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Potential impact of noise from shipping on key species of marine mammals in waters off Western Greenland-Case Baffinland

Final Report

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Glossary

Audiogram	A graphical depiction of the hearing sensitivity of a species as a function of frequency.
Cetaceans	Whales, dolphins and porpoises.
Critical ratio	Ratio between a sound signal level and the noise level, where a sound is just discernible to an animal.
Decibel	Logarithmic unit used to describe the magnitude of sound.
Fitness	An individual's reproductive success and relative contribution to the gene pool of the next generation.
Hearing sensitivity	Magnitude of sound detectable at a given frequency.
Lombard effect	Increase in intensity of communication sounds in a noisy environment.
Pinnipeds	Seals, sea lions and walrus.
Psychoacoustics	The study of sound perception.
Threshold	Lowest level of sound detectable to an animal, or lowest level of noise causing a specific effect.
Threshold shift	Decrease in sound sensitivity, compared to baseline threshold.
Ultrasound	Sound with frequencies above the human hearing limit (20 kHz).

Summary

Baffinland is planning regular shipping of iron ore through Baffin Bay as part of the Mary River Mining Project. A shipping route passing through Greenland waters close to the west coast has been proposed, with possible reloading to larger ships at Maniitsoq or Nuuk. There is a significant overlap between the frequencies produced by different ship types such as icebreakers and container ships and the known or likely hearing range of the marine mammals considered here (beluga whales, narwhals, bowhead whales, ringed seals, bearded seals and walruses). This increases the likelihood of potential impacts of noise on e.g. behaviour and stress hormone levels in the different species. Furthermore there is a significant frequency overlap between shipping noise and underwater communication sounds produced by all the marine mammals considered here. Masking of communication signals of these species is therefore a potential risk, which would result in reduced communication ranges, and could among other things make it more difficult to find a mate.

Rough estimates of maximum detection ranges based on beluga whale, ringed seal and walrus hearing sensitivity indicate that effects of shipping noise can occur at ranges of many tens of kilometres. One scenario with ice cover suggests that ringed seals may be able to detect an icebreaker at distances of more than 150 km. More precise estimates of detection ranges will require measurements made in the areas of concern and more detailed information on hearing thresholds, critical ratios etc. of the focal marine mammal species.

Central Baffin Bay, Disko Bay and Store Hellefiske Banke are identified as being particularly sensitive areas in relation to the effects of the proposed shipping route. Central Baffin Bay is an important wintering and foraging ground for narwhals, and Disko Bay and Hellefiske Banke are important winter/spring foraging grounds for beluga whales, narwhals, bowhead whales and bearded seals, whelping grounds for bearded seals, and possible mating grounds for bowhead whales. Affecting these areas could thus potentially affect a large number of individuals, at sensitive times for the species. The shipping route also cuts across or directly follows the spring and fall migration routes for beluga whales, narwhals and bowhead whales with potential negative consequences, such as icebreakers creating "dead end" leads in the ice that animals might accidentally follow.

One fruitful way to ensure a sustainable use of Baffin Bay could be to avoid shipping in sensitive areas at sensitive times. This could perhaps involve avoiding Disko Bay and Store Hellefiske Banke during bowhead mating season.

1 Background

Baffinland is planning regular shipping of iron ore through Baffin Bay as part of the Mary River Mining Project. A shipping route passing through Greenland waters close to the west coast has been proposed, with possible reloading to larger ships at Maniitsoq or Nuuk (Baffinland, 2015). The proposal would result in a substantial increase in shipping, which could potentially affect local wildlife in West Greenland waters through increased disturbance either from noise or physical presence. This includes several species of marine mammals. There may be additional concerns for marine mammals in seasons with ice cover, as icebreakers may open up new "dead end" leads which could result in entrapments in the ice for individuals following such leads (Richardson et al., 1995; Laidre and Heide-Jørgensen, 2005; Laidre et al., 2012). For pinniped species giving birth on ice (e.g. ringed seal, bearded seal and walrus) icebreaking could also affect pup survival. It could result in destruction of birth lairs of ringed seals, or force small pups to flee into the water at a serious energetic cost (Wilson et al., 2014), as well as potentially disrupt nursing behaviour, or cause abandonment of pups (Fay et al., 1984; Wilson et al., 2014).

The following report will focus on evaluating potential effects of underwater noise from shipping on six Arctic marine mammal species: beluga whales, narwhals, bowhead whales, ringed seals, bearded seals and walruses, in West Greenland waters. These species may already experience increasing environmental pressures from e.g. climate change (Heide-Jørgensen et al., 2017) and various pollutants (Desforges et al., 2016).

Effects are explored in relation to shipping noise, and potential noise impact ranges and sensitive areas are estimated for the different species, based on available knowledge. Possible mitigation measures in relation to shipping noise are also briefly discussed.

2 Shipping noise

Sound is generally defined as noise if it clutters and masks other sounds of interest (Richardson et al., 1995). Noise can largely be divided into two categories; continuous noise from e.g. ships, and impulsive noise from e.g. air-guns. There is often some overlap between these categories, and noise from shipping often also contains impulses or tones (Arveson and Vendittis, 2000). Examples of the frequency content and sound energy at different frequencies (power spectral density) back-calculated to 1 m from an icebreaker can be seen in Figure 4.

Underwater noise from ships is mainly caused by the propulsion system (McKenna et al., 2012; Arveson and Vendittis, 2000; Trevorrow et al., 2008) and particularly from the propeller of the ship due to cavitation (Ross, 1976). Noise is also linked to speed with higher speed generating higher noise levels for some types of ships (Thiele, 1988; Trevorrow et al., 2008). Icebreaking ships have been found to be louder than regular cargo ships when they move through the ice. This does not seem to be related to the breaking of ice, but rather due to increased cavitation, as the ship alternates between ramming into the ice and backing up again (Peterson, 1981; Thiele, 1988; Richardson et al. 1995). Thiele (1988) reported noise levels 5 to 10 dB higher when the icebreaker was reversing, than when it was sailing full ahead. Similar findings have been reported by Roth et al. (2013), who found that noise levels increase by 10 dB between 20 Hz and 2 kHz during icebreaking operations (see Figure 4). Some icebreakers are also equipped with a bubbler system, to push broken ice away from the ship by blowing high pressure air into the water. This can create an additional noise source over short ranges (Erbe and Farmer, 2000).

3 Hearing and sound production in central marine mammal species in West Greenland waters

In the aquatic environment light attenuates rapidly, whereas sound propagates well over long distances (Medwin and Clay, 1998). Marine mammals therefore rely largely on sound for underwater communication, orientation and when finding prey. Sound is likely used for navigation through passive listening, as done by seals, walruses and bowhead whales, or in echolocation used by beluga whales and narwhals. Sound and low frequency vibrations are also important sensory cues for seals locating prey (Dehnhardt et al., 2001). Communication sounds are important between conspecifics during different specific activities e.g., mating, mother-offspring interactions, group coherence and aggression.

The hearing sensitivity of an animal is usually investigated in low-noise laboratory conditions using psychoacoustic testing either through behaviour with trained animals or using the auditory brainstem response (ABR) on wild or captive individuals. The result is an absolute or slightly masked hearing threshold which is presented as a function of frequency and sound intensity – an audiogram. In general, audiograms have a U-shape with the areas of best sensitivity at the lowest values. The hearing sensitivity has only been investigated in a limited number of species; though generalizations between species should be avoided, it may sometimes be the only option available.

In the following available information on hearing sensitivity and sound production parameters is presented for six marine mammal species found in West Greenland waters.

3.1 Cetaceans

Cetaceans have evolved from terrestrial mammals that probably had hearing systems well-adapted for air-born sound (Hoelzel, 2002). The group cetaceans can largely be divided into the toothed whales such as beluga whales and narwhals, and the baleen whales such as bowhead whales. Toothed whales and baleen whales have both adapted to a fully aquatic life style and their hearing apparatus has had to adapt to register sound pressure underwater (Nummela, 2008). Hearing sensitivity has been studied in several species of toothed whales, but so far no such studies have been possible in baleen whales.

Sound produced by toothed whales and baleen whales is also very different. Toothed whales use echolocation, where they emit intense ultrasonic clicks, and use the returning echoes reflected by objects impinged by the sound to navigate and locate prey (Au, 1993). Though it has been suggested that one species of baleen whale, the humpback whale (*Megaptera novaeangliae*), may use a form of echolocation (Stimpert et al., 2007), it has not been found in any other baleen whale species. Most toothed whales like beluga whales and narwhals also produce sound with lower frequencies, known as whistles, and pulsed calls for communication (Sjare and Smith 1986; Richardson et al. 1995; Ridgway et al. 2001; Marcoux, 2012). Lowering the frequency in communication signals may facilitate communication in a group, as the lower frequency whistles are emitted more omnidirectionally than echolocation clicks (Lammers and Au 2003). Baleen whales such as fin and blue whales are known to produce very low frequency (<100 Hz), high intensity calls for communication (Širović et al., 2007), and can potentially communicate over entire ocean basins (Payne and Webb, 1971; Širović et al., 2007). Bowhead whale communication signals are of somewhat higher frequency (see below), resulting in shorter communication ranges compared to fin and blue whales, but they can still potentially communicate over distances of several hundred kilometres (Tervo et al., 2012).

3.1.1 Beluga whale (*Delphinapterus leucas*)

The hearing sensitivity has been investigated in the beluga whale both behaviourally and using ABR (Awbrey et al. 1988; Klishin et al. 2000; Ridgway et al. 2001; Finneran, 2005) and the resulting audiograms from Ridgway et al. (2001) and Finneran et al. (2005) are presented in Figure 1. The beluga whale's hearing becomes increasingly directional with higher frequencies. This increase in hearing directionality at the frequencies relevant for echolocation makes them less susceptible to background noise and clutter (i.e. returning echoes from other objects than the intended target; Mooney et al. 2008; Popov and Supin, 2009).

The echolocation clicks of beluga whales are centred around 40-60 kHz and have peak-to-peak source levels of up to 225 dB re 1µPa (Au et al., 1985, Au, 1993). Beluga whales produce a variety of sounds for communication such as whistles and pulsed calls (Richardson et al. 1995; Sjare and Smith 1986). Whistles range from 260 Hz to 20 kHz, but with dominant frequencies of 1 to 5.9 kHz (Richardson et al. 1995; Sjare and Smith 1986). Pulsed calls are series of echolocation clicks, with a different inter click interval pattern compared to during echolocation (Richardson et al., 1995) Communication using echolocation clicks has also been described in harbour porpoises (Clausen et al., 2010).

3.1.2 Narwhal (*Monodon monoceros*)

Hearing in narwhals has not yet been investigated, but as it is a close relative of the beluga whale, their hearing is assumed to be comparable. Hearing directionality has also not been demonstrated in narwhals, but is likely, as it has been demonstrated in other echolocating toothed whales including beluga whales (Au and Moore, 1984; Kastelein et al. 2005; Mooney et al. 2008).

Narwhals produce high frequency broad band clicks with peak frequencies ranging between 55-83 kHz and a mean frequency between 69 and 71 kHz (Rasmussen et al., 2015; Koblitz et al. 2016), and with energy extending beyond 150 kHz (Rasmussen et al., 2015). Click source levels have been measured up to 222-227 dB re 1µPa peak-to-peak (Møhl et al. 1990; Koblitz et al., 2016), but with mean apparent source levels of 214-215 dB re 1 µPa (Rasmussen et al. 2015; Koblitz et al., 2016). Narwhals also produce a variety of sounds such as whistles and pulsed calls for communication (Marcoux, 2012; Stafford et al., 2012), with whistles ranging in frequency from 405 Hz to 14.5 kHz (Marcoux, 2012).

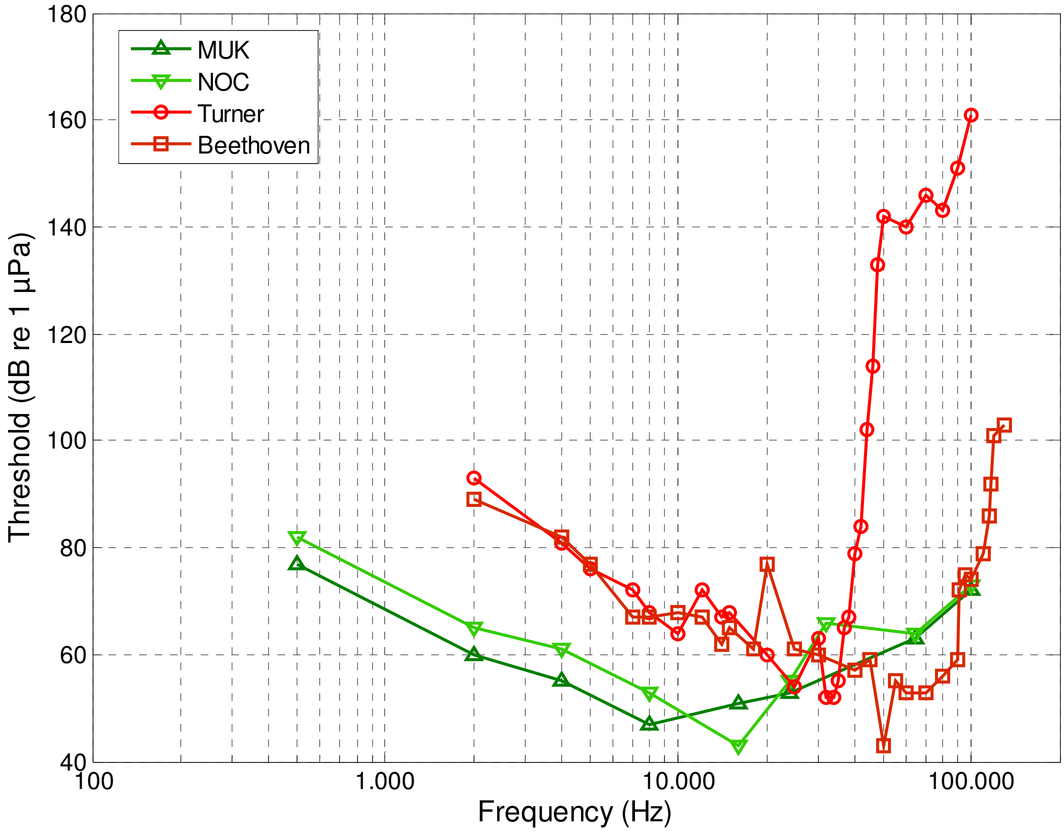

Figure 1: Hearing sensitivity of beluga whale. MUK and NOC (green lines) are modified from Ridgeway et al., 2001, and Turner and Beethoven (red lines) are modified from Finneran et al., 2005.

3.1.3 Bowhead whale (*Balaena mysticetus*)

The hearing in any baleen whales remains to be tested in a live animal. However, anatomical studies of the inner ear in the northern right whale (*Eubalaena glacialis*), a close relative of the bowhead whale, suggest that this species has a hearing range from 10 Hz to 22 kHz (Parks et al. 2007).

Bowhead whales produce high intensity communication sounds (Tervo et al., 2012), of relatively high frequency compared to some other baleen whale species (Ljungblad et al., 1982; Stafford et al., 2008; Tervo et al., 2009). They produce a wide repertoire of sounds for communication including constant frequency (CM) or frequency modulated (FM) calls, amplitude modulated (AM) calls or songs notes that are narrow band FM signals (Tervo et al., 2009). All types of sounds are within the frequency range 20 Hz to 5.6 kHz (Stafford et al., 2008; Tervo et al., 2009). The number of different song notes recorded in Disko Bay seems to be connected to the time of year, with call repertoire being the higher in winter, where mating presumably takes place (Tervo et al., 2009).

3.2 Pinnipeds

Pinnipeds, like ringed seals, bearded seals and walruses, though they spend a good part of their life at sea, have maintained an amphibious life style, with important parts of their life cycle, such as giving birth and nursing taking place on land or ice. They therefore have had to adapt to hearing sound underwater, while retaining the ability to detect sound in air (Reichmuth et al., 2013).

Pinnipeds likely mainly use underwater sound for navigation and finding prey through passive listening, however for species such as ringed seals and bearded seals, underwater communication sounds are mainly being produced by males during territorial and courtship behaviour (Stirling and Thomas, 2003; van Parijs et al. 2001), though some sounds are likely produced year round (Stirling, 1973).

3.2.1 Ringed seal (*Pusa hispida*)

Hearing in ringed seals has so far been investigated in two studies. One study found that ringed seals had a fairly poor hearing compared to other seal species (Terhune and Ronald, 1975), whereas a more recent study using behavioural psychophysical methodology found their hearing sensitivity to be comparable to and even slightly more sensitive than that of harbour seals (Sills et al., 2015; Figure 2).

Ringed seal underwater vocalizations have also been recorded in ice covered habitats, when seals maintain breathing holes and during mating season (Stirling and Thomas, 2003). Several types of calls have been described for ringed seals such as low and high pitched barks, yelps and chirps, knocks, clicks and woofs. The frequency content of the different sounds is between 100 Hz and 5 kHz (Stirling, 1973; Jones et al., 2014; Mizuguchi et al., 2016). A recent study of three captive ringed seals seems to confirm previous hypotheses, that calls are used in intraspecific competition and during mating behaviour (Mizuguchi et al., 2016).

3.2.2 Bearded seal (*Erignathus barbatus*)

The hearing sensitivity of bearded seals has not yet been investigated. However, bearded seals are known to produce a variety of underwater sounds largely associated with mating (van Parijs et al., 2001 and 2003; Risch et al., 2007). Several call categories have been described including trills, sweeps and moans that range in frequency from around 150 Hz to around 6.4 kHz (Risch et al., 2007).

3.2.3 Walrus (*Odobenus rosmarus*)

The underwater hearing sensitivity has been tested in a single male Pacific walrus (Kastelein, 2002), and the resulting audiogram can be seen in Figure 2.

Walrus underwater sound production like that of ringed seals and bearded seals is likely mostly associated with mating (Sjare and Stirling, 1996). Their sounds have been characterized as bell tones, clicks, knocks and grunts (Richardsen et al. 1995) and have frequencies mainly below 1-2 kHz, though there may be significant energy even at 10 kHz (Richardson et al. 1995; Schusterman and Reichmuth, 2008; Mouy et al. 2012).

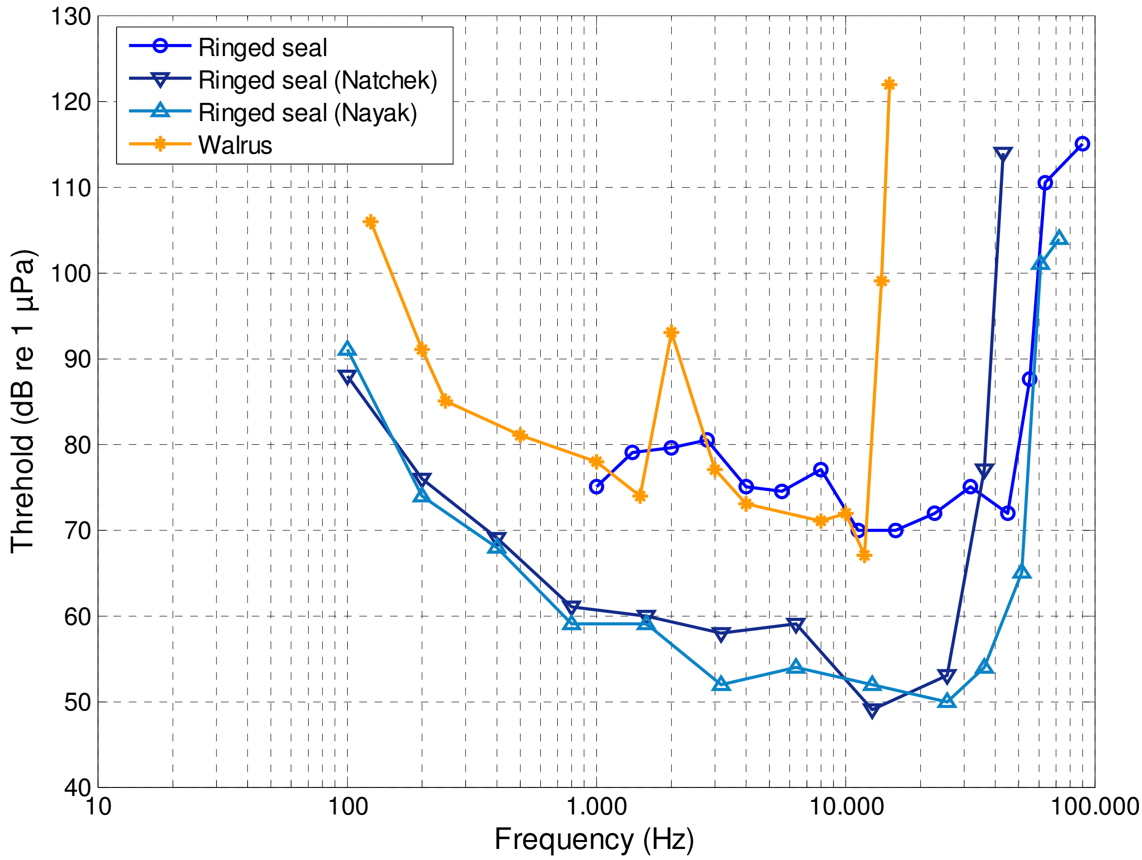

Figure 2: Hearing sensitivity of ringed seal and walrus. The ringed seals (blue lines) are modified from Terhune and Ronald, 1975, and from two individuals, a young female (Nayak) and an older male (Natcek) from Sills et al., 2015. The walrus (orange line) is modified from Kastelein et al., 2002.

4 Possible effects of underwater noise

Noise can affect marine mammals in various ways. Effects can range from masking of biologically important signals, increases in physiological stress levels, changes in behaviour such as avoidance or cessation of ongoing behaviour, and potentially even temporary or permanent changes in hearing sensitivity.

The circumstances in which the different effects occur depend on a wide variety of factors such as frequency content and duration of the noise, and the existing ambient noise level. An animal's proximity to the noise source is also an important factor, with the number and severity of potential effects increasing the closer the animals is to the source. Other variables like age, sex and general physiological and behavioural states of individual animals also influences the likelihood of an animal being affected (Popov et al., 2011; Southall et al., 2007). For some species the direction in which the noise source is moving in relation to an individual can also influence the scale of an effect (Richardson et al., 1995).

The range at which the different impacts occur is ideally defined by a species specific threshold for each effect, creating species specific zones of impact (see Figure 3). However, in reality these zones are not sharply defined, and there are large overlaps between the different zones, due to all the different contributing factors mentioned above.

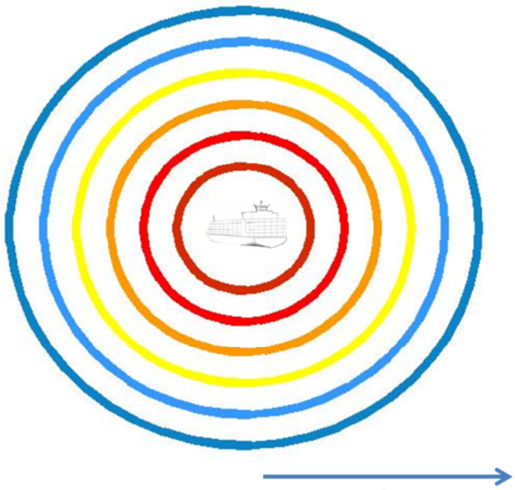

Figure 3: Schematic of zones of noise impact. As the distance to the noise source increases, the severity and number of different effects experienced by an animal decreases. Injury and permanent hearing loss (dark red) are only induced very close to the sound source, and are unlikely to occur from shipping noise. Temporary hearing loss (red), behavioural reactions and stress (orange) can also occur further away along with masking (yellow), and furthest away from the sound source an animal is just able to detect the sound above the background noise (light blue). The zones of impact are not as sharply defined as depicted here and there is a large degree of overlap between the different zones. The figure is modified from Richardson et al. (1995).

4.1 Permanent and temporary hearing loss

Intense noise levels, or prolonged continuous noise exposure can lead to noise-induced changes in animal detection thresholds either temporarily (TTS) or permanently (PTS) through fatiguing, damaging or even killing sensory cells in the inner ear (Kastak et al., 2005; Popov et al., 2011; Kastelein et al., 2012a and b; Ketten, 2012). In relation to shipping noise an animal would need to be very close to a sound source for a prolonged period of time to experience PTS inducing noise levels from a single shipping event, which would be highly unlikely. If hearing loss is induced, it will more likely be temporary with the animal regaining its original detection abilities after a recovery period. Noise intensity, frequency, and duration of exposure are important factors determining the degree and magnitude of hearing loss (Popov et al., 2011). Prolonged exposures to noise, where the ear does not have time to recover, may result in an accumulating TTS, and TTS of 50 dB or more will often result in permanent hearing loss (Kastak et al. 2008; Ketten et al. 2012).

TTS has only been investigated in one of the species considered here, the beluga whale, and mainly in relation to exposures of relatively high sound intensity and short duration (Finneran, 2015). However, Popov et al. (2013) found that TTS increased with duration of exposure, and Popov et al. (2015) found that aside from TTS, a beluga whale’s ability to discriminate fine spectral content was also reduced while TTS persisted.

Though single shipping events are unlikely to cause temporary hearing loss, as animals will likely leave an area before TTS is induced, significant elevation of background noise levels due to a significant increase in shipping could potentially lead to levels high enough to induce temporary hearing loss. However studies investigating this are lacking.

4.1 Behavioural changes

Behavioural reactions to noise can range from very strong reactions, such as panic or flight close to the noise source, over more moderate reactions where animals may orient themselves towards the noise source or move slowly away from it, to cessation of normal ongoing behaviour. However, changes in behaviour are inherently difficult to evaluate, particularly when animals are difficult to observe (e.g. living under water, or too far away to observe). Reactions may also vary with season, initial behavioural state (such as foraging, migrating or nursing), age, sex, and previous experience. For some species the direction in which the noise source is moving in relation to an individual can also influence the scale of an effect (Richardson et al., 1995). Reactions also vary with intensity, frequency and time structure of the noise in question. Several studies have sought to investigate the behaviour of Arctic marine mammals in relation to noise from shipping and icebreaking activities.

In ice-covered waters, beluga whales have been shown to exhibit avoidance behaviour up to 35-50 km from a ship and an icebreaker, and they likely produced alarm calls at distances of more than 80 km (Finley et al., 1990; Cosens and Dueck, 1993; Richardson et al. 1995). Reactions of beluga whales to shipping noise in other habitats and under other circumstances have ranged from avoidance to almost no reactions at all (Richardson et al., 1995). Narwhals have also been shown to avoid a ship and an icebreaker. However, whereas beluga whales swam away from the ships, some individual narwhals exhibited a “freezing” behaviour, resembling their reactions to killer whales (Finley et al., 1990; Richardson et al., 1995; Laidre et al. 2006). This illustrates that even though different species may be equally sensitive to noise, their behaviour as a consequence of the noise may be vastly different.

Bowhead whales have been shown to react by swimming rapidly away from approaching ships, and only ceasing when the distance to the ship is several kilometres (Richardson et al., 1990, 1995). Shipping noise elicited an avoidance response at approximately 4 km distance (Richardson and Greene, 1993). Some individuals returned to the site they were displaced from, but whether this will also be the case if disturbance is continuous remains to be investigated (Richardson et al., 1995). Reactions do not seem to be as strong if a ship is moving slowly, and does not approach the whale (Richardson and Greene, 1993; Richardson et al., 1995).

Behavioural reactions in walruses depend on whether the animal is hauled out or in the water, as individuals in the water tend to be much less responsive (Fay et al., 1984). For walruses hauled out on ice reactions depend on the distance to and activity of the vessel. Individuals may enter the water when a ship underway comes within 1 km, whereas for icebreaking vessels avoidance behaviour starts occurring at distances of up to 10-15 km (Fay et al., 1984; Richardson et al. 1995), these reactions are however a consequence of air-borne stimulus, and not underwater noise.

Ringed seals hauled out on ice show short-term escape responses when a ship comes within 250-500 meters, but are less reactive when they are in the water (Richardson et al. 1995). In relation to icebreakers both ringed and bearded seals hauled out on ice showed avoidance behaviour when the vessel was more than 1 km away (Richardson et al. 1995). Again these reactions are a consequence of air-borne stimulus, and not underwater noise.

Though behavioural reactions to shipping or icebreaker noise have been observed for all species considered here, it is still not certain how these relatively short-term reactions can be linked to long term impacts on the general fitness of the animals. Cumulative effects on animal fitness from the combined disturbances by ships and e.g., climate change and oil and gas production also remain to be ascertained.

4.2 Physiological stress

Changing behaviour is one aspect of reacting to noise, but within the body of an individual other processes are also set into motion. All these responses are collectively known as the integrated stress response (Randall et al., 2002). The stress response is initially an adaptive response to avoid the negative effects of a stressor, such as noise. In terrestrial mammals the increase in hormones (e.g. cortisol) associated with the stress response causes an increased oxygen uptake, and redistribution of blood and oxygen to necessary tissues (Randall et al., 2002). However, in marine mammals, where the ability to restrict oxygen consumption is vital to their diving abilities, the hormonal stress response may be somewhat different (Atkinson et al., 2015).

Stress hormones also cause allocation of energy resources from long-term investments, like growth and reproduction, to the more immediate needs for survival (Wingfield, 2003; Atkinson et al., 2015).

Prolonged or often reoccurring exposure to noise can result in a chronic state of stress, with constant high levels of stress hormones. A single study related a significant reduction in ambient noise levels, due to a period of reduced shipping activities, to a reduction in metabolized glucocorticoids in fecal matter from Northern right whales (*Eubalaena glacialis*) (Rolland et al., 2012). The study thereby indicated that an elevated stress-hormone level was the "normal" state.

Negative effects of increased cortisol levels have been demonstrated in terrestrial mammals (Wingfield, 2013). However, this effect remains to be investigated in marine mammals (Atkinson et al., 2015).

4.3 Masking and sound detection

Masking is a naturally occurring phenomenon in the environment, where animals are masked by biotic background noise (e.g. communication signals from other conspecifics) and abiotic background noise (e.g. wind and wave action). In areas with human activities detection ranges for important signals may be further reduced due to anthropogenic noise levels. Masking of signals can occur, if there is an overlap in frequency between the signal of interest and the ambient noise level.

The distance at which an animal is able to detect a sound source depends on the animals' hearing ability under noisy conditions. This ability is determined by the critical ratio. The critical ratio is defined as the lowest signal-to-noise ratio at which an animal is just able to detect a tone in broadband masking noise, with the noise being measured in 1 Hz bands (Kastelein et al., 2009). The lower an animal's critical ratio is for a given frequency, the better the animal is at detecting a signal of that frequency in noise. If the masking sound exceeds the critical ratio within the critical band of the signal of interest the detection distance will decrease (Frisk et al., 2003). However, for a signal to provide useful information, mere detection of the signal may not be enough, and an excess of signal of some dB above the detection threshold is likely required (Erbe et al., 2016).

Critical ratios have been determined for two of the species of interest in this report, the beluga whale (Johnson et al., 1989; Erbe et al., 2008), and the ringed seal (Sills et al., 2015).

Compensatory mechanisms to overcome masking of communication signals have been described in several marine mammal species. Northern right whales and beluga whales have been shown to increase the amplitude of their signal (the so-called Lombard effect; Lombard, 1911) or shift the frequency of their signals (Au et al., 1985; Parks et al. 2011). Changes in call rate or call duration could make it more probable that a signal is detected (Brumm and Slabbekoorn, 2005). Changes in call rate have been found in bowhead whales, beluga whales, and narwhals in relation to shipping noise (Richardson et al., 1995), though it is not clear whether this is a reaction to overcome masking, or a consequence of other behavioural changes. Fluctuation in the time/frequency structure of the masking noise can result in a release from masking known as comodulation masking release, which has been demonstrated in vertebrates as diverse as the bottlenose dolphin (Branstetter and Finneran, 2008) and the goldfish (Fay, 2011). This makes it likely to be more general phenomenon among vertebrates, and could also be occurring for the species considered here. In pinnipeds spatial release from masking due to directional hearing has been described (Holt and Schusterman, 2007), and one study has shown that signals composed of a number of different frequencies is more readily detectable by pinnipeds than predicted from the audiogram and critical ratio (Cunningham et al., 2014).

5 Detection distance estimates for focal marine mammal species

Several parameters affect how far away from a sound source an animal is able to detect its presence. Some of the parameters have been outlined in sections above (e.g., absolute hearing thresholds for several species). In the sections below the different parameters are briefly outlined, and estimates of maximum detection ranges are presented for three of the species, where hearing thresholds were available: beluga whale, ringed seal, and walrus.

5.1 Detection parameters

In nature an animal's detection threshold is either limited by the internal "noise" of the hearing apparatus (absolute hearing threshold), or limited by the ambient noise level in the area (masked hearing threshold). The critical ratio defines how much a sound of interest (in this case shipping noise) must be above the spectral noise (i.e. the noise measured in 1 Hz bands) for it to be detectable. In Figure 4 the minimum hearing threshold for the three species: beluga whale, ringed seal, and walrus are shown along with three examples of ambient noise, and three examples of noise from an icebreaker.

The three examples of ambient noise used for the calculations are: mean ambient spectral noise level in Disko Bay recorded on March 6 and 9, 2009, at a depth of 25 m (modified from Tervo et al., 2012), the spectral noise level for sea state 1 on the Beaufort scale (corresponding to a wind speed of 1 m/s), and sea state 6 on the Beaufort scale (corresponding to a wind speed of 11-13 m/s; both are modified from Urick, 1984).

The minimum hearing thresholds for the three species used in the calculations have been created by selecting the most sensitive thresholds for each tested frequency from the available audiograms for the species (see section 3). In addition critical ratios for beluga whale and ringed seal are used for the respective species, but as critical ratios are not available for walrus it is assumed that it is similar to that of ringed seals.

The source levels of shipping noise, the initial sound level against which the other parameters are compared used in the calculations are: Source level for a container ship (modified from McKenna et al., 2012), and the source levels for an icebreaker moving ahead at full speed and moving astern at full speed (modified from Thiele, 1988).

5.2 Detection distance estimates

As sound propagates through the water column sound energy is lost with increasing distance to the source. Two terms contribute to this loss of energy; the geometrical spreading loss, and the acoustic absorption. Both terms vary with location, season and other parameters. In Baffin Bay the presence of a sound propagation channel, or "sound duct" in the 40-100 m depth layer was documented by Thiele (1988) and Thiele et al. (1990). This sound channel reduces the loss of energy through geometrical spreading, making the detection distance longer compared to areas with no sound propagation channel. A model for the sound transmission loss in Baffin Bay has been developed by Thiele et al. (1990) for scenarios with open water and scenarios with ice cover (For further details of the underlying equations please consult Thiele et al., 1990).

The basic acoustic model for geometrical spreading and acoustic absorption developed by Thiele et al. (1990) was used to calculate estimates of maximum detection ranges based on the parameters outlined above for two scenarios; a winter scenario with ice cover, and a summer scenario with open water, no ice and a sea state of 1 on the Beaufort scale. The results are presented in Table 1.

Table 1: Maximum detection range of a container ship and an icebreaker by a beluga whale, a ringed seal, and a walrus, in an ice cover and an open water scenario. Acoustic modelling is based on models from Thiele et al. (1990). Beluga whale hearing is based on audiograms from Ridgway et al. (2001) and Finneran et al. (2005). Ringed seal hearing is based on audiograms from Sills et al. (2015). Walrus hearing is based on an audiogram from Kastelein et al. (2002). Ambient noise level in ice cover is from Tervo et al. (2012). Ambient noise level in open water is from Urick (1984). Source level of a container ship is from McKenna et al. (2012). Icebreaker source levels are from Thiele (1988).

Maximum detection range (km)	*Winter (Ice cover)*			*Summer (Open water sea state 1)*		
	Container Ship	*Icebreaker (full ahead)*	*Icebreaker (full astern)*	*Container ship*	*Icebreaker (full ahead)*	*Icebreaker (full astern)*
Beluga whale	*48*	*43*	*57*	*75*	*53*	*79*
Ringed seal	*77*	*75*	*154*	*137*	*106*	*323*
Walrus	*77*	*75*	*154*	*53*	*37*	*64*

Detection ranges are generally quite long for all species in these two scenarios. However, detection ranges for beluga whales are shorter, than for ringed seals and walruses in the winter/ice cover scenario. This may be because ringed seals and walruses are both more sensitive at the lower frequencies than the beluga whale, and higher frequencies are attenuated faster in ice cover, likely due to the very irregular lower surface of the ice (Thiele et al., 1990).

With increasing sea state ambient noise levels also increase (Knudsen et al. 1948; Urick, 1983, 1984). To illustrate the differences in maximum detection range of an icebreaker sailing ahead at full speed, if sea state changes from 1 (light air, water surface with scaly ripples, but no foam crests; Beaufort scale) to a sea state of 6 (strong breeze, water surface with larger waves, and common whitecaps) is presented in Table 2. The estimates indicate a substantial reduction in detection range as the wind speed increases. Estimates of maximum detection ranges are shown in Figure 6 andFigure 7 in relation to the shipping route for summer/open water and winter/ ice cover scenarios for an icebreaker moving forward, and with a sea state of 1 in the open water as a "worst case scenario".

Given the uncertainties underlining the assumptions made for the calculations, the estimates of maximum detection ranges presented here should be viewed only as rough estimates, serving to illustrate possible implications of a new shipping route. Should an environmental impact assessment take place at a later stage, these estimates should be replaced by real measurements and detailed acoustic modelling based on current environmental data.

Table 2: Maximum detection range of an icebreaker by a beluga whale, a ringed seal, and a walrus, in two open water scenarios (sea state 1 and 6 on the Beaufort scale). Acoustic modelling is based on models from Thiele et al. (1990). Beluga whale hearing is based on audiograms from Ridgway et al. (2001) and Finneran et al. (2005). Ringed seal hearing is based on audiograms from Sills et al. (2015). Walrus hearing is based on an audiogram from Kastelein et al. (2002). Ambient noise levels are from Urick (1984). Source level of a container ship is from McKenna et al. (2012). Icebreaker source levels are from Thiele (1988).

Maximum detection range (km)	*Summer (Open water sea state 1)*	*Summer (Open water sea state 6)*
	Icebreaker (full ahead)	*Icebreaker (full ahead)*
Beluga whale	*53*	*20*
Ringed seal	*105*	*82*
Walrus	*36*	*31*

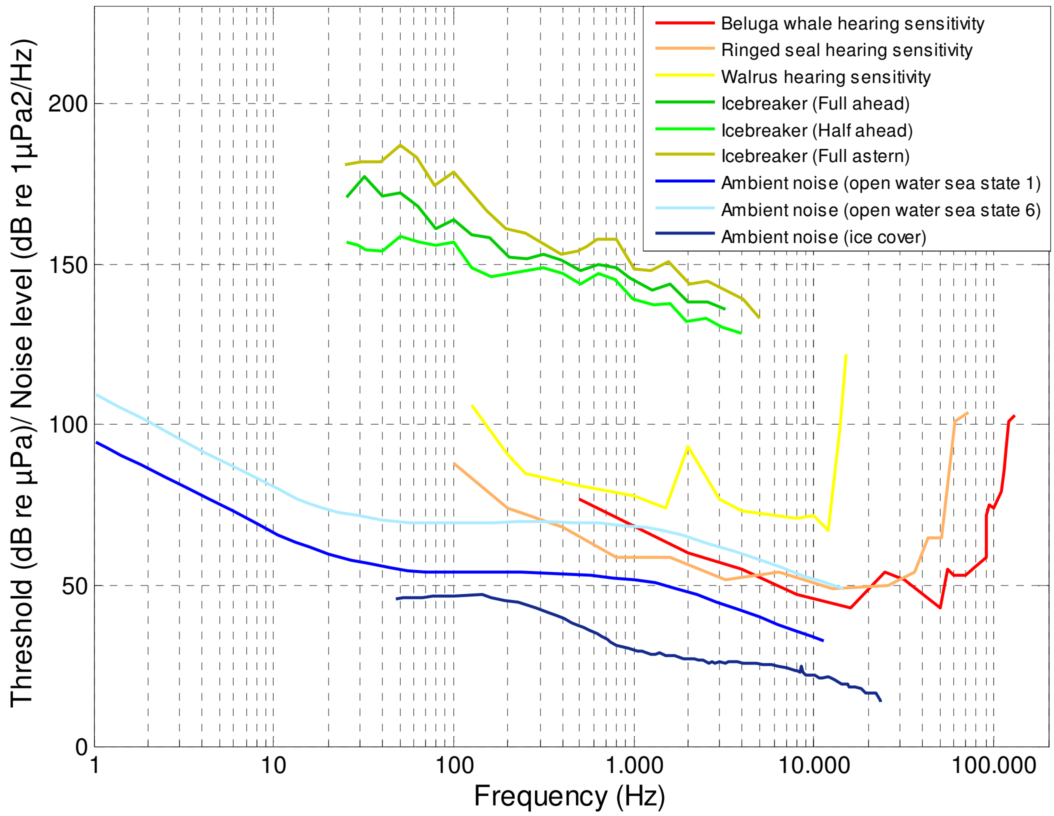

Figure 4: Assumed ambient noise level for ice cover (modified from Tervo et al., 2012), assumed ambient noise levels for sea states 1 and 6 (modified from Urick, 1984), most sensitive audiogram for ringed seals combined from Nachek and Nayak (modified from Sills et al., 2015), most sensitive audiogram for beluga whale (combined and modified from Ridgway et al., 2001 and Finneran et al., 2005), audiogram for walrus (modified from Kastelein et al., 2002), icebreaker sailing ahead at half and full speed and astern at full speed (modified from Thiele, 1988).

6 Sensitive areas with risk of noise exposure for selected marine mammal species in Western Greenland waters

Many Arctic marine mammal species show a high degree of site fidelity both in terms of wintering and summer grounds as well as migration routes (e.g., narwhals and bowhead whales; Heide-Jørgensen et al., 2006; 2010a; and 2015). The location of these areas are often associated with sea ice features such as polynyas, ice leads and the advancing or retreating ice edge (Laidre et al., 2008).

Several of the species found in the area of interest here (e.g., the North Atlantic right whale, *Eubalaena glacialis*; and the fin whale, *Balaenoptera physalus*) are listed as endangered in the IUCN red list of species, whereas other species (e.g., the beluga and the narwhal) are listed as near threatened (IUCN, 2017). However, the threat status especially for species closely associated with ice may change in the coming years, as the rising global temperatures will result in changing ice conditions which may affect important habitats differently for different Arctic species.

In view of climate changes and the possible use of previously undisturbed areas for shipping, a number of Arctic Marine Shipping Assessment areas with heightened ecological and cultural significance have been identified (AMAP/CAFF/SDWG 2013). In the Greenlandic part of Baffin Bay and Davis Strait, the North Water Polynya, Melville Bay, Central Baffin Bay, and Disko Bay and Store Hellefiske Banke are of particular importance (Christensen et al., 2012; AMAP/CAFF/SDWG 2013).

6.1 Sensitive areas for selected marine mammal species

Important winter and summer grounds and areas used for migration in the Greenlandic part of Baffin Bay and Davis Strait are presented in Table 3 for the selected species based on available information. The areas identified are of particular importance, but species are not confined to these areas only and may be found throughout Baffin Bay, if conditions allow it. Sensitive areas and migration routes are also presented for summer/open water and winter/ ice cover scenarios in Figure 5 A-D.

Ice cover in the summer and winter scenarios are based on information of the monthly median ice extent between in 1981-2010 from the National Snow and Ice Data Centre (NSIDC), along with data from the Danish Meteorological Institute (DMI), and Canadian Ice Service (CIS). It is a rough estimate and recent data from DMI shows that central part of Baffin Bay is ice free from August to October (DMI mean monthly ice-cover). The detection ranges used in summer/open water are therefore all from the open-water scenario, though the summer/open water map (Figure 6) shows some ice-cover in part of the route.

Table 3: Overwiev of inportant areas and time periods for the focal species in the Greenlandic part of Baffin Bay and Davis Strait.

Species	*Important area*	*Period of importance*	*Reference*
Beluga whale	*North Water Polynya*	*Wintering grounds (Summering grounds for beluga whales from Lancaster Sound)*	*Richard et al., 2001; AMAP/CAFF/SDWG, 2013; Heide-Jørgensen et al., 2016.*
	Northwest Greenland Shelf	*Migration corridor*	*Richard et al., 2001; Heide-Jørgensen et al., 2003.*
	Central Baffin Bay	*Critical Autumn and winter foraging grounds*	*AMAP/CAFF/SDWG, 2013;*
	Disko Bay and Store Hellefiske Banke	*Wintering grounds (November-May)*	*Heide-Jørgensen et al., 2003 and 2010b; AMAP/CAFF/SDWG, 2013.*
Narwhal	*North Water Polynya, Melville Bay, Inglefield Bredning*	*Critical summering grounds*	*Heide-Jørgensen et al.,2010c and 2013.*
	Northwest Greenland Shelf	*Migration corridor between winter and summer grounds*	*Dietz et al., 2001 and 2008.*
	Central Baffin Bay	*Critical Autumn and winter foraging grounds*	*Heide-Jørgensen et al., 2003 and 2013; Laidre and Heide-Jørgensen, 2011.*
	Disko Bay and Store Hellefiske Banke	*Winter grounds (dense pack-ice and coastal areas close to South entrance of Disko Bay)*	*Mosbech et al., 2004; AMAP/CAFF/SDWG, 2013.*
Bowhead whale	*Disco Bay*	*Spring (March-June) feeding ground and possible mating ground in winter*	*Mosbech et al., 2004; AMAP/CAFF/SDWG, 2013; Tervo et al., 2009; Stafford et al., 2008. Heide-Jørgensen et al., 2010a*
	Central Baffin Bay	*On the spring migration route*	*AMAP/CAFF/SDWG, 2013.*
Ringed seal	*North Water Polynya*	*Wintering ground for young ringed seals*	*Born et al., 2002 and 2004.*
	Central Baffin Bay	*Found at least during summer*	*Finley et al., 1983.*
	Inner parts of Melville Bay	*Important spring breeding area*	*AMAP/CAFF/SDWG, 2013.*
Bearded seal	*North Water Polynya*	*Wintering ground*	*Heide-Jørgensen et al., 2016.*
	Disko Bay and Store Hellefiske Banke	*Winter/Spring area whelping ground*	*AMAP/CAFF/SDWG, 2013.*
Walrus	*North Water Polynya*	*Wintering grounds*	*Andersen et al., 2014; Heide-Jørgensen et al., 2016*
	Disko Bay and Store Hellefiske Banke	*Critical wintering habitat*	*Dietz et al., 2014; Heide-Jørgensen et al., 2014; Christensen et al., 2012.*

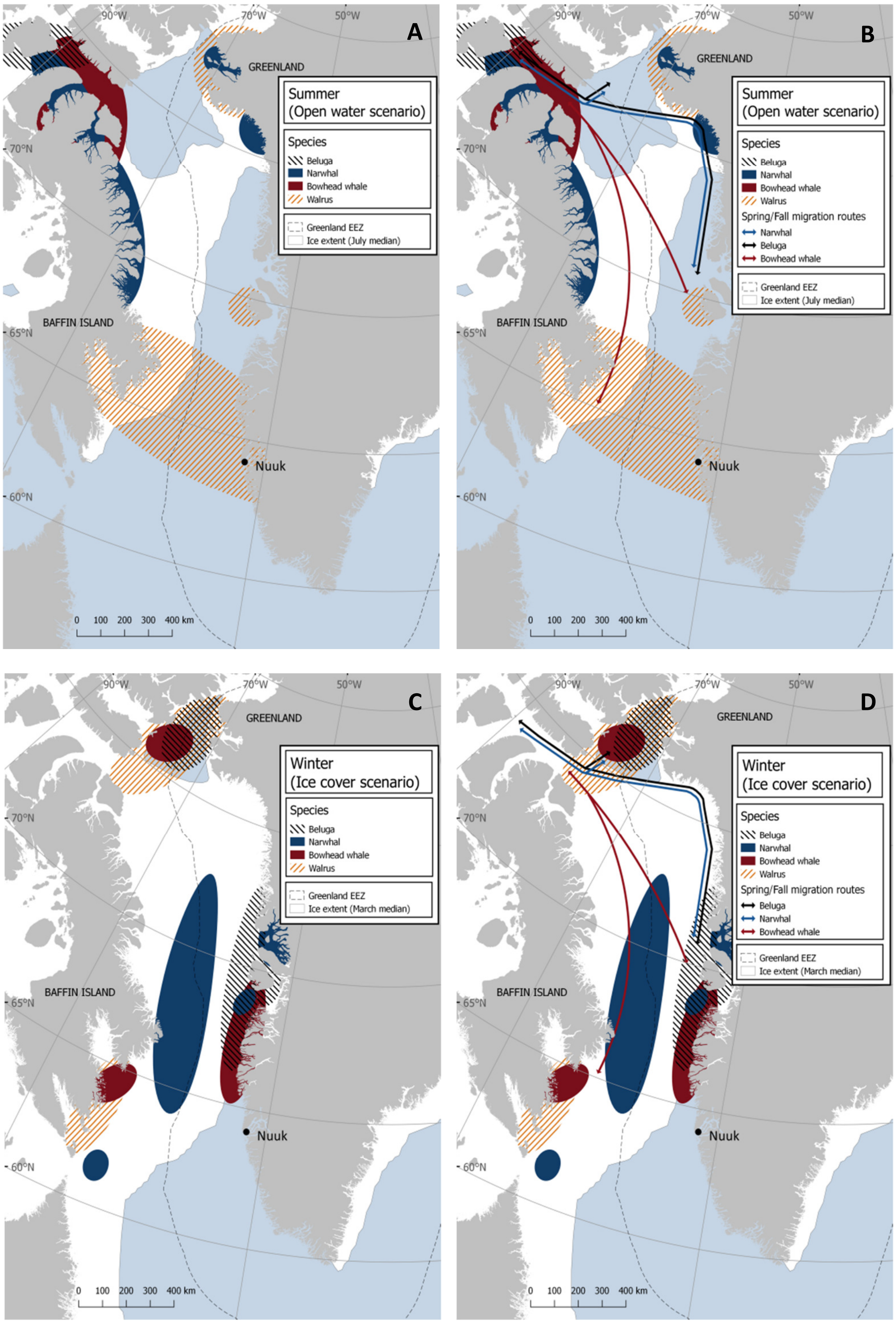

Figure 5: Important areas for beluga, bowhead whale, narwhal and walrus. A) Important summering grounds; B) important summering grounds and spring/fall migration routes (Sources: beluga: Boertman and Mosbech, 2017; bowhead whale: Boertman and Mosbech, 2017, Committee on the Status of Endangered Wildlife in Canada (COSEWIC; http://www.cosewic.gc.ca/); narwhal: Heide-Jørgensen et al., 2015; Heide-Jørgensen et al., 2013; walrus: NAMMCO Scientific Publication Vol. 9, 2014; Ice extent: NSIDC); C) Important wintering grounds; B) important wintering grounds and spring/fall migration routes (Sources: beluga: Boertman and Mosbech 2017; bowhead whale: Boertman and Mosbech 2017, Committee on the Status of Endangered Wildlife in Canada (COSEWIC; http://www.cosewic.gc.ca/); narwhal: Heide-Jørgensen et al., 2015; Heide-Jørgensen et al., 2013; walrus: NAMMCO Scientific Publication Vol. 9, 2014; Ice extent: NSIDC).

6.2 Areas with risk of noise exposure for focal marine mammal species

Identifying sensitive areas where species are at risk of increased noise exposure, is an important step in determining if and what mitigation measures may be required to minimise negative effects of noise on marine mammal populations, as a consequence of increased shipping from the Mary River Mining Project.

Maps combining the identified sensitive areas and the detection range for beluga whales, ringed seals and walruses of a forward moving ice-breaker in a summer/open-water scenario, and a winter/ice-cover scenario are presented in Figure 6 and Figure 7.

Keeping in mind all underlying assumptions previously mentioned, the maps illustrate that especially critical wintering grounds in central Baffin Bay, Disko Bay and Store Hellefiske Banke are at risk of being affected, but also spring and fall migration routes for beluga whales, narwhals and bowhead whales going from the North Water and Baffin Island, transverse or are overlaid by the proposed shipping route.

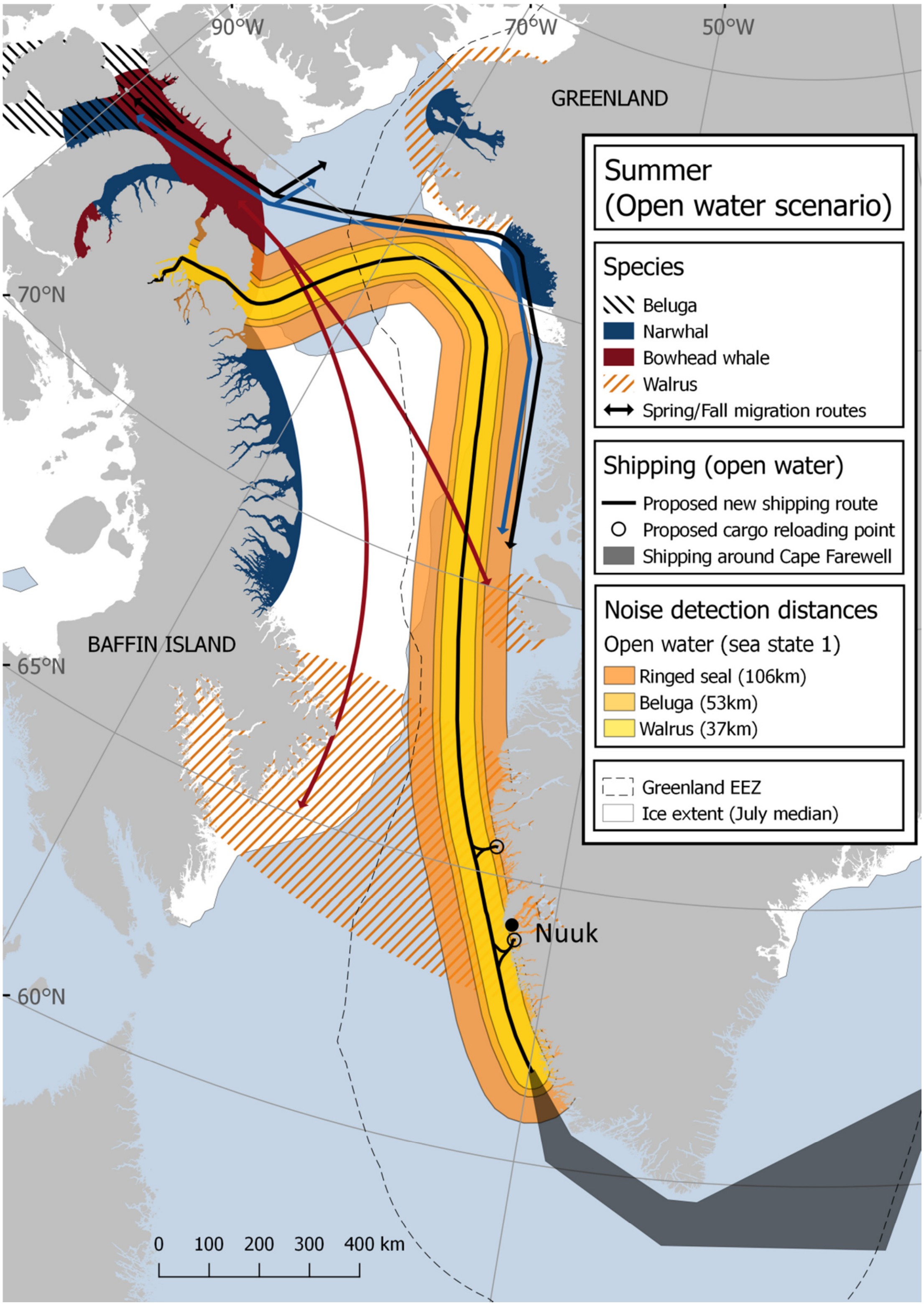

Figure 6: Noise detection ranges of an icebreaker moving forward in sea state 1 conditions by a beluga whale, ringed seal and walrus at open water conditions along the proposed new shipping route at West Greenland waters. Summer distribution estimates for beluga, bowhead whale, narwhal and walrus. (Sources: shipping route: Baffinland 2015; shipping around Cape Farewell: AIS data (marinetraffic.com); beluga: Boertman and Mosbech, 2017; bowhead whale: Boertman and Mosbech, 2017, Committee on the Status of Endangered Wildlife in Canada (COSEWIC; www.cosewic.gc.ca); narwhal: Heide-Jørgensen et al., 2015; Heide-Jørgensen et al., 2013; walrus: NAMMCO Scientific Publication Vol. 9, 2014; Ice extent: NSIDC).

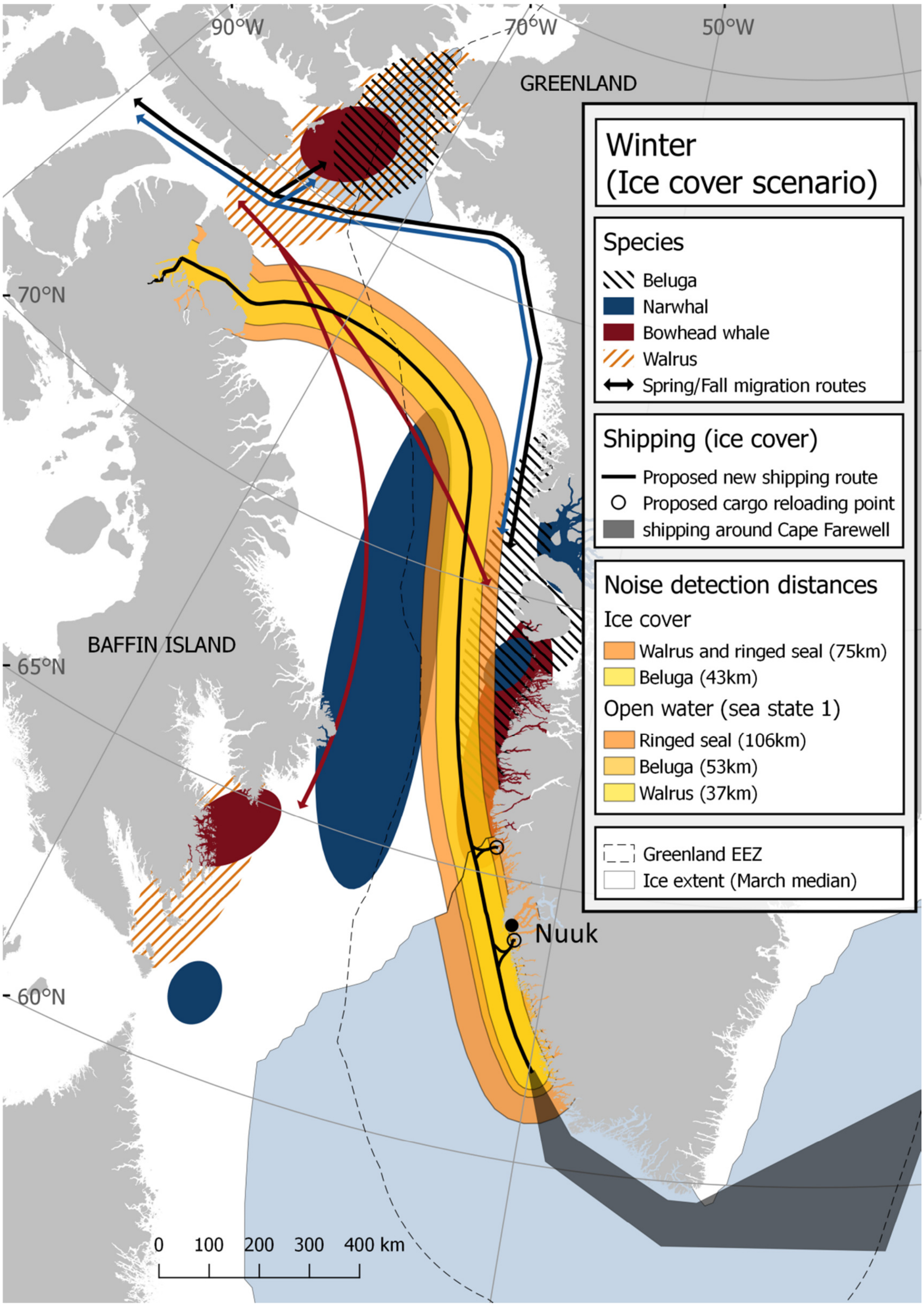

Figure 7: Noise detection ranges of an icebreaker moving forward by a beluga whale, ringed seal and walrus in ice cover and open water (sea state 1) conditions along the proposed new shipping route at West Greenland waters. Winter distribution estimates for beluga, bowhead whale, narwhal and walrus. (Sources: shipping route: Baffinland 2015; shipping around Cape Farewell: AIS data (marinetraffic.com); beluga: Boertman and Mosbech 2017; bowhead whale: Boertman and Mosbech 2017, Committee on the Status of Endangered Wildlife in Canada (COSEWIC; www.cosewic.gc.ca); narwhal: Heide-Jørgensen et al., 2015; Heide-Jørgensen et al., 2013; walrus: NAMMCO Scientific Publication Vol. 9, 2014; Ice extent: NSIDC).

7 Possible mitigation measures for shipping noise

Underwater noise from shipping comes mainly from the propulsion system as a result of cavitation around the propeller (see Chapter 2). Mitigating the noise created by shipping can broadly be done in one of two ways; 1) take measures that reduce the noise being produced (e.g. change propeller design, reduce speed; Weilgart, 2007; IMO, 2014) or, 2) take measures that reduce the likelihood of animals encountering ships (e.g. using marine mammal observers, moving the noise source in space or time; Richardson et al., 1995; Weilgart, 2007; Andre et al., 2011).

The International Maritime Organization (IMO) has addressed the issue of underwater noise from commercial shipping, by presenting non-binding guidelines to reduce underwater noise from commercial shipping (IMO, 2014). The guidelines propose several measures to "silence" new ships, such as optimal propeller design to reduce cavitation (see e.g. Southall and Scholik-Schlomer, 2008), and hull designs to ensure a homogenous flow across the surface of the ship. In terms of noise radiated from on-board machinery, IMO (2014) suggests that switching to a diesel/electric engine or a four stroke engine could result in a considerable noise reduction. For ships already in operation proposed measures involve cleaning of the propeller and hull to maintain an even flow, and for ships with a fixed propeller reducing cruising speed may be an efficient way of reducing noise emission (Weilgart, 2007; Jefferson et al., 2009; Merchant et al., 2012). However, for ships with controllable pitch propellers, the relationship between speed and noise production is not as straight forward (IMO, 2014).

Additionally temporal or geographical restrictions, such as avoiding important biological areas (e.g. central Baffin Bay) at certain times of the year (e.g. during winter) can also be used to minimize the potential negative effects of noise (Weilgart, 2007; Jefferson et al., 2009; IMO, 2014). This strategy has been employed in association with the nickel-copper-cobalt mine in Voisey Bay, where shipping has been suspended for six weeks during the pupping season for the local population of ringed seals (Baffinland, 2014).

8 Knowledge gaps to address in future

Though underwater noise has been an issue of concern in relation to marine mammals for several decades (see Richardson et al., 1995), there continues to be large gaps in our understanding of how noise affects marine life, both concerning the short and long term.

Basic data on hearing sensitivity is only available for a few individuals of a few species, and as there may be significant variation in hearing sensitivity between individuals even within a species (Castellote et al., 2014), extrapolating hearing sensitivity from one species to another can inevitably only be made with the risk of large errors. Hearing sensitivity data from baleen whales is especially needed, as there currently is no data from any living individual of any species of baleen whale.

Information on behavioural reactions to different kinds of noise is, like hearing sensitivity data, limited to a few species in relation to a few sources of noise. Assuming some type of behavioural reactions from individuals of a species based on information from another species can result in critical misinterpretations of effects, since different species may react very differently to the same stimulus. This is highlighted by the differences in reactions to shipping noise found in beluga whales and narwhals (Finley et al., 1990).

How short term effects of noise such as behavioural changes or temporary hearing loss could affect the fitness of an animal (e.g. through reduced foraging opportunities, or chronically elevated stress hormone levels) is also not very well understood. Though there are some indications that a reduction in disturbance level could reduce stress hormone levels (Rolland et al., 2012) and that an increased presence of whale watching boats could be linked to a decline in a local population of bottlenose dolphins in Shark Bay, Australia (Bejder et al., 2006), it is unclear what the underlying mechanisms are, and how these relate to noise specifically. Development of population models like the ones for harbour porpoises (Nabe-Nielsen and Harwood, 2016) may be a way to gain insight into how noise could potentially affect populations. However, the development of such models requires species specific information on a number of variables, such as hearing sensitivity, which is rarely at hand. The problem becomes even more complex when the impact of noise must be coupled with impact from e.g., climate change and chemical pollution.

Knowledge of effects of noise in mammals is constantly developing. A recent study in a rodent species suggests that prolonged exposure to noise may result in epigenetic changes in the brain (Guo et al., 2017). Such studies illustrate the complexity of predicting effects of noise in mammals, and indicate that increasing noise levels may have subtle, but very significant, effects.

Elucidating the complex effects of noise on marine mammal populations, is daunting and may seem an impossible task. But investigating hearing sensitivity in more marine mammal species and several individuals within a species, and using new technology such as passive acoustic monitoring (PAM) and drones to investigate changes in behaviour are good first steps toward a better understanding of possible effects of shipping noise in Arctic marine mammals. Even as this report is being written a large scale study investigating the effects of noise on blue whales (Balaenoptera musculus) is under way in Skjálfandi Bay, Iceland, using acoustic tags, PAM and drones (Magnus Wahlberg pers. com.). This illustrates that the studies of effects of noise are constantly in progress, and the continuation of such studies will provide more and more pieces of the puzzle.

9 Conclusion

Masking and behavioural changes seem the two most likely immediate effects of shipping noise. There is a significant overlap between the frequencies produced by the different ship types, and the range of hearing and underwater communication sounds for all the marine mammal species considered here. Masking of communication signals could result in reduced communication ranges for the individual species making it harder to e.g. find a mate, and the overlap in shipping noise and hearing range increases the likelihood of potential impacts of noise on animal behaviour, stress hormone levels etc.

The effect of shipping noise on stress hormone levels may be a serious issue, but the lack of knowledge in this field prevents the prediction of the scale and fitness cost of such an effect.

Assuming that detection thresholds of narwhals and bearded seals are comparable to those of beluga whales and ringed seals, respectively, the rough estimates of maximum detection ranges presented above indicate that effects of shipping noise can occur at ranges of many kilometres. Detection ranges for bowhead whales cannot be calculated at this point, as there is not yet information available on their hearing thresholds. However information on behavioural changes and noticeable reactions to masking noise indicates that they can also be affected at distances of several kilometres. More precise estimates of detection ranges require measurements of several different parameters, such as background noise levels, and transmission loss, and more detailed information on hearing thresholds etc. of the focal marine mammal species and areas, and such measurements should be conducted and used in detailed modelling in the case of an environmental impact assessment.

Central Baffin Bay, Disko Bay and Store Hellefiske Banke are identified as areas in Baffin Bay and Davis Strait at particularly at risk of being affected the proposed shipping route. Central Baffin Bay is an important wintering and foraging ground for narwhals, and Disko Bay and Hellefiske Banke are important winter/spring foraging grounds for beluga whales, narwhals, bowhead whales and bearded seals, whelping grounds for bearded seals, and possible mating grounds for bowhead whales. Affecting these areas could thus potentially affect a large number of individuals, at sensitive times for the species. The shipping route also cuts across or directly follows spring and fall migration routes for beluga whales, narwhals and bowhead whales going between Melville and Inglefield Bay, the North Water and Baffin Island. This could potentially have negative consequences, such as icebreakers creating “dead end“ leads in the ice that animals might accidentally follow.

There are several possible ways to mitigate the potential negative impacts of shipping noise, but avoiding sensitive areas at sensitive times, seems to be one fruitful way to ensure a sustainable use of Baffin Bay.

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