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Effects of chemical dispersants on feathers from Arctic seabirds

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ABSTRACT

Chemical dispersion is an oil spill response strategy where dispersants are sprayed onto the oil slick to enhance oil dispersion into the water. However, accidental application could expose seabirds to dispersants, thereby negatively affecting their plumage. To understand the possible impacts on seabirds, feathers from common eider (*Somateria mollissima*) and thick-billed murre (*Uria lomvia*) were exposed to different dosages of the dispersant Dasic Slickgone NS. For all exposure dosages the feathers increased in weight, and mostly for common eider. Analysing the feather microstructure, e.g., the Amalgamation Index, showed that larger damages were found on thick-billed murre than common eider. A no-sinking limit was established at 0.109 ml/m^2. Relating this value to desktop simulations of potential sea-surface dosages in real-life situations, and to published accounts of response operations, showed that the limit is likely to be exceeded. Thus, our results show that chemical dispersants in realistic dosages could impact seabirds.

1. Introduction

The majority of seabirds spend 90 % of their life at sea where they forage over large areas or dive to depths of several hundred meters (Gaston, 2004). In order to survive in a wet and often cold environment, seabirds rely on an intact plumage. An intact plumage will ensure that the plumage is water repellent, that the seabird have the best diving and floating capacities (buoyancy, hydro- and aerodynamic abilities) and that there is an airspace between the surface of the plumage and the skin to secure thermal insulation and thereby thermal regulation (Jenssen and Ekker, 1991; Stephenson, 1997). The physical phenomenon that determines the intact plumage is the surface tension (Stephenson, 1997; Stephenson and Andrews, 1997). According to Stephenson (1997), the critical surface tension where feathers will be wetted is 38–50 mN/m. The surface tension of pure water is approximately 72 mN/m, but this can be reduced to the critical surface tension or below if oil or surfactants are introduced. This would result in a reduction of the natural space between barbs, which would cause wetting of the feathers (Stephenson, 1997). If a seabird is exposed directly to oil, for example in case of an oil spill, the oil will stick to the feathers thereby changing the surface tension of the feather, and thus allowing seawater to enter the insulating airspace between the surface of the plumage and the skin of the seabird leading to hypothermia (Jenssen, 1994). This loss of temperature regulation would be especially harmful in cold environments such as the Arctic.

In general, oil spills are known to result in severe environmental impacts and it is crucial to be able to respond both quickly and efficiently to reduce the potential impacts. One oil spill response technique is the application of chemical dispersants. Chemical dispersants are sprayed onto the oil slick and with sufficient mixing energy the oil is removed from the sea surface and dispersed into the water column. Chemical dispersants consists of two main compounds; the surface-active compound (surfactant) and the solvent. The solvent carries the surfactant into the oil where the surfactant migrates to the oil/water interface due to its chemical composition, and reduces the interfacial tension between oil and water, and thereby allows small oil droplets to break from the slick into the water column (Canevari, 1969). With sufficient dispersant and external energy applied e.g. by waves, the oil slick may be permanently dispersed into the water column, as oil droplets smaller than 70 μm (Blondina et al., 1999). However, according to Peakall et al. (1987) it might be likely that the dispersion will be incomplete "*due to depletion of the surfactant from the slick*". For high viscous oils, the penetration of dispersant could be very slow, resulting in possible wash-off of the dispersant (Brandvik and Faksness, 2009).

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This may be the case after long time weathering of an emulsified oil at sea. Even when still dispersable, oils with a high viscosity may require multiple rounds of application to be successfully dispersed (Daling et al., 1990). During the response to the Deepwater Horizon oil spill in the Gulf of Mexico in 2010, over 25,000 barrels (4000 m^3) of dispersants were applied on the surface (in addition to subsea application at the wellhead). According to Lehr et al. (2010), surface dispersants were typically applied by aircraft, at a dose of 5000 l per square kilometre, corresponding to a film thickness of about 5 μm on the sea surface. Lehr et al. (2010) also pointed out that it is likely that some of the dispersants would have missed the oil, and been applied on open water instead, and that 25,000 barrels (4000 m^3) is in itself a large spill.

In the case of spills in ice-covered waters, dispersants may be applied to oil in open water between ice floes. This presents a risk of misapplication of the dispersant and thereby loss of dispersant as the dispersant is not soaked into the spilled oil (Lewis and Daling, 2007). Open water areas in between ice floes, are of particular interest as these are often used to feed in by many seabirds, e.g. black guillemots (*Cepphus grylle*), and king eiders (*Somateria spectabilis*) (Boertmann et al., 2004; Boertmann et al., 2006). Therefore, even though the intention behind application of dispersants is to remove oil from the sea surface, and thus reduce the risk of damage to birds there is a clear possibility that seabirds might get in contact with dispersants, as also pointed out by Fiorello et al. (2016). Therefore, there is a need to investigate effect of chemical dispersants on seabirds, to have a full picture of the potential environmental impacts of the use of chemical dispersants.

Few studies have looked into the effect of chemical dispersants in combination with oil on seabirds. Lambert et al. (1982) studied the impact on the basal metabolic rate of mallards (*Anas platyrhynchos*) from oil and oil-dispersant mixtures. They found that both oil and oil-dispersant mixtures had an effect on the metabolic rate of the mallards, but exposure to seawater and dispersant alone (Corexit 9527) did not show any increase in metabolic rate. Jenssen and Ekker (1991) looked at the effects of plumage contamination with crude oil-dispersant mixtures on the thermoregulation of mallards and common eiders (*Somateria mollissima*). The dispersants were Finansol OSR-5® and OSR-12® and the crude oil Statfjord A. The birds were exposed to oil or mixtures of oil and dispersants. It was found that both crude oil and oil-dispersant mixture had an effect on the heat production (increase), but that much less oil-dispersant mixture was needed to give an effect. The authors suggest that this is due to the surfactants in the dispersant, that more easily adhere to the feathers binding to the hydrophobic waxes (Jenssen and Ekker, 1991). Of the two species examined by Jenssen and Ekker (1991) the common eiders were found to be the most sensitive one, most likely due to the soft and air-filled plumage of eiders adapted to spend most of the year in the marine environment. This highlights the importance of studying several bird species as the effect may not be directly comparable due to the different structures of their plumage. Moreover, Whitmer et al. (2018) evaluated the effects of dispersants and crude oil on live common murre (*Uria aalge*) and found that the waterproofing ability of the plumage was negatively affected in a similar, dose-dependent manner by both crude oil and chemically dispersed crude oil. They also found that birds exposed to high concentrations of dispersant alone experienced an immediate life –threatening loss of waterproofing and buoyancy.

This paper seeks to increase the knowledge base regarding chemical dispersants and their potential impact on seabird feather microstructure. Feathers from two arctic seabird species, common eider and thick-billed murre, were exposed to the chemical dispersant Dasic Slickgone NS to measure the feather weight increase, possible sinking and damages on the feather microstructure. The experimental dosages are compared to a simulated dispersant application and corresponding dosages at the sea surface and to published accounts of response operations in order to relate the results to realistic conditions during oil spill operations.

Dasic Slickgone NS was selected as a dispersant as it is included in the oil spill response equipment for Greenland, where it may be applied in ice-covered water. Daisc Slickgone NS is likewise approved in the United Kingdom, Norway and Australia among others. Dasic Slickgone NS is efficient on a broad spectrum of oils also at low temperatures (GOSR, 2021). The type of dispersant selected as well as those referred to in the literature have different optimum for efficiency, but overall are built based on the same principles.

While the intention behind application of dispersants is to remove oil from the sea surface, and thus reduce the risk of damage to birds, it is relevant and necessary to weigh this against the potential damage from the dispersants themselves. Hence, dispersant alone without oil was selected to study the hazard potential of dispersant in the case of misapplication offshore, in open water areas between ice floes or in case of an unintended dispersant spill.

2. Materials and methods

The laboratory study included exposure of seabird feathers in different dosages of chemical dispersants and subsequent measurements of impacts and damages on the feather microstructure following a modified methodology of O'Hara and Morandin (2010) and described in Fritt-Rasmussen et al. (2016). In addition, changes in the total weight of the feathers due to increased uptake of water were measured.

The samples for testing were seawater with different amounts of chemical dispersants applied and as controls, pure seawater exposures were included. The chemical dispersant used for the project was Dasic Slickgone NS, provided from the stock at Greenland Oil Spill Response A/S. It is a chemical dispersant developed for marine and coastline oil spills. Feathers used in this study came from legally hunted Common eider (*Somateria mollissima*) and Thick-billed murre (*Uria lomvia*) bought in Nuuk, Greenland. Both Common eider and Thick-billed murre are seabirds widespread in the coastal areas in Greenland as well as the rest of the Arctic. The feathers from the chest of the birds were carefully removed and stored to avoid any unwanted disturbances of the feather structure. At no point were the feathers frozen.

2.1. Exposure experiments on seabird feathers

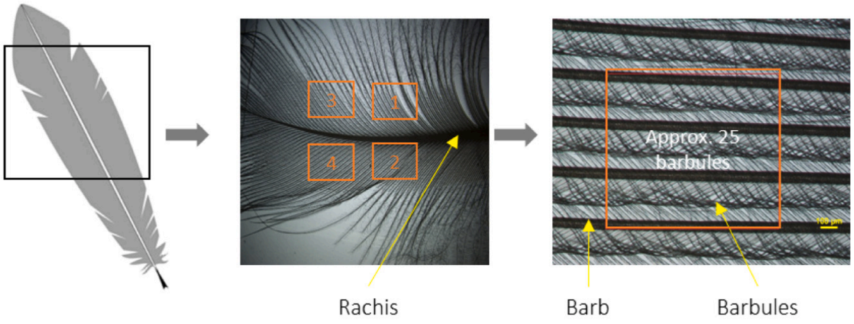
Different amounts of dispersant (Table 1) were applied to the dishes (two sizes: Petri dish ($A = 0.0095$ m^2) and Large dish ($A = 0.11$ m^2)).

The mechanical exposure follows the same procedure as described in Fritt-Rasmussen et al. (2016): A glass dish (Petri dish or Large dish) was filled with seawater (30 ‰). The preferred amount of dispersant was carefully transferred to the seawater surface with a glass micropipette. The feather was weighed and subsequently placed on the surface film in the dish for 15 s using tweezers and picked up by the calamus. Hereafter, the feather was drawn three times over the surface (to simulate mechanical stress) and finally the feather was placed on the surface for 15 s. The feather was then weighed. The feather was placed on a microscope slide, with the convex surface upwards and a smaller cover glass was place over the tip of calamus to fix the feather. The feather was inspected in microscope and photographed in four locations with a magnification of 11.25×, two locations on each side of the middle (Fig. 1). The photos were used for quantifying the damages on the feather microstructure by use of the ‘Barbule Amalgamation Index (AI)’. The AI index was developed by O'Hara and Morandin (2010) and used to quantify the clumping of barbules. The clumping relates to the capacity of the feather to repel water, which, among other things, is dependent on the ratio of barb thickness and distance between barbs (Stephenson, 1997). Thus, the AI is a measure of the damages to the microstructure of the feathers, where a higher number indicates larger damages. Three sections of approximately 25 barbules on each of the magnified photographs for each feather were assessed and AI calculated as mean number of barbules per clump (Fig. 1). This results in 12 AI for each feather.

Table 1
Test setup and calculated film thickness.

Bird	Dispersant [µl]	Water surface area [m^2]	Amount dispersant relative to the water surface area [ml/m^2]	Calculated film thickness [µm]	*n* feathers per treatment
Common Eider[a]	0	0.11	0	0	2
Common Eider	1.2	0.11	0.011	0.011	3
Common Eider	12	0.11	0.109	0.109	3
Common Eider[a]	0	0.0095	0	0	4
Common Eider	1.2	0.0095	0.13	0.13	3
Common Eider	6	0.0095	0.63	0.63	3
Common Eider	48	0.0095	5.05	5.05	3
Common Eider	96	0.0095	10.11	10.11	3
Thick-billed Murre[a]	0	0.11	0	0	2
Thick-billed Murre	1.2	0.11	0.011	0.011	3
Thick-billed Murre	12	0.11	0.109	0.109	3
Thick-billed Murre[a]	0	0.0095	0	0	3
Thick-billed Murre	1.2	0.0095	0.13	0.13	3
Thick-billed Murre	6	0.0095	0.63	0.63	3
Thick-billed Murre	48	0.0095	5.05	5.05	3

[a] Controls, no dispersant is added and pure seawater exposure.



Feather ID	Photo ID	Replicates	No. of barbules	Amalgamation	AI
E1	E1-1	1	25	1 1 1 1 1 1 1 2 1 1 2 4 2 4 2	1.64
		2	25	1 1 1 1 1 4 1 2 1 3 1 4 4	1.43
		3	24	3 4 2 4 2 1 4 4	3.00

Fig. 1. Overview of feather details (top), with indications of where the photos (no.1–4) were taken on each feather (top middle). Example of a detailed photo with a magnification of 11.25× and indication of the three sections of barbules counted to calculate the AI (to right). Table below is an example of the AI results from Common eider control experiments.
Adapted from Fritt-Rasmussen et al. (2016).

2.2. Data treatment

Ordinary regression analyses were applied to test the relationship between weight differences after exposure and amount of dispersant/surface area. The AI of each feather was calculated as the mean of the AI count on the four photos on which three locations were counted. The relationships between the AI mean and the log-transformed amount of dispersant/surface area were estimated by linear regression. Ninety five percent confidence limits of the AI control mean were used as baseline level. Statistical analyses were done by using the software R version 3.1.3 (R Core Team, 2015).

2.3. Chemical dispersant simulation

A theoretical analysis was performed to simulate the dispersant concentration, thickness and spreading on the surface in a situation where the dispersant is not hitting the oil, i.e. an unsuccessful oil dispersion operation. To calculate the time development of the thickness of a film of dispersant on the sea surface, it is assumed that the dispersant does not dissolve readily, that it behaves as a film on the water surface and that the mechanism of gravity spreading will occur. Gravity spreading is relevant for oils and any other (Newtonian) fluids that do not dissolve readily and are lighter than water. According to its material data sheet (TODNEM AS, 2015), the dispersant is less dense than water and weakly soluble to not soluble in water, in support of our assumptions. We also assume that we may ignore emulsification, and other effects of the surfactants. The validity of these assumptions will in practice depend on the weather conditions, and the calculations below may be seen as an estimated thickness in calm weather conditions, intended mainly to provide some context for the experimental results.

The rate of spreading is calculated from the balance of two forces: The spreading force due to the density difference, and the retarding force due to the dynamic viscosity of the water. For calculation of the slick radius and thickness as a function of time Eq. (1) was used, taken from Brönner et al. (2018), assuming an instantaneous release with a given initial film thickness over a circular area. This ordinary differential equation was solved numerically to calculate the radius and thickness as a function of time. We have assumed a density of the dispersant of 0.87 kg/l, and a dynamic viscosity of the water of 0.0015 Pa s, which corresponds to seawater at about 8 °C.

$$\frac{d}{dt}R^{\frac{4}{3}} = c\left(h_0^2\rho g'\right)^{\frac{2}{3}}(\rho_w\mu_w)^{-\frac{1}{3}} \qquad (1)$$

where h_0 is the oil film thickness in the centre of the slick, ρ and ρ_w are the density of oil and water, $g' = g(\rho_w - \rho)/\rho_w$ is the reduced gravity, R is the radius of the slick, μ_w is the dynamic viscosity of water, and c is a

Table 2
Initial values for the two scenarios simulating unsuccessful dispersant applications.

	Amount of dispersant	Application area	Application radius
Scenario 1	7000 l	1,400,000 m^2	667 m
Scenario 2	7000 l	1260 m^2	20 m

constant to be determined empirically (for additional details see Brönner et al., 2018).

Two scenarios have been selected for the simulation of unsuccessful dispersion operations (Table 2). Scenario 1 imitates a dispersant application operation over a large sea area, whereas Scenario 2 simulates an unintended release of dispersant in a small patch. Both scenarios are surface releases.

3. Results

3.1. Increase in feather weight by dispersant exposure

Common eider feathers had significant (Two-way ANOVA, $p < 0.001$) higher weight increase compared to thick-billed murre (Fig. 2). For thick-billed murre a significant relationship ($p < 0.001$) was found between weight increase and amounts of dispersant applied, while the null hypothesis for this relationship for common eider was just above the significant level of 5 % ($p = 0.063$). The only feathers that did not sink were those exposed to the lowest amounts of dispersant applied in the larger dish (0.011 ml/m^2). This is valid for both bird species.

3.2. Changes in Amalgamation Index by dispersant exposure

No significant relationship was found between average AI and the amount of dispersant relative to the surface area in the experiments (ml/m^2) for eider ($p = 0.143$), while the relationship was significant for thick-billed murre ($p = 0.009$) (Fig. 3). The results showed that somewhat larger damages were seen on the microstructure of the thick-billed murre feathers than the eider feathers.

From the magnified photographs, indications of a weak trend of increasing barbule thickness besides also clumping of the barbules were possibly seen; though not possible to measure or quantify. Photographs of a feather for each of the exposure dosages are given as examples in Figs. S1 and S2.

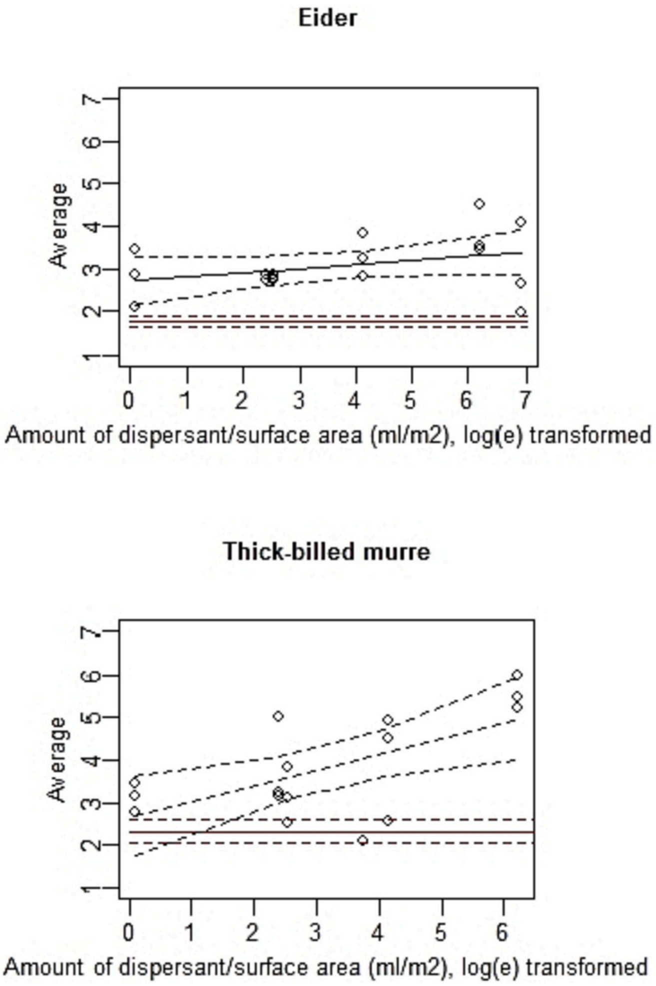


Fig. 3. Amalgamation Index (AI) as a function of amount of dispersants relative to the surface area (ml/m^2) for common eider (top) and thick-billed murre (bottom). Note that the x-axes are logarithmic (log (e) transformed). The red lines represent the mean of the salt water control. Broken lines 95 % confidence limits of the mean. Note that the x-axes vary, due to variations in exposure tests, see Table 1 for details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

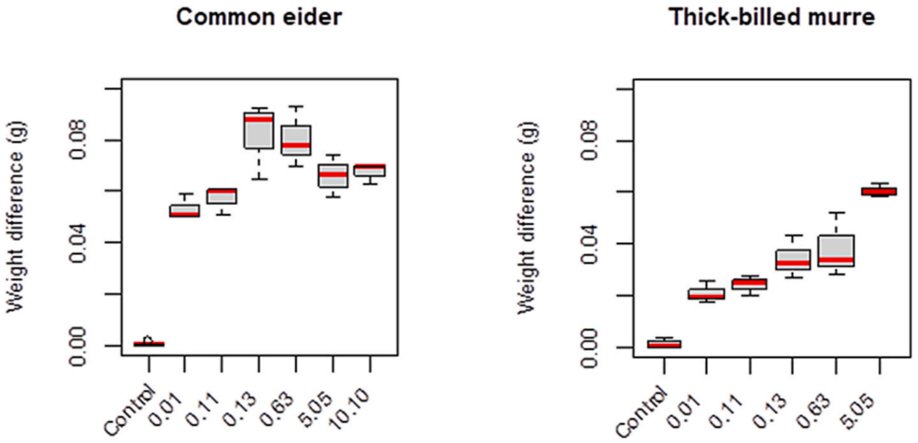


Fig. 2. Weight increase of feathers as a function of the amount of dispersant/surface area (ml/m^2) for Common Eider and Thick-billed Murre feathers.

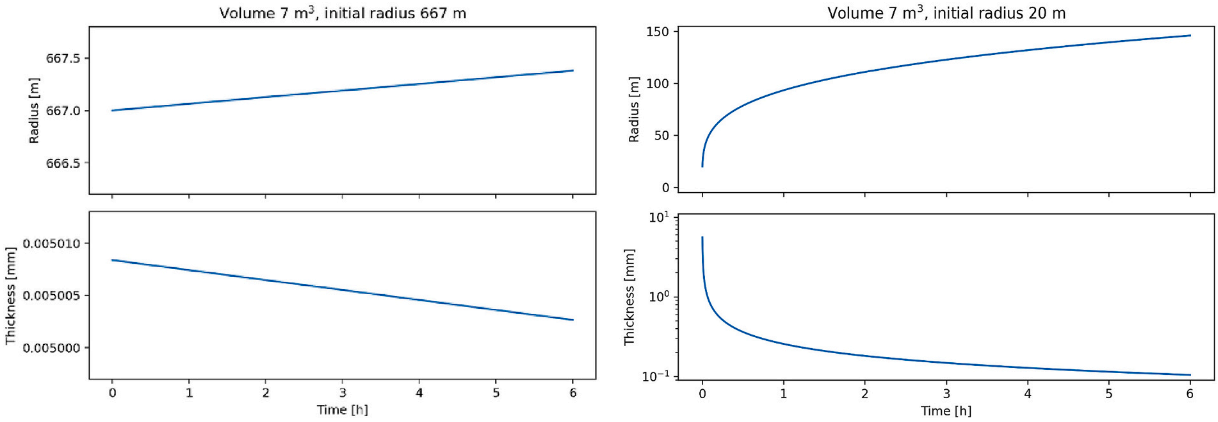


Fig. 4. Slick radius and slick thickness development with time for Scenario 1 (left) and Scenario 2 (right). Note that the vertical axes do not start at zero in the left panel, and that the radius and thickness are approximately unchanged after 6 h for Scenario 1. For Scenario 2, the thickness is shown on a logarithmic scale.

3.3. Chemical dispersant model simulation

For the model simulation scenario with a large initial radius (Scenario 1), essentially no gravity spreading is seen during the 6 h simulation period (Fig. 4). This is caused by the very thin initial film thickness that entails only very small gravity spreading forces in addition to the very large circumference of the slick, where the friction from the water inhibits the spreading. For Scenario 1 it is therefore more likely that waves and current eddies would be more relevant for the break-up and spreading of the dispersant. However, for Scenario 2, where a large initial dispersant amount was released at a small initial area, a large amount of gravity spreading is seen, and after 6 h the radius increased to about 150 m and the film thickness decreased to about 0.1 mm (Fig. 4).

The initial amount of dispersant relative to the water surface area was calculated from the initial amount of dispersant and area (Table 2), assuming even distribution, and was 5 ml/m^2 and 5500 ml/m^2 for Scenarios 1 and 2, respectively. After 6 h this was reduced to 105 ml/m^2 for Scenario 2. For Scenario 1, the area and thickness essentially did not change, due to the initially very low thickness, and it must be assumed that wind and wave action with time will break down the dispersant into minor patches.

4. Discussion

4.1. Effects on feathers from exposure

The results from the weight increase measurements showed that for all the dosages there was an increase in feather weight compared to the experiments conducted with seawater only. The weight increase is a result of water and/or dispersant uptake. It was not possible to quantify the proportion of dispersant to water contributing to the weight gain. However, the weight gain can be seen as a simple indication of that the critical surface tension where the feathers are wetted have been met.

The weight increase was higher for common eider than for thick-billed murre. This was also observed in Buist et al. (2017), where both common eider and thick-billed murre feathers were exposed to chemical herders (a surface active product which contracts an oil slick on the water surface by exerting a higher spreading pressure than the oil slick) and the highest feather weight increases were seen for common eider feathers. This interspecies difference in sensitivity, is most likely related to the difference in the feather microstructure as common eiders have a soft and air-filled plumage that more easily collapses than other species (Jenssen and Ekker, 1991; D'alba et al., 2017). This explanation, was however not fully supported by the AI. The AI is a measure of the damages to the microstructure of the feathers, where a higher number indicates larger damages. The results show that somewhat larger damages were seen on the microstructure of the thick-billed murre feathers than common eider feathers based on the AI assessment (Fig. 3).

There is a relatively large spreading in the AI results for each dosage exposure experiment, which might be a result of the weakness of the AI method. The method was developed to quantify impact of oil on feathers, by calculating the clumping of the barbules (O'Hara and Morandin, 2010). However, in the magnified photos it was seen that exposure to a chemical dispersant possibly also increases the thickness of each barbule in addition to clumping of the barbules (Fig. 5B and D, and Figs. S1 and S2). This increase of thickness of barbules, is however not directly reflected in the AI result and might explain the large variation in experimental results and the lack of correlation between increased dosage and AI. Changes in the structure of the feathers (geometry and orderliness) as well as different crystalline or amorphous matrix salts being more abundant in feathers exposed to dispersants was shown in Duerr et al. (2009). Duerr et al. (2009) suggests that these immediate alterations are "…due to direct disruptive effects on the waterproofing characteristics of the feathers, leading to large amount of water remaining on each feather…". Hence, the possible increase in barbule thickness could be a result of water adhesion.

Further studies are needed to understand this mechanism as well as the long term effects from chemical dispersants on seabirds, which has not been studied here.

4.2. Chemical dispersant model simulation

From the experiments it was shown that all feathers sank, except those exposed to the lowest dosage (0.01 ml/m^2), hence a 'no sinking limit' is somewhere in the interval between 0.01 ml/m^2 and 0.109 ml/m^2 of dispersant. However, it should be noted that significant weight increases were still seen for the lowest dosage. As our study does not address directly individual or population level impacts, there is a challenge of translating feather level impacts to individual or even population level impacts. The exposed feathers from our study originated from the chest of the bird, and are thus likely to encounter a surface dispersant slick on the surface. Therefore we speculate that for a seabird swimming through a dispersant film with a thickness above the 'no sinking limit' it could possibly result in changes in buoyancy and loss of insulation. The same conclusions were also suggested by Duerr et al. (2009). Lambert et al. (1982) also observed that Mallard ducks "*sank to a much lower level than normal*" (Lambert et al., 1982) when swimming in water sprayed with the dispersant Corexit 952. The surfactant is suggested to break the water repellent barrier of the feathers and the birds could not shake or preen the water off their plumage and remained wet for a long period (Lambert et al., 1982). Lambert et al. (1982) also measured the metabolic rates by measuring the exchange of respiratory gasses, and no sign of increase in the basal metabolic rate was found for the birds swimming

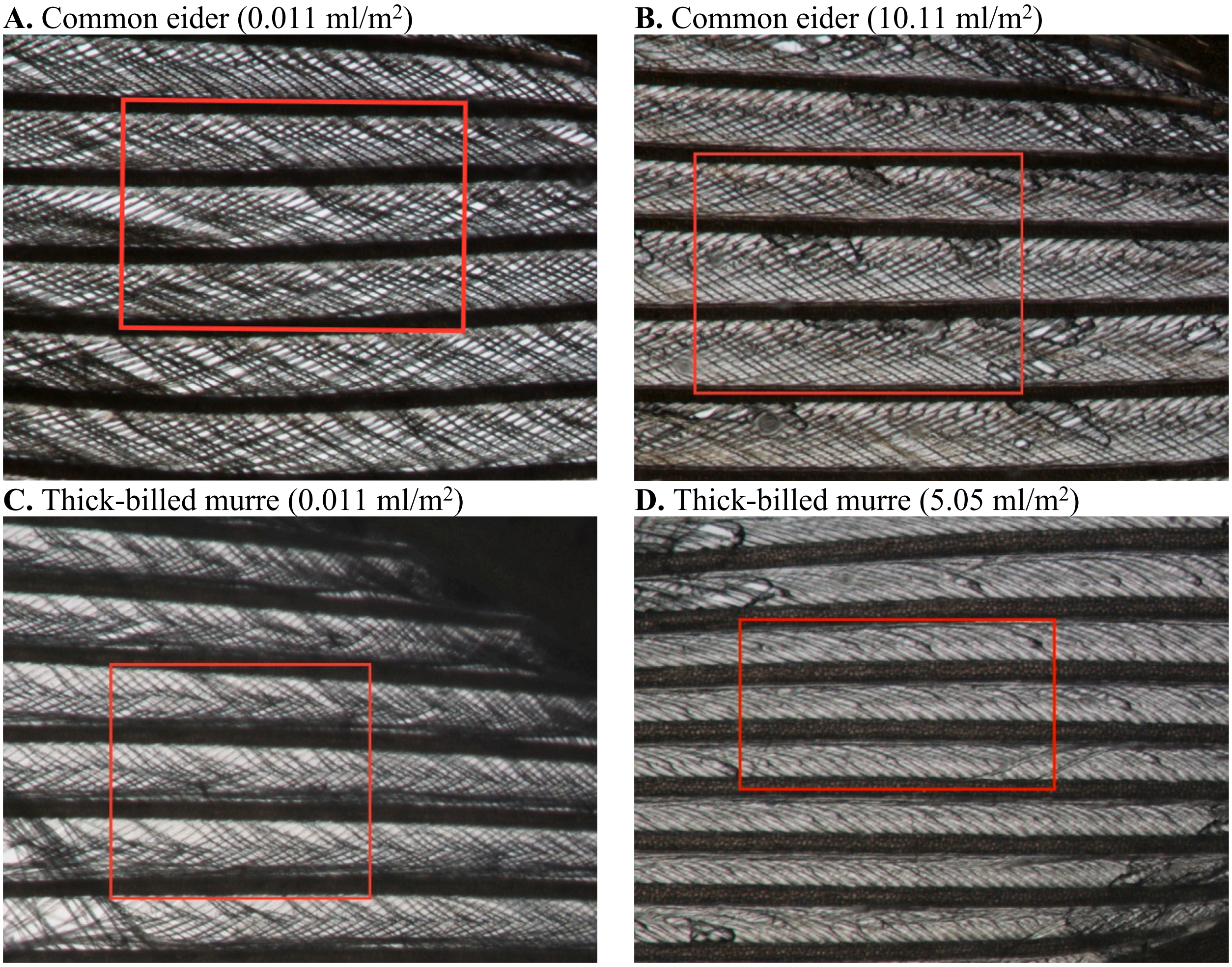


Fig. 5. Examples of low and high dispersant exposure dosage of feathers from common eider (A and B) and thick-billed murre (C and D). Magnification of 11.25×.

in water sprayed with dispersants, suggesting that only the surface feathers were soaked in water.

The population level impact will depend on how large a proportion of the population is affected by the dispersant and the general status and vulnerability of the affected population, i.e. if the number of dead individuals exceeds a certain limit the population may not recover. Studies on seabird mortality from oil exposure indicate little correlation between oil spill size and number of dead seabirds, and that bird density (location) and weather (including seasonal and climatic factors) largely determine the number of dead seabirds (Clark, 1984). This also seem applicable for a potential dispersant exposure. Further, the species vulnerability vary depending on species behaviour, e.g. bird species resting and foraging on the surface may be more likely to be exposed to a surface slick than a plunge diver spending more time in the air (Morandin and O'Hara, 2014).

To relate the ‘no sinking limit’ identified in this work to potential dosages found on the sea surface in case of an unsuccessful oil dispersion operation, two desktop simulations were completed (Section 3.3), and these are also related to published accounts of dispersant application operations during oil spill response. The two simulations of the fate of a surface dispersant slick revealed surface dosages of 5 ml/m^2 and 105 ml/m^2, respectively for Scenario 1 and Scenario 2, after 6 h of spreading. Scenario 1 was designed to simulate application of dispersant over a large area of on the sea surface, similar to regular application of dispersants, whereas Scenario 2 simulates an unintended release of dispersant to a confined area. However, for both scenarios the “no-sinking limit” is exceeded. This points out that the “no-sinking” limit could be exceeded in a real-life situation. The initial thickness in Scenario 1, 5 μm, corresponds to the normally applied dosage in surface dispersant application from aircraft during the Deepwater Horizon oil spill (Lehr et al., 2010). This corresponds to a dosage of 1:200, assuming a 1 mm slick thickness, which according to Bejarano et al. (2013) is a standard recommendation for aerial application. Note however that dosing to some degree is adjusted according to oil slick thickness and weathering state of the oil, with higher dosages required for more heavily weathered oil. A dosage of, for example, 1:50, would correspond to a 2 μm dispersant film when treating a 0.1 mm thick oil slick.

The simulations do not take wind and wave action into consideration, and it is expected that with time the dispersant will break down into smaller patches and disperse. Thus, the potential impact period of seabirds is not known. The biodegradation of dispersant surfactants in cold seawater, i.e. the biotransformation of the surfactants dioctyl-sodium sulfosuccinate (DOSS), Tween 80, Tween 85, and α/β-ethylhexylsulfosuccinate (EHSS, expected DOSS hydrolysis product) in the commercial dispersants Corexit 9500, Dasic Slickgone NS and Finasol OSR52 were studied by Brakstad et al. (2018). The studies were performed in natural seawater at 5 °C over 54 days at concentrations of 1, 5, and 50 mg/l. 1 mg/l was assumed close as possible to expected field concentrations and showed rapid biotransformation of Tween 80 and Tween 85, with depletion after 8 days, DOSS showed rapid biotransformation after a lag period of 16 days and EHSS showed limited degradation. This study shows that the surfactants DOSS, Tween 80 and Tween 85 in the three chemical dispersants studied are biodegradable in cold seawater, however after a lag period, during which the dispersant could potentially impact the environment, including seabirds.

5. Conclusions

Oil spills are known to result in severe environmental impacts. For seabirds, that spend the majority of their life at sea resting or diving, exposure to an oil spill, even in small amounts, will result in damages to the plumage and subsequently lethal hypothermia. Chemical dispersants may be considered for removing oil spill from the sea surface. Chemical dispersants are sprayed onto the oil slick and with sufficient mixing energy; the oil disperses into the water column. During application of chemical dispersants, there is a risk of misapplication of the dispersant, outside the oil covered sea surface and therefore it is possible for seabirds to be exposed to the dispersant on the sea surface. While the intention behind application of dispersants is to remove oil from the sea surface, and thus reduce the risk of damage to birds, it is still relevant and necessary to weigh this against the potential damage from the dispersants themselves.

Our study showed that exposure of seabird feathers to chemical dispersants even in low dosages may have an impact, through the uptake of water and subsequent weight increase, sinking and damages on feather microstructure. The water uptake was mostly significant for the common eider compared to the thick-billed murre. Common eiders feathers are also considered to create a softer and more air-filled plumage. At the same time more damages were identified on the feather microstructure of thick-billed murre compared to common eider, based on the AI assessment. However, we speculate that the AI, a well-established method for oil impact assessment, is an uncertain method for dispersant impact assessment, as the dispersant results in increased water uptake of the individual barbules besides the clumping effect assessed with AI.

A no-sinking limit on feathers was established to be in the interval between 0.01 ml/m^2 and 0.109 ml/m^2 of dispersant. Relating this level to our model simulations of potential dosages found on the sea surface we use the upper end of the interval as no-sinking limit. In case of an unsuccessful dispersion operation our simulation indicates that the no-sinking limit is likely to be exceeded, at least for some time. These concentrations have also been reached during response operations for oil spill incidents, such as during the Deepwater Horizon oil spill (Lehr et al., 2010), where dispersants were applied at the surface at dosages far exceeding the no-sinking limit found here. We conclude that, our results indicate that chemical dispersants at realistic dosages could impact seabirds which should be accounted for as a risk during the planning of oil spill response operations.

CRediT authorship contribution statement

Janne Fritt-Rasmussen: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Jannie Fries Linnebjerg:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Tor Nordam:** Formal analysis, Writing - original draft, Writing - review & editing. **Frank F. Rigét:** Formal analysis, Writing - original draft, Writing - review & editing. **Paneeraq Kristensen:** Investigation, Formal analysis. **Jørgen Skancke:** Formal analysis, Writing - original draft, Writing - review & editing. **Susse Wegeberg:** Conceptualization, Methodology. **Anders Mosbech:** Conceptualization, Funding acquisition, Writing - original draft, Writing - review & editing. **Kim Gustavson:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Bejarano, A.C., Levine, E., Means, A.J., 2013. Effectiveness and potential ecological effects of offshore surface dispersant use during the Deepwater Horizon oil spill: a retrospective analysis of monitoring data. Environ. Monit. Assess. 185, 10281–10295.

Blondina, G.J., Singer, M.M., Lee, I., Ouano, M.T., Hodgins, M., Tjeerdema, R.S., Sowby, M.L., 1999. Influence of salinity on petroleum accommodation by dispersants. Spill Sci. Technol. Bull. 5 (2), 127–134.

Boertmann, D., Lyngs, P., Merkel, F.R., Mosbech, A., 2004. The significance of Southwest Greenland as winter quarters for seabirds. In: Bird Conservation International, 14, pp. 87–112.

Boertmann, D., Mosbech, A., Merkel, F.R., 2006. The importance of Southwest Greenland for wintering seabirds. Br. Birds 99, 282–298.

Brakstad, O.G., Størseth, T.R., Brunsvik, A., Bonauneta, K., Faksness, L.G., 2018. Biodegradation of oil spill dispersant surfactants in cold seawater. Chemosphere 204, 290–293.

Brandvik, P.J., Faksness, L.G., 2009. Weathering processes in Arctic spills: meso-scale experiments with different ice conditions. Cold Reg. Sci. Technol. 55 (1), 160–166.

Brönner, U., Johansen, Ø., Leirvik, F., Nordam, T., Sørheim, K.R., 2018. Spreading of waxy oils on calm water. Mar. Pollut. Bull. 129 (1), 135–141.

Buist, I., Cooper, D., Trudel, K., Fritt-Rasmussen, J., Wegeberg, S., Gustavson, K., Lassen, P., Alva, W.U.R., Jomaas, G., Zabilansky, L., 2017. Research Investigations Into Herder Fate, Effects and Windows-of-opportunity. In: International Association of Oil & Gas Producers, p. 174 s..

Canevari, G.P., 1969. General dispersant theory. In: International Oil Spill Conference Proceedings, 1969, pp. 171–177, 1.

Clark, R.B., 1984. Impact on oil pollution on seabirds. Environ. Pollut. (Ser. A) 33, 1–22.

D'alba, L., Carlsen, T.H., Ásgeirsson, Á., Shawkey, M.D., Jónsson, J.E., 2017. Contributions of feather microstructure to eider down insulation properties. J. Avian Biol. 48 (8), 1150–1157.

Daling, P.S., Brandvik, P.J., Mackay, D., Johansen, Ø., 1990. Characterisation of crude oils for environmental purposes. Oil Chem. Pollut. 7, 199–224.

Duerr, R.S., Massey, J.G., Ziccardi, M.H., 2009. Physical effects of Prudhoe Bay crude oil water accommodated fractions (WAF) and Corexit 9500 chemically enhanced water accommodated fractions (CEWAF) on common murre feathers and California sea otter hair. In: SSEP Study: Effects of Chemically and Physically Dispersed Oil on Wildlife, 12 p.

Fiorello, C.V., Freeman, K., Elias, B.A., Whitmer, E., Ziccardi, M.H., 2016. Ophthalmic effects of petroleum dispersant exposure on common murre (Uria aalge): an experimental study. Mar. Pollut. Bull. 113, 387–391.

Fritt-Rasmussen, J., Linnebjerg, J.F., Sørensen, M.X., Brogaard, N.L., Rigét, F.F., Kristensen, P., Jomaas, G., Boertmann, D.M., Wegeberg, S., Gustavson, K., 2016. Effects of oil and oil burn residues on seabird feathers. Mar. Pollut. Bull. 109 (1), 446–452.

Gaston, A.J., 2004. Seabirds: A Natural History. T & AD Poyser Ltd (A & C Black), London.

GOSR, 2021. Equipment, Dasic Slick Gone NS. https://gosr.gl/da/udstyr/ (accessed December 23, 2022).

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

Jenssen, B.M., Ekker, M., 1991. Effects of plumage contamination with crude oil dispersant mixtures on thermoregulation in common eiders and mallards. Arch. Environ. Contam. Toxicol. 20, 398–403.

Lambert, G., Peakall, D.B., Philogéne, B.J., Engelhardt, F.R., 1982. Effect of oil and oil dispersant mixtures on the basal metabolic rate of ducks. Bull. Environ. Contam. Toxicol. 29, 520–524.

Lehr, B., Bristol, S., Possolo, A., 2010. Oil Budget Calculator Deepwater Horizon: A report to the National Incident Command. https://www.restorethegulf.gov/sites/default/files/documents/pdf/OilBudgetCalc_Full_HQ-Print_111110.pdf (Accessed Aug. 25, 2022).

Lewis, A., Daling, P.S., 2007. Evaluation of dispersant spray systems and platforms for use on spilled oil in seas with ice present (JIP Project 4, Act 4.21). In: SINTEF Report No. A16088, 978-82-14-05007-3, 21 p.

Morandin, L.A., O'Hara, P.D., 2014. Fish oil disrupts seabird feather microstructure and waterproofing. Sci. Total Environ. 496, 257–263.

O'Hara, P.D., Morandin, L.A., 2010. Effects of sheens associated with offshore oil and gas development on the feather microstructure of pelagic seabirds. Mar. Pollut. Bull. 60, 672–678.

Peakall, D.B., Wells, P.G., Mackay, D., 1987. A hazard assessment of chemically dispersed oil spills and seabirds. Mar. Environ. Res. 22, 91–106.

R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.

Stephenson, R., 1997. Effects of oil and other surface-active organic pollutants on aquatic birds. Environ. Conserv. 24 (2), 121–129.

Stephenson, R., Andrews, C.A., 1997. The effect of water surface tension on feather wettability in aquatic birds. Can. J. Zool. 74, 288–294.

TODNEM AS, 2015. "Sikkerhetsdatablad Dasic Slickgone NS", version 3.0, 2015. https://www.nofo.no/globalassets/pdfs/hms/edocs9451-v1-dasic-slickgone-ns-no-sds-todnem.pdf (accessed December 21, 2022).

Whitmer, E.R., Elias, B.A., Harvey, D.J., Ziccardi, M.H., 2018. An experimental study of the effects of chemically dispersed oil on feather structure and waterproofing in common murre (Uria aalge). J. Wildl. Dis. 54 (2), 315–328.