers and 3.0 μm crude oil sheens for Dovekie feathers. Microstructure alterations were highly evident after exposure to the 25 μm oil slick but we were not able to quantify these changes using our measure of alteration. The microstructure alterations that we observed were similar to what is described by Hartung (1967). He described oiled feathers as having barbules with a 'deranged' appearance and severe matting. In general, there was a trend of increasing AI in both Common Murre and Dovekie feathers with increasing sheen thickness, however, Dovekie feathers in our study were not significantly affected by sheens of less than 3.0 μm. Studies with greater replication may detect differences with thinner sheen treatments.

AI is a potentially useful way of quantifying feather microstructure alteration following exposure to oil sheens, and because of the use of this measure, we were able to show that feather microstructure was altered even when quantity of oil absorption was negligible as measured by feather weight change. This is consistent with studies that have shown that small amounts of oil on feathers results in considerable and sometimes lethal effects on birds (Hartung, 1967; Orbell et al., 1999). Our study did not assess whether feathers would continue to absorb oil if re-dipped in the same oil sheen thickness, and if they do at what rate would they absorb oil. Therefore, while longer exposure to a sheen likely would cause more feathers on a bird to be oiled, we can not speculate on whether length of time that a bird is in contact with a sheen would cause variable amounts of oil transfer to individual feathers.

Stephenson and Andrews (1997) developed a technique for measuring feather penetrability and found that water surface tension and moult intensity during feather collection were important factors determining the water repellency of a feather. Our experiment is the first to quantify alterations on microstructure within individual feathers after exposure to oil sheens; alterations that relate to the ratio of distances between barbs and barb thickness that is also important for determining water repellency (Stephenson, 1997). However, it is important to consider our results within a biological context. Our results indicate that thin oil sheens (0.1 and 0.3 μm) can impact the microstructure of seabird feathers, but it is not clear whether this will translate into considerable fitness impacts on individual birds exposed to thin sheens. A light sheen is approximately 0.1 μm thick and has a hydrocarbon volume of approximately 0.1 ml/m^2 of surface. As mentioned earlier, 10 ml of oil significantly decrease thermoregulatory capacity in marine and aquatic avifauna, and Hartung (1964) described moderately oiled dead birds near a spill site as having approximately 7 g (approximately 8.4 ml) of oil on their plumage. In order for a bird to pick up approximately 10 ml of oil from a trace colour sheen (0.1 μm), it would have to swim through the equivalent of approximately 100 m^2 of the sheen, assuming that all oil in the area is absorbed by the feathers. Dark colour sheens are approximately 3 μm thick with a volume of 3 ml/m^2 of surface. A bird would need to swim through only 3 m^2 of a dark colour sheen and absorb all of the oil from this area in order to collect a total of about 9 ml of oil. Lambert et al. (1982) did observe that mallard ducks in a swim tank 50 × 52 × 30 cm with a 50 μm thick oil slick picked up almost all of the oil from the surface within a few minutes. Their results suggest that repeated exposure to oil sheens may result in an accumulation of oil on the feathers with time of exposure.

Repeated and prolonged exposure to thin sheens may occur for some species of seabirds because of their attraction to structures and procedures associated with offshore oil and gas production. Wiese et al. (2001) outlined a number of hypotheses that have been proposed to account for these phenomena including structural stimuli of platforms, increased food concentrations, and light stimulus. In particular, storm-petrels (*Oceanodroma* spp.), Dovekies (*A. alle*), and shearwaters (*Puffinus* spp.) are thought to be attracted to light given off from the platforms (Wiese et al., 2001). Note however that one study of seabirds surveyed at points from 250 m to 20 km from Nova Scotia drilling operations showed no evidence of avoidance or attraction to the project area (Hurley, 2000). Regardless of the mechanism(s) resulting in greater seabird concentrations in the vicinity of offshore drilling and production operations, attraction of seabirds will increase impacts that may occur from chronic low-level discharges, and must be taken into account when effects of hydrocarbons from offshore operations are assessed, and potential mitigation procedures are implemented.

Future studies are also necessary to fully understand the potential impacts of thin sheens on seabirds. Currently, there is no information linking feather exposure to various sheen thickness and subsequent microstructure alteration to effects on water penetration and bird metabolism. For example, cohesion among feathers is an essential component for maintaining thermal regulation and buoyancy and should be examined following sheen exposure. There are no data on threshold number of affected feathers before an individual bird would begin to be affected by exposure to oil sheens. Birds likely would reach this threshold number at different rates depending on factors such as sheen thickness, oil type, preening capacity, patchiness of oil/drilling fluid, and movement patterns of the bird at the sea surface. Furthermore, data on rates of removal and ingestion attributable to preening are crucial to understanding effects of sheens on pelagic seabirds. There is a general lack of information on the metabolic effects of contact and ingestion of various types of petroleum products, which can lead to both lethal and sub-lethal effects on seabirds. While one study has shown that a small spot of oil can result in impacts to metabolic-rate, the amount was not specified (Hartung, 1967) and further research quantifying amounts of oil that cause negative impacts in relation to sheen thickness and exposure levels are crucial.

Internationally, legal limits of allowable operational hydrocarbon discharges are largely determined by the formation of visible sheen during discharge. For example, regulations outlined by the International Maritime Organization (http://www.imo.org/) state that operational discharges must cease if visible sheens form (see MARPOL 73/78: International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto. It appears that operational discharges from offshore oil and gas production follow similar regulatory rationales. Although the global accord on regulating maritime hydrocarbon discharges represented by MARPOL is a huge achievement, the standards are not necessarily supported ecologically. There is little or no information regarding sub-lethal impacts of low-concentration hydrocarbons on marine ecosystems and associated flora and fauna, and for this reason, there is little to guide policy and regulatory framework development. Here we have shown that sub-visible sheens can result in damage to feather microstructure, and this provides a plausible link between operational discharges of low-concentration hydrocarbon and increased seabird mortality, particularly around structures that attract and aggregate seabirds in close proximity to these discharges.

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References

Baird, P.H., 1990. Concentrations of seabirds at oil-drilling rigs. Condor 92, 768–771.

Burger, A., Fry, D., 1993. Effects of oil pollution on seabirds in the northeast Pacific. In: Vermeer, K., Briggs, K., Morgan, K., Siegel-Causey, D. (Eds.), The Status, Ecology, and Conservation of Marine Birds of the North Pacific. Canadian Wildlife Service Special Publication, Ottawa.

Camphuysen, C.J., 1989. Beached bird surveys in the Netherlands 1915–1988; seabird mortality in the southern North Sea since the early days of oil pollution. In: Technisch Rapport Vogelbescherming 1, Werkgroep Noordzee, Amsterdam, p. 322.

ERIN and OCL, 2003. Sheens Associated with Produced Water Effluents – Review of Causes and Mitigation Options. ERIN Consulting Ltd. and OCL Services Ltd. for Environmental Studies Research Funds Report, Calgary.

Fraser, G., Russell, J., von Zharen, W.M., 2006. Produced water from offshore oil and gas installations on the Grand Banks, Newfoundland and Labrador: are the potential effects to seabirds sufficiently known? Marine Ornithology 34, 147–156.

GESAMP, 2007. Estimates of oil entering the marine environment from sea-based activities. GESAMP (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) – Rep. Stud. GESAMP No. 75, 96 pp.

Hartung, R., 1964. Some effects of oils on waterfowl. Ph.D. dissertation, University of Michigan, Ann Arbor, MI.

Hartung, R., 1967. Energy metabolism in oil-covered ducks. Journal of Wildlife Management 31, 798–804.

HAZMAT, 1996. Aerial Observations of Oil at Sea. Hazardous Materials Response and Assessment Division, National Oceanic and Atmospheric Administration, Seattle, WA.

Hurley, G.V., 2000. Nearshore and offshore environmental effects monitoring at the sable offshore energy project. In: Gordon, D.C., Griffiths, L.D., Hurley, G.V., Muecke, A.L., Muschenheim, D.K., Wells, P.G. (Eds.), Understanding the Environmental Effects of Offshore Hydrocarbon Development. Canadian Technical Report of Fisheries and Aquatic Sciences, p. 2311.

Jenssen, B.M., 1994. Review article – effects of oil pollution, chemically treated oil, and cleaning on the thermal balance of birds. Environmental Pollution 86, 207–215.

Jenssen, B.M., Ekker, M., 1988. A method for evaluating the cleaning of oiled seabirds. Wildlife Society Bulletin 16, 213–215.

Jenssen, B.M., Ekker, M., 1989. Rehabilitation of oiled birds – a physiological evaluation of 4 cleaning agents. Marine Pollution Bulletin 20, 509–512.
King, K.A., Lefever, C.A., 1979. Effects of oil transferred from incubating gulls to their eggs. Marine Pollution Bulletin 10, 319–321.
King, J.G., Sanger, G.A., 1979. Oil vulnerability index for marine oriented birds. In: Bartonek, J.C., Nettleship, D.N. (Eds.), Conservation of Marine Birds of Northern North America, pp. 227–239.
Lambert, G., Peakall, D.B., Philogene, B.J.R., Engelhardt, F.R., 1982. Effect of oil and oil dispersant mixtures on the basal metabolic-rate of ducks. Bulletin of Environmental Contamination and Toxicology 29, 520–524.
Leighton, F.A., 1991. The toxicity of petroleum oils to seabirds; an overview. In: White, J. (Ed.), The Effects of Oil on Wildlife. Sheridan Press, Hanover, PA, pp. 43–57.
Levy, E.M., 1980. Oil pollution and seabirds – Atlantic Canada 1976–77 and some implications for northern environments. Marine Pollution Bulletin 11, 51–56.
MARPOL 73/78. International Convention for the Prevention of Pollution from Ships, 1973,as modified by the Protocol of 1978 relating thereto. International Maritime Organization. Available from: <http:///www.imo.org>.
McEwan, E.H., Koelink, A.F.C., 1973. Heat production of oiled mallards and scaup. Canadian Journal Of Zoology-Revue Canadienne De Zoologie 51, 27–31.
NRC, 2003. Oil in the Sea III: Inputs, Fates, and Effects. Ocean Studies Board, Marine Board, Divisions of Earth and Life Studies, and Transportation Research Board of the National Research Council of the National Academies. National Academies Press, Washington, DC, 265 pp.
Orbell, J.D., Tan, E.K., Coutts, M., Bigger, S.W., Ngeh, L.N., 1999. Cleansing oiled feathers magnetically. Marine Pollution Bulletin 38, 219–221.
Ricklefs, R.E., 1990. Seabird life histories and the marine-environment – some speculations. Colonial Waterbirds 13, 1–6.
Stephenson, R., 1997. Effects of oil and other surface-active organic pollutants on aquatic birds. Environmental Conservation 24, 121–129.
Stephenson, R., Andrews, C.A., 1997. The effect of water surface tension on feather wettability in aquatic birds. Canadian Journal of Zoology 74, 288–294.
Tasker, M.L., Hope-Jones, P., Blake, B.F., Dixon, T.J., Wallis, A.W., 1986. Seabirds associated with oil production platforms in the North Sea. Ringing and Migration 7, 7–14.
Tuck, L.M., 1960. The Murres: Their Distribution, Populations and Biology, A Study of the Genus *Uria*. Canadian Dept. Northern Affairs and Natl. Resources, Natl. Parks Br., Wildl. Serv., Ottawa. 260 pp.
Wiese, F., Montevecchi, W.A., 2000. Marine bird and mammal surveys on the Newfoundland Grand Banks from offshore supply boats 1999–2000. In: Unpublished Husky Oil Contract Report. St. John's, NL.
Wiese, F., Robertson, G., 2004. Assessing seabird mortality from chronic oil discharges at sea. Journal of Wildlife Management 68, 627–638.
Wiese, F., Ryan, P., 2003. The extent of chronic marine oil pollution in southeastern Newfoundland waters assessed through beached bird surveys 1984–1999. Marine Pollution Bulletin 46, 1090–1101.
Wiese, F.K., Montevecchi, W.A., Davoren, G.K., Huettmann, F., Diamond, A.W., Linke, J., 2001. Seabirds at risk around offshore oil platforms in the North-west Atlantic. Marine Pollution Bulletin 42, 1285–1290.
Williams, J.M., Tasker, M.L., Carter, I.C., Webb, A., 1995. A method of assessing vulnerability to surface pollutants. Ibis 137 (Suppl. 141), S147–S152.