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POLAR BEARS (*URSUS MARITIMUS*) IN THE BARENTS SEA AREA:

Population biology and linkages to sea ice change, human disturbance and pollution

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Polar bears (*Ursus maritimus*) in the Barents Sea area:

Population biology and linkages to sea ice change,

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2. Summary

Polar bears in the Barents Sea population have been protected from hunting in Russia since 1956 and following the signing of the international Polar Bear Agreement in 1973 in Norway. This thesis seeks to summarise current knowledge on key population biology issues four decades after the Norwegian protection and almost six after the Russian. Further, it discusses threats that have developed in the decades following protection against human harvesting. It concludes with a discussion of the effect of multiple stressors on the population, and some thoughts on future research, monitoring and management.

Polar bears in Svalbard and the Barents Sea area have been studied during the last 40 years with the aim of gaining knowledge regarding population biology and to evaluate potential sources of impact on the population from anthropogenic activity and changes to their habitat. The initial threat to polar bears in the region was unquestionably overharvest. Polar bear numbers were reduced quite drastically and hunting was clearly not sustainable. After the harvesting was stopped, the population grew in size to an estimated 2650 (1900-3600) in 2004. We believe that population recovery led to a wider distribution of maternity denning in the Svalbard Archipelago, compared to the period just after the protection of the population in 1973. However, during recent decades, the population has faced challenges from a variety of new anthropogenic impacts. The population has been exposed to a range of pollutants and an increasing level of human presence and activity within their range. Contaminants are bioaccumulated through the trophic levels in the marine food web, culminating in this top predator that consumes primarily ringed, bearded and harp seals. Females with small cubs use the land-fast sea ice for hunting, and are vulnerable to human disturbance. Changes in sea ice conditions also affect polar bears in the region, and reduced access to denning areas on the eastern islands of Svalbard is currently a concern. A decrease in spring land-fast ice close to important denning areas could negatively affect the survival of cubs.

Research and monitoring provides advice to management bodies both locally and globally. Information on the presence of toxic compounds in High Arctic systems has resulted in progress in recent decades in having better control of harmful substances and in some cases international bans on their production and use. This has resulted in declining contaminant burdens in polar bears. Unfortunately, new harmful substances are finding their way to the Arctic,

while others, such as radionuclides, are stored locally (within Russian Territories) in large quantities, representing potential sources of pollution. The protection of important habitats locally with restrictions on motorized traffic may help reduce negative impacts from human activity on polar bears in the region. The fate of polar bears with regard to climate change is uncertain, but significant negative effects have been documented and these impacts are expected to increase in the coming decades. Relevant research and monitoring of polar bears is essential for future management of the species. The arctic environment should be managed in such a way that the combined effects of stressors on polar bear populations are minimized.

3. List of papers included in the thesis

Paper 1. Aars J, Marques T A, Buckland ST, **Andersen M**, Belikov S, Boltunov A, Wiig Ø. 2009. Estimating the Barents Sea polar bear subpopulation size. Marine Mammal Science, 25: 35-52

Paper 2. **Andersen M**, Derocher AE, Wiig Ø, Aars J. 2008. Movements of two Svalbard polar bears recorded using geographical positioning system satellite transmitters. Polar Biology, 31: 501-507

Paper 3. Freitas C, Kovacs KM, **Andersen M**, Aars J, Sandven S, Mauritzen M, Pavlova O, Lydersen C. 2012. Importance of fast ice and glacier fronts for female polar bears and their cubs during spring in Svalbard, Norway. Marine Ecology Progress Series, 447: 289-304

Paper 4. **Andersen M**, Derocher AE, Wiig Ø, Aars J. 2012. Polar bear (*Ursus maritimus*) maternity den distribution in Svalbard, Norway Polar Biology, 35: 499-508

Paper 5. Derocher AE, **Andersen M**, Wiig Ø, Aars J, Hansen E, Biuw M. 2011. Sea ice and polar bear den ecology at Hopen Island, Svalbard. Marine Ecology Progress Series, 441: 273-279

Paper 6. **Andersen M** and Aars J. 2008. Short-term behavioural responses of polar bears to disturbance by snowmobiles. Polar Biology, 31: 501-507

Paper 7. Derocher AE, Wiig Ø, **Andersen M.** 2002. Diet composition of polar bears in Svalbard and the western Barents Sea. Polar Biology, 25: 448-452

Paper 8. **Andersen M**, Lie E, Derocher AE, Belikov SE, Bernhoft A, Boltunov AN, Garner GW, Skaare JU, Wiig Ø. 2001. Geographic variation of PCB congeners in polar bears (*Ursus maritimus*), from Svalbard to the Chukchi Sea. Polar Biology, 24: 231-238

Paper 9. **Andersen M**, Gwynn JP, Dowdall M, Lydersen C, Kovacs KM. 2006. Radiocaesium in marine mammals from Svalbard, the Barents Sea and the North Greenland Sea. The Science of the Total Environment, 363: 87-94

4. Introduction

The polar bear (*Ursus maritimus*) is a large, charismatic mammal that represents both an important mythical symbol and a subsistence resource for local peoples of the Arctic, as well as being a “flagship” species in modern nature conservation. It is currently a highly political species that is iconic in the context of climate change. Polar bear science has a history that involves extensive international cooperation regarding both research and management, which has taken place over a period of about 50 years (Larsen and Stirling 2009).

Polar bears are widely distributed across the circumpolar Arctic, including regions of drifting sea ice. The world population size is suggested to be 20,000 – 25,000 animals, contained within 19 sub-populations (Obbard et al. 2010). Polar bears are specialised predators that mainly feed on seals and other marine mammals (Stirling and Archibald 1977; Smith 1980), and because of their close association with the ocean they are characterised as marine mammals. Polar bears not only rely on sea ice to get access to their prey, but also as a substrate facilitating travel between hunting and denning habitats. Polar bears hunt primarily on sea ice, but they utilize land for denning throughout most of their range. Further, sea ice characteristics are important for reproduction in most polar bear populations, because males search the sea ice in spring to locate mates (Molnar et al. 2008).

Polar bears are highly mobile and individuals can roam over large areas. However, significant variations in movement behaviours have been documented even within populations with home ranges varying from less than 200 square kilometres to almost 400 000 square kilometres in the Barents Sea region (Mauritzen et al. 2001). In Svalbard some bears move over the entire Barents Sea during their annual seasonal movements while others remain local within the Svalbard Archipelago (Wiig 1995; Mauritzen et al. 2001). Polar bears are generally found in low densities throughout the Arctic, but can also concentrate close to or on land during parts of the year, either during maternity denning in winter (for example Kong Karls Land, Norway) (Larsen 1986) or during summer and autumn when they are stranded until the sea ice freezes (for example Hudson Bay, Canada) (Derocher and Stirling 1990).

Odd Lønø started to study the ecology of polar bears in Norway in an organised way in 1964. His early work was summarized in “The polar bear (*Ursus maritimus*, Phipps) in the Svalbard area”, published in 1970. This publication was the first to describe the population biology of polar bears in the archipelago. The issue of hunting and human impacts on the bears was also thoroughly addressed. Lønø (1970) collected and analysed all available data on polar bear hunting in Svalbard up to a few years before protection of the population was enacted. His work documented the very high take of polar bears in this region from about 1870 to 1970. Between 100 and 900 bears were shot annually in northern Greenland and the Barents Sea region during this period. The hunt was controlled only to a limited degree, and it soon became apparent that the population was in danger of being extirpated if the harvest was allowed to continue (Anon 1965). The same situation was seen in other Arctic regions, and consequently international action to protect polar bears was initiated (Prestrud and Stirling 1994). In the late 1960s and early 1970s polar bears became an animal of political interest, and as more scientific data became available, it became clear that immediate action was needed if polar bear populations throughout the Arctic were going to be conserved (Anon 1965).

Initiatives among the polar bear nations, which at that time were Canada, Denmark (now Greenland), Norway, the Soviet Union (now Russia), and the USA, which were facilitated by the IUCN, resulted in the signing of ”The Agreement on the conservation of polar bears” (hereafter called “the Agreement”) in 1973 (http://pbsg.npolar.no/en/agreements/agreement1973.html). Article II in the Agreement states that “each Contracting Party shall take appropriate action to protect the ecosystems of which polar bears are a part, with special attention to habitat components such as denning and feeding sites and migration patterns, and shall manage polar bear populations in accordance with sound conservation practices based on the best available scientific data”. Further, Article VII states that, to achieve this goal: “the Contracting Parties shall conduct national research programmes on polar bears, particularly research relating to the conservation and management of the species. They shall as appropriate co-ordinate such research with research carried out by other Parties, consult with other Parties on the management of migrating polar bear populations, and exchange information on research and management programmes, research results and data on bears taken”. This Agreement has subsequently spawned management actions and monitoring activities with the aim to secure the well-being of the world’s polar bears.

During the period between the first meeting among polar bear nations in 1965 and the signing of the Agreement, the scientific “branch” of the negotiating parties established the IUCN/Species Survival Commission (SSC) Polar Bear Specialist Group (PBSG). The work of the PBSG was important in the process leading to the Agreement. It provided the necessary scientific data. The Parties to the Agreement have not met between 1981 and 2009, but the PBSG has managed the Agreement and guided national authorities in their management of polar bears, and since 2009 they have been acting as an independent advisor to the Parties of the Agreement. Polar bears have now been included in The Bern Convention and the Washington Convention (CITES). In Norway, the Svalbard Environmental Protection Act (http://www.regjeringen.no/en/doc/ Laws/Acts/Svalbard-Environmental-Protection-ct.html?id=173945) defines how management of the environment in Svalbard shall be conducted, and several regulations are in place to protect polar bears and their habitat. The Norwegian Ministry of the Environment, who is responsible for nature conservation and management in Norway, has ambitious goals for the management of Svalbard and its wildlife, and the polar bear is a key species. Status of polar bears and population threats are therefore specifically dealt with in the Management Plan for Lofoten and the Barents Sea (Anon. 2010), which was presented to the Norwegian Parliament in March 2006, and revised in 2010.

The first IPCC report to mention the consequences of climate change for sea ice cover in the Arctic was the Third Assessment, which was published in 2001 (IPCC 2001). Based on this report the IUCN asked the PBSG for a new evaluation of the international Red List status of polar bears, leading to a classification change from Near Threatened to Vulnerable in 2006. As part of the work with the national evaluation in the USA, under the Endangered Species Act, US Fish and Wildlife Service called for a meeting in 2007. Polar bear authorities from all polar bear nations (Range States) were invited, with an aim to exchange information about polar bear research and management and to discuss status of populations and measures to conserve the species. It was agreed that a meeting of the parties to the Polar Bear Agreement of 1973 should be held biannually. During the meetings in 2009 and 2011 the main goal was to develop a range-wide Action Plan for polar bears, and this work is still ongoing; it will be finalized at the next meeting in Russia in 2013 (www.polarbearmeeting.org).

The above mentioned initiatives came as a response to concerns that had been raised about climate change effects on polar bears. Global warming (Comiso 2002; IPCC 2007; Comiso et al. 2008) is believed to represent a threat to polar bear populations throughout their range due to the declining area, connectivity (Sahanatien and Derocher 2012), and suitability of sea ice habitats for bears (Stirling and Derocher 1993; Derocher et al. 2004; Amstrup et al. 2008; Wiig et al. 2008; Durner et al. 2009; Molnar et al. 2010, 2011). The decrease in available habitat for polar bears and their main prey (ringed seals) may lead to reduction in population sizes and possibly to complete loss of some populations (Amstrup et al. 2008, 2010; Durner et al. 2009; Molnar et al.

2010). The Barents Sea population has been identified as one of the populations where predicted reductions in sea ice in coming decades are particularly severe (Durner et al. 2009).

In 2010, an initiative was taken under the auspices of the Arctic Council working group Conservation of Arctic Flora and Fauna (CAFF) to develop a circumpolar monitoring plan for polar bears. A background paper was presented at the CAFF biennial meeting in February 2011 (Vongraven and Peacock 2011), and a circumpolar monitoring framework has been developed (Vongraven et al. in 2012). This framework identifies several threats and stressors on polar bear populations, identifies recommended monitoring parameters, knowledge gaps and suggestions on how to fill these gaps and improve monitoring. The conclusions are in agreement with threats previously identified for the Barents Sea population, in a plan designed to monitor Svalbard and Jan Mayen (MOSJ - Sander et al. 2005), but argue that a more comprehensive monitoring program is needed on a circumpolar level to coordinate monitoring activities, utilize monitoring capacities in a more efficient manner and facilitate monitoring that feeds into an adaptive management regime. The framework presented by Vongraven et al. (2012) uses the ecoregion classification concept, outlined in Amstrup et al. (2008). Polar bear populations throughout the Arctic are categorised according to the characteristics and predicted changes in the sea ice habitat (divergent, convergent, archipelago and seasonal sea ice). Vongraven et al. (2012) recommend that high intensity monitoring should be conducted in at least 6 of the 19 polar bear populations throughout the Arctic; the Barents Sea is one of the chosen areas. The Barents Sea population is chosen as a representative of a divergent sea ice ecoregion (Amstrup et al. 2008) because baseline data is available, there is a high risk of climate change effects and high pollution levels are well documented.

The first polar bear was live-captured and tagged as part of the Norwegian polar bear research program in 1966 (Larsen 1967; 1970), initiating a new era in polar bear research and management in the region. In the years following, a range of population studies were conducted (e.g. Harington 1965; Lentfer 1969; Jonkel 1970; Larsen 1972). In 1975 concern was raised for the first time regarding high levels of pollutants found in polar bear tissues (Bowes and Jonkel 1975). The contaminant issue continues to be a significant threat to polar bear health (Obbard et al. 2010; Sonne 2010) and recent findings of effects on immune responses and metabolism highlights the complexity of this issue (Lie et al. 2004; Braathen et al. 2004; Lie et al. 2005; Villanger et al. 2011). Today, several polar bear monitoring programs take place because polar bears are seen as indicators of the environmental condition of the Arctic and because of international obligations (Monitoring of Svalbard and Jan Mayen (MOSJ) (Sander et al. 2005), Arctic Monitoring and Assessment Program (AMAP) (AMAP 2009), Conservation of Arctic Flora and Fauna (Vongraven and Peacock 2011; Vongraven et al. 2012)).

Since the time of protection of polar bears in Svalbard, the Norwegian Polar Institute has been responsible for the polar bear research and monitoring programme in Norway. The main aim of the programme has been to develop relevant knowledge needed by management authorities. As new questions have appeared, the program has adapted to answer these questions, while also maintaining a long-term perspective. The main focus of the NPI programme was initially to study the effect of hunting, but later pollution, anthropogenic development and tourism, and most recently climate change, have been major issues given address.

Our understanding of the importance of distributional changes and abundance dynamics in relation to sea ice changes affiliated with climate change are growing with respect to polar bears. It is believed that polar bears worldwide will face significant challenges in the years ahead (e.g. Amstrup et al. 2008, 2010; Durner et al. 2009; Stirling and Derocher 2012). Further, questions of the combined effects of different stressors (e.g. climate change, pollution, harvest, human activity and disturbance) acting simultaneously have been raised (Jenssen 2006; UNEP/AMAP 2011; Dietz et al. 2013), and this issue will undoubtedly be given significant research attention in the future. It is thus more important than ever to study polar bear ecology with the aim of reducing negative human impacts on populations.

5. Objectives

This thesis presents nine peer-reviewed papers published from 2000 until 2012, stemming from the NPI Polar Bear Research Program. The papers herein are based on various data collected during the period from 1972 to 2011.

5.1. Overall objective

The main objective of the thesis is to describe key aspects of polar bear population biology in Svalbard and the broader Barents Sea Region, after hunting stopped in 1973, and to explore potential impacts of new threats such as sea ice change, human disturbance and pollution. The findings are discussed in relation to future management and monitoring of polar bears.

5.2. The specific objectives of the thesis are to:

1. Estimate the population size of polar bears in the Svalbard and Barents Sea area, to evaluate the current status of the population and provide a reference point for future monitoring. (Paper 1).
2. Study activity and habitat use of female polar bears in Svalbard, with the aim to describe movement behaviour, identify critical habitat and evaluate the effects of sea ice reduction on the population (Papers 2, 3 and 5).
3. Describe denning distribution and analyse the effect of sea ice reductions on denning (Papers 4 and 5).
4. Study behavioural responses of polar bears to the main type of motorized traffic (snowmobiles) in Svalbard, in the fast ice habitat (Paper 6).
5. Describe predator prey relationships in the population, through studying the diet of polar bears in Svalbard, and evaluate the numerical and energetic importance of different prey species (Paper 7).
6. Analyse tissues from polar bears from the Svalbard and adjacent populations to determine levels of anthropogenic contaminants (persistent organic and radionuclide pollutants) (Papers 8 and 9).

6. Results and discussion

6.1. Population biology and linkages to threats

6.1.1. A population estimate for the Svalbard and Barents Sea polar bears; how has the population developed during the last 40 years?

The Barents Sea polar bear population is shared between Norway and Russia (Mauritzen et al. 2002), and has been protected against hunting since 1956 in Russia and 1973 in Norway (Prestrud and Stirling 1994). Larsen (1986) suggested that there were between 3000 and 6700 polar bears (depending on the population borders) in the Barents Sea in the beginning of the 1980s. This was based on data from multiple sources including den counts and spatially restricted non-random aerial surveys, which were extrapolated to larger areas. No study covering the whole area in question was available prior to the survey conducted in 2004 (Aars et al. 2009, hereafter Paper 1). Most population estimates for polar bears have been derived using capture-recapture methods (e.g., DeMaster et al. 1980; Taylor et al. 2005). But, obtaining sufficiently large sample sizes is time consuming and expensive (Wiig and Derocher 1999), but on the other hand the method yields valuable data on individuals for a range of other population ecology studies. Recent statistical developments have made distance sampling one of the most widely used methods for estimating animal abundance in the last decade (Buckland et al. 2004), and is today regarded as being more cost efficient than capture-recapture to achieve high levels of precision (Borchers et al. 2002), in particular for populations occurring at low densities over large areas, such as the Barents Sea polar bear population.

Our study concluded that the Barents Sea population had approximately 2,650 (95% CI approximately 1,900–3,600) bears in August 2004. We found significant geographic variability in densities of bears across different types of habitats in the study area. The density of bears on land-fast ice and pack ice in the Russian areas to the east were much higher (> 2 bears/100 km^2) than farther west in the Norwegian territories (0.4 - 1 bears/100 km^2). The mean density of polar bears across the whole region was however, close to the densities described elsewhere in the Arctic (Taylor and Lee 1995; Evans et al. 2003). Polar bear spatial patterns are known to vary with both season and year. Individual polar bears in the Barents Sea show high seasonal fidelity to specific areas (Mauritzen et al. 2001). Many of the polar bears that are distributed around the islands of Svalbard in spring, are distributed along the ice edge further north-east in the Russian area and around Franz Josef Land in August. During our survey there were three times as many bears in the Russian parts of the northern Barents Sea compared to the Norwegian area. Both the number of maternity dens (Larsen 1986; Andersen et al. 2012, hereafter Paper 4) and the relatively high number of recaptures of bears in the Svalbard area (Derocher 2005) indicate that more polar bears are present in the Svalbard area in spring compared to other times of the year. This is partly explained by the need for pregnant females to find suitable denning habitat on land and raise cubs in a stable ice habitat in spring. Bears may also be attracted by the generally good breeding habitat for ringed (*Phoca hispida*) and bearded seals (*Erignathus barbatus*) in Svalbard fjords and the resulting good spring hunting habitat for the polar bears, particularly on the east coast (see Freitas et al. 2012, hereafter Paper 3; Paper 4; Derocher et al. 2002, hereafter Paper 7).

Between 1909 and 1970 an average of 320 polar bears were harvested annually in Svalbard and adjacent areas (Lønø 1970). Assuming an even sex ratio in the harvest, the sustainable take of a closed polar bear population under optimal conditions is considered to be 3.2 % (Taylor et al. 1987). This implies that the Barents Sea population should have numbered some 10,000+ polar bears to have sustained the recorded harvest. The harvest obviously was not sustainable, but the calculation still indicates that the historical population size must have been significantly higher than the current size. The large difference between this number and the upper confidence limit (3,600) of our estimate in 2004, after 40 years of protection is noteworthy. Larsen (1986) indicated that the population approximately doubled in size over a decade after protection in 1973, and suggested that there were close to 2,000 bears in the Svalbard area, and 3,000– 6,700 in the area between East Greenland and Franz Josef Land in 1980. The growth rate from then and up to 2004 is unknown. Changes in population age structure suggest that population growth has been positive, but also that the growth rate today is much lower than earlier (Derocher 2005). One possible explanation for the large difference in the estimated size in 2004 and the theoretical historical size (10,000) could be a significant immigration from less hunted neighbouring areas. However, the discrepancy between our recent estimate and the historical harvest levels are so significant that it is not likely that migration alone can explain the difference. We speculate that either the population size today is far from the carrying capacity of the region, or the carrying capacity has changed. Derocher et al. (2003) and Derocher (2005) suggested that the population recovery may have been slow after protection due to high levels of organic pollutants (see for example Andersen et al. 2001, hereafter Paper 8) in polar bears in the area, having a negative effect on survival and reproductive rates (Derocher 2005). The time needed for the population to recover to its carrying capacity could therefore be longer than expected from demographic rates typical for other, less polluted, populations. The carrying capacity in the area may also have decreased during the last few decades and may continue to decrease in the future as a response to sea ice loss (Derocher 2005; Schliebe et al. 2006; Heggberget et al. 2006; Durner et al. 2009).

6.1.2. Movements and habitat use by polar bears, and their vulnerability to sea ice change

Polar bears depend on sea ice as a platform for hunting ice-associated seals (Stirling and Archibald 1977; Smith 1980; Thiemann et al. 2008; Paper 7). Sea ice is also a platform for mating and travelling to and from terrestrial maternity denning areas (see Wiig et al. 2008; Derocher et al. 2011, hereafter Paper 5). Evidence of declines in polar bear body condition, reproductive success, survival and abundance have been documented in the Canadian Arctic and Beaufort Sea in Alaska, and are thought to be caused by nutritional limitations imposed by declining sea ice (Stirling et al. 1999; Regehr et al. 2007; Regehr et al. 2010; Rode et al. 2010; Stirling and Derocher 2012). It is essential to describe polar bear habitat use and identify especially important habitats to be able to make predictions regarding the future impacts of climate change. It is believed that polar bear habitat in Svalbard and the Barents Sea will be significantly reduced during the coming decades, and it has been suggested that the population will decrease as a consequence (Amstrup et al. 2008, 2010; Durner et al. 2009).

The use of satellite telemetry in the study of polar bear movement and distribution was first applied between Svalbard, Norway and Greenland in 1979, when four polar bears were equipped with satellite transmitters (IUCN/SSC 1981; Larsen et al. 1983). One of the latest technological developments for studies of wildlife has been to use the Global Positioning System (GPS) to determine the location of animals (e.g., Johnson et al. 2002; Gau et al. 2004; Frair et al. 2004; Morales et al. 2004), and to use the Argos System to collect these data from the transmitters remotely (e.g., Yasuda and Arai 2005; Parks et al. 2006).

Andersen et al. (2008) (hereafter Paper 2) was the first study that deployed GPS collars on polar bears, and also the first to investigate the effectiveness of GPS satellite collars in polar bear studies. The location data generated in this project described activity and movement patterns of individuals in far more detail than previously reported in the polar bear literature (e.g., Messier et al. 1992; Wiig 1995; Amstrup et al. 2000; Mauritzen et al. 2001; Wiig et al. 2003). The data also described in great detail the behaviour of the animals, including data on diurnal activity patterns. Stirling (1974) described the behaviour of polar bears on the sea ice at Devon Island, Canada, through direct observations. He found that polar bears spent 66.6% of their time inactive (sleeping, lying and still-hunting). He related the activity patterns to the haul out behaviour of ringed seals, the main prey of polar bears. We found no diurnal activity pattern during summer when the bears were on sea ice. We did, however, find low activity (relative to other times of the day) late in the day when bears were stranded on land in summer and during long range directional movements northward on the pack ice in late summer. Both in winter and autumn the pattern was opposite, with higher activity late in the day compared to early in the day.

Messier et al. (1992) studied the seasonal activity patterns of female polar bears in the Canadian Arctic. They found clear seasonal patterns with peak activity periods in May-July for all females, regardless of reproductive status, and concluded that there was a close link between activity and the behaviour of ringed seals. Females with cubs-of-the-year (COYs) had decreasing activity from June to November, low activity until March, and then increasing activity until June. In Paper 2, the bear that was accompanied by two COYs showed a pattern similar to that decribed by Messier et al. (1992).

The movement rates we reported (Paper 2: maximum 4.6 km/h during a 4 hour period) are at the high end of those previously reported for polar bears (between 5.3 and 18.2 km/day)(Garner et al. 1990; Born et al. 1997; Ferguson et al. 2001; Wiig et al. 2003). Movement rates were affected by changes in the number of positions included in calculations of the paths, a pattern also discussed by others (Amstrup et al. 2001; Parks et al. 2006). We showed that low sampling frequency significantly underestimated actual movement rates, and home range estimates that were 30% smaller than those calculated using GPS data with a higher sampling frequency (lower step length). As the number of locations increased (step length decreased), home range estimates moved towards an asymptote; these findings are similar to those of Girard et al. (2002). Thus, in Paper 2, we showed how GPS collars are useful for studies of fine-scale habitat use, movement behaviour, energetics and activity patterns. For large scale studies, such as distribution and annual home range size, conventional Argos positioning collars may be suitable if the position collection frequency is sufficiently high.

The GPS collar technology gave us the opportunity to further explore polar bear habitat use on a fine scale (Paper 3). Previous studies have shown that polar bear distribution is significantly affected by sea ice concentration and sea ice type. Polar bears typically select ice concentrations ranging from 25 to 100%, depending on the season and the region (Stirling et al. 1993; Arthur et al. 1996; Ferguson et al. 2000a; Ferguson et al. 2001; Mauritzen et al. 2003; Durner et al. 2009). In the Canadian Arctic, females with COYs select landfast ice with pressure ridges during the spring, while lone adult females and males show strong preferences for ice-edge areas (Stirling et al. 1993). Females with COYs were thought to select landfast ice habitats to feed on ringed seal pups, and also to avoid adult males, that are rare in this habitat; male bears sometimes prey on cubs (Stirling et al. 1993). In Svalbard and the Barents Sea area, female polar bears with COYs also show a year-round tendency to be located on more solid ice than lone adult females (Mauritzen et al. 2003).

In Paper 3 we found that female polar bears with COYs predominantly occupied inshore landfast ice areas during spring (April), and within this habitat they spent most time close to glacier fronts. In an aerial-survey study in the Canadian Arctic, Stirling et al. (1993) also reported that females with COYs showed a strong preference for landfast ice during spring. However, in Svalbard they concentrated their time in landfast ice close to glacier fronts while in the Canadian Arctic they selected fast-ice with snow drifts along pressure ridges, which were sometimes located far offshore. These preferred areas, in the respective locations, are linked to ringed seal pupping habitat. Ringed seals give birth during spring inside lairs that are constructed in snow that accumulates in stable sea-ice areas (Smith and Stirling 1975; Kingsley et al. 1985; Furgal et al. 1996). Nutritionally stressed polar bear females with COYs need a predictable food source when emerging from the maternity dens in spring and hence these ringed seal pupping areas are a vital resource. In such areas, the female bears hunt the ringed seal pups and sometimes their mothers (Stirling and McEwan 1975; Pilford et al. 2012; C. Lydersen, personal communication) without having to move long distances. Accordingly, most females with COYs in the present study spent their entire tracking period/spring in the landfast ice habitats, close to known denning areas (Paper 4).

Ringed seals occur in high densities in landfast ice areas (Krafft et al. 2007) during April and bearded seals and harp seals (*Pagophilus groenlandicus*) also occur in the pack ice close to shore around Svalbard during spring (Haug et al. 1994; Isaksen and Wiig 1995) All of these species have been recorded in the diet of polar bears from this area (Lønø 1970; Paper 7). Even if seal density is lower in the pack-ice, bearded and harp seals are larger prey and thus represent a larger energy package for polar bears than ringed seals. It is possible that female polar bears in Svalbard face a trade-off between being in landfast ice areas that provide a safe substrate (habitat), especially for cubs, and where prey items are predictable but small, and being in less stable drift ice where prey items are more unpredictable but also more profitable when they are captured.

Paper 3 clearly emphasizes the importance of coastal fast-ice, in particular close to glacier fronts, for polar bear females with young cubs in Svalbard. Reductions in the extent of landfast ice have been observed in recent years in Svalbard (Haarpainter et al. 2001; Gerland and Hall 2006; Gerland et al. 2007; Høyland 2009). Glacier fronts that have contact with the ocean have also retreated in Svalbard in recent years (Blaszczyk et al. 2009). The eventual disappearance of these prey-rich and stable sea-ice habitats close to the preferred denning habitat, where polar bear with COYs concentrate during spring, is likely to alter present distribution and hunting patterns and also reduce the survival of cubs.

6.1.3. Maternity den distribution and the effect of sea ice reduction on denning behaviour

The use of maternity dens in snow is a characteristic adaptation in polar bears to the harsh Arctic environment (Blix and Lentfer 1979). Polar bears typically den at low densities throughout the circumpolar Arctic, but concentrated denning areas exist at Wrangel Island, Russia (Belikov 1980), Kong Karls Land, Svalbard, Norway (Larsen 1985), and SW Hudson Bay, Canada (Jonkel et al. 1972). Most maternity dens are located on land, although a small amount of denning does occur in multiyear sea ice off the Alaskan coast (Harington 1968; Lentfer 1975; Amstrup and Gardner 1994; Fischbach et al. 2007). In Hudson Bay, polar bears den in earth dens that are sometimes far inland, up to 80 km from the coast but they move into snow dens as snow accumulates in autumn (Jonkel et al. 1972; Richardson et al. 2005). Denning philopatry among female polar bears has been shown in Hudson Bay (Ramsay and Stirling 1990), in Svalbard (Zeyl et al. 2010) and the Beaufort Sea (Amstrup and Gardner 1994).

In Paper 4, we found that most maternity dens in Svalbard are close to the coast (< 10 km). Denning occurs in most parts of the Svalbard Archipelago, but the number of dens seems to be highest in the eastern parts of the Archipelago. The six most important denning areas are: 1) north-western Spitsbergen, 2) southern Spitsbergen, 3) northern parts of Nordaustlandet, 4) Barentsøya and Edgeøya, 5) Kong Karls Land and 6) Hopen. Our data revealed that polar bears captured in the Svalbard or in the central parts of the Barents Sea also den in the Franz Josef Land Archipelago in Russia, as noted by Wiig (1998).

Lønø (1970) suggested that denning in Svalbard was restricted to the eastern parts, including Kong Karls Land, Nordaustlandet, and along the northern part of the east coast of Spitsbergen. Larsen (1985) concluded that Kong Karls Land was the main denning area and that 90% of all dens in the Archipelago were on the islands Edgeøya, Barentsøya, Nordaustlandet and Kong Karls Land. The small island Hopen was not considered an important denning site by Lønø (1970) or Larsen (1985), because only a few observations of dens or females with COYs had been made there. Based on these earlier findings (Lønø 1970; Larsen 1985), we believe that denning distribution in Svalbard is currently wider than it was in the decades before protection from hunting in 1973. We suggest that this apparent expansion is a result of reestablishment of denning areas after a long period of harvest. Fidelity to denning areas by female polar bears (Ramsay and Stirling 1990; Zeyl et al. 2010) might have delayed re-establishment associated with the population recovery.

Factors determining the distribution of polar bear dens are poorly understood but in Svalbard some areas can only be used for denning if sea ice in autumn reaches them, making them accessible (Paper 5). The linkage between denning and sea ice conditions has also been described by others (Ferguson et al. 2000b). Early snow cover is also necessary in most areas, and the terrain is important for snow accumulation. In the Beaufort Sea, about half of the dens were on drifting pack ice, half on land, and some few on landfast ice (Amstrup and Gardner 1994). There has been no evidence of offshore denning in Svalbard (Lønø 1970; Larsen 1986), and the highly dynamic sea ice conditions in the region may explain why this behavior is not seen. Our study indicates that most denning areas in Svalbard are close to fast ice areas where ringed seals give birth to their pups. This agrees well with the findings in Paper 3, that in April females with COYs use landfast ice areas and single females or females with older cubs use other habitat types more frequently.

Human activities can influence polar bear denning distribution (Lentfer and Hensel 1980; Stirling and Andriashek 1992; Amstrup 1993). Svalbard has a long history of polar bear harvest

(Larsen 1986). A substantial part of the harvest occurred with the use of set-guns (a baited gun, typically built into a wooden box, which the bear fires when taking the bait) onshore, and females emerging from dens with COYs were particularly vulnerable (Lønø 1970). Set-guns were widely used and were very effective, but also non-selective. Larsen (1985) argued that denning in the Edgeøya region had been heavily affected by more than 70 years of hunting, and that only after 10 years of protection, in the early 1980s, the area was again used frequently for denning. The same could be the case for both Hornsund in the south and the fjords in the north of Spitsbergen, because both of these areas also experienced high hunting pressure during the decades before protection in 1973.

Both trappers and station personnel hunted bears on Hopen from the early 1900s onwards (Lønø 1970). During the early to mid-1900s only two dens were recorded on Hopen (Lønø 1970). The reason for the larger number of dens on Hopen during the years 1995 to 2008 (Paper 5) compared to the earlier period when sea ice was likely more suitable for denning, is unknown, but it may be related to the difference in the number of adult females in the population. Between 1945 and 1970, an average of 41 bears per year were harvested at Hopen (total reported harvest on Hopen was 951 bears from 1946 to 1968; Lønø 1970). The population was thought to have been depleted before hunting ended in 1973 (Larsen 1986; Prestrud and Stirling 1994) and protection allowed the population to recover over the next 30 years (Derocher 2005). The larger number of maternity dens we observed may be a result of the re-establishment of Hopen as a denning area as the population increased (Papers 1 and 5).

Papers 3 and 4 describe den distribution and female habitat use just after den emergence in spring, respectively. However, sea ice is also a critical habitat for female polar bears in autumn, when they prepare to enter their winter birthing dens (Paper 5). The dates of arrival and departure of sea ice near Hopen has varied substantially over time, reflecting its location near the southern edge of where sea ice exists in the Barents Sea (Shapiro et al. 2003). A trend towards later arrival of sea ice has been observed at Hopen, coinciding with a reduction in sea ice thickness observed over the last four decades (Gerland et al. 2008). The arrival of sea ice at Hopen in autumn shifted from late October to mid-December during the period from 1979-2010. In Paper 5, we show that fewer maternity dens were found on Hopen in years when sea ice arrived later in the autumn. If sea ice formed too late, no dens were found.

Further, later arrival of sea ice in autumn was correlated with lower body mass of adult females and their cubs at den emergence in the spring. This relationship suggests that recent environmental conditions have negatively affected female condition. Body mass is an indication of energy stores (Molnár et al. 2009) that are critical for supporting female polar bears during the denning period when energy is required for maternal maintenance, gestation and nursing until cubs can leave the den (Watts and Hansen 1987; Derocher et al. 1993; Molnár et al. 2011). Maternal body mass in spring has been correlated with body mass of cubs and with cub survival (Derocher and Stirling 1996, 1998). Our finding that cub mass was lower when the date of arrival of sea ice was later, suggests that the timing of arrival of pregnant females at den areas may impact reproductive success.

After leaving the den, young polar bear cubs are vulnerable to hypothermia if exposed to cold water (Blix and Lentfer 1979; Aars and Plumb 2010). In most years, it was evident that there was sufficient sea ice for females with young cubs to leave Hopen without having to cross open water. However, the suitability of a maternity denning area for raising cubs is determined in part by the timing of sea ice arrival, sea ice departure and sea ice type and stability (see Paper 3). There is reason to believe that the fast ice habitat has deteriorated around Hopen in recent years, an effect of the generally lower sea ice concentration and thickness in the area. The reproductive success of females that manage to den on Hopen could be negatively affected if the sea ice departs earlier in spring in the future.

Climate change is the most important conservation concern for polar bears due to the declining area, connectivity (Sahanatien and Derocher 2012), and suitability of sea ice habitats (Stirling and Derocher 1993; Derocher et al. 2004; Amstrup et al. 2008; Wiig et al. 2008; Durner et al. 2009; Molnar et al. 2010, 2011). The loss of one maternity denning area may not be a major cause for concern because females are able to den in other areas. However, the loss of habitat is symptomatic of larger ecosystem changes that cumulatively may threaten the persistence of polar bears (Hunter et al. 2010; Amstrup et al. 2010; Molnar et al. 2010, 2011). Further, the Hopen situation might reflect the situation at other important denning areas in Svalbard (Norwegian Polar Institute, unpublished data). Monitoring maternity denning areas at the margin of the polar bear range will be important to better understand how adult female polar bears, and ultimately the species, will respond as sea ice patterns change.

6.1.4. The effect of human disturbance of polar bears in the critical fast ice habitats

Although polar bears are not harvested in Norway at present, as they were prior to the signing of the Polar Bear Agreement (Prestrud and Stirling 1994), they are still vulnerable to human presence and impacts (Lunn et al. 2002). Recreational activities (e.g. tourism, camping trips) are the source of most polar bear–human encounters in the Svalbard area. Tourism and the local use of snowmobiles have increased in Svalbard over the last 40 years (Overrein 2002; MOSJ 2012 (http://mosj.npolar.no/en/influence/traffic/indicators/snowmobile)). A large part of the snowmobile driving in Svalbard occurs on landfast sea ice, due to the steep and mountainous terrain. On the ice, polar bears hunt ringed seals (Paper 7), and the stable fast ice habitat is particularly important for females with COYs (Paper 3). The sea ice is also a substrate for movement between hunting habitats and denning areas (Mauritzen 2002; Papers 3, 4 and 5).

Increasing anthropogenic activity in many Arctic regions made it important to have a more complete understanding of issues related to human disturbance of wildlife in the region. Studies of disturbance are rarely able to assess effects on survival or reproductive success or other effects at the population level. Population level studies would be extremely demanding both in terms of resources and effort, and we will therefore most likely have to depend on studies of effects on behaviour and physiological responses as indicators. Such studies can be valuable if the biology of the species is well understood and one can make plausible interpretations about how these responses link to demographic processes. Another limitation apparent in many disturbance studies is that the effect measured on an individual has a short duration. Cumulative population level effects are difficult to assess in most wild populations, and particularly in a long-lived and highly mobile species such as the polar bear.

Andersen and Aars (2008 - hereafter Paper 6) found that polar bears in Svalbard reacted to snowmobile disturbance at relatively long distances, although the variability between individuals was significant. Except for adult males, bears typically had a pronounced response and frequently fled from snowmobiles and continued to flee at long distances (up to 5 km). Females with COYs in particular showed strong reactions to this disturbance source.

Polar bears are highly mobile on large temporal and spatial scales, but when considering small scale movement behaviour within a limited period of time (such as within a fjord) polar bears can have restricted movements (Paper 2 and 3). Stirling (1974) described the behaviour of polar bears on the sea ice at Devon Island, Canada, through direct observations. He found that polar bears spent most of their time inactive. In Paper 6, we observed polar bears running at least one km after being disturbed by snowmobiles, and several bears left the ringed seal breathing hole where they were still-hunting when vehicles approached. We believe that repeated disturbance in this important fast ice habitat (Paper 3), leading to running and interrupted hunting could result in increased energetic stress on the animals, during a time when they are rebuilding energy stores that are critical for survival of cubs. Additionally, polar bears are not adapted to running quickly over extended distances, and large individuals in particular overheat quickly if pursued for very long (Øritsland 1970). Paper 6 demonstrates that females with cubs respond most strongly to snow-mobile disturbance, and the added stress experienced by the family group could have negative effects on reproductive success of females and perhaps even survival. Such stress could force polar bears to use sub-optimal habitats and spend more time in the water (polar bears tend to take refuge in water when startled). It could also lead to more frequently interrupted hunting situations or suckling/feeding bouts, which both could affect body condition and growth of both adults and cubs/COYs.

Tourism and associated disturbance is a potential stressor that can act on a local spatial scale during short periods of the year. Local planning and regulations could significantly reduce the negative effects of tourism if relevant and sufficient knowledge of polar bear ecology locally is available. In Svalbard regulations on snowmobile traffic in sensitive areas in spring have been implemented, giving the authorities the ability to limit traffic, and reduce disturbance of females with cubs that have just emerged from their dens.

6.1.5. Spring diet of polar bears in the Svalbard and Barents Sea area

Both movement patterns and choice of denning locations by polar bears can largely be explained by the accessibility of suitable prey. Polar bears are the most carnivorous of the ursids and are adapted to hunt seals on sea ice (Stirling and Archibald 1977; Smith 1980; Gjertz and Lydersen 1986; Stirling and Øritsland 1995). The diet of polar bears is still poorly understood in large parts of their range; little is known regarding the relative energetic contribution of prey species and the seasonal composition of prey.

The only previous study of polar bear diet in Svalbard comes from bears harvested throughout the year near Svalbard, and remains of 52 ringed seals, 10 bearded seals, and 6 harp seals that were found in their stomachs (Lønø 1970). Harp seals were only found during summer

(June-August) and most bearded seals (9/10) were found in the same period. These findings were similar to the composition of the 114 samples of known species in Paper 7 (76% ringed seal, 15% bearded seal, and 9% harp seal). Similar to earlier studies, ringed seals are the dominant prey of polar bears numerically. However, on a biomass basis, the results from Lønø (1970) together with our study suggest that the diet of polar bears in Svalbard and the western Barents Sea has a significant contribution from bearded seals, due to their large body size compared to ringed seals (Andersen et al. 1999). In the eastern Barents Sea, a Russian study reported 68% ringed seal, 22% walrus (*Odobenus rosmarus*) and other miscellaneous items in the diet of polar bears (Parovshchikov 1964), perhaps reflecting further geographic variation in the same population. Most information on polar bear diet from our areas is from spring, but Iversen (2011) reported findings based on scat samples from both spring and summer. Their study showed that polar bears in Svalbard feed on eggs, reindeer (*Rangifer tarandus platyrhynchus*) and vegetation in addition to seals. Reindeer predation by Svalbard polar bears was also documented by Derocher et al. (2000), and Hedberg et al. (2011) who found fatty acids in polar bear milk that indicated that they had fed on reindeer.

Distribution and abundance of marine mammal resources available to polar bears in Svalbard are only partially described. Bearded seals are widely distributed throughout Svalbard and the western Barents Sea (Benjaminsen 1973). The abundance of bearded seals is uncertain but may number a few hundred thousand in the North Atlantic (Burns 1981; Kovacs et al. 2009). The size of the ringed seal population in the Svalbard area is unknown but the global population likely numbers in the millions (Reeves 1998; Kovacs et al. 2009). In Svalbard and the western Barents Sea, ringed seals give birth in both landfast ice (Smith & Lydersen 1991) and in drifting pack ice (Wiig et al. 1999). Paper 3 showed that landfast ice is especially important for female polar bears with COYs, and explained this by the combination of a stable substrate and the high density of ringed seal breeding lairs in this habitat. The Barents Sea harp seal population is approximately 2.2 million animals (Nilssen et al. 2000) and represents a seasonally abundant food source for polar bears. However, harp seals do not usually reach polar bear habitat until April-May and then increase in abundance along the drift ice edge until October when they return south (Haug et al. 1994; Nordøy et al. 1998).

Annual home range size of adult female polar bears in Svalbard ranged from 185 to 373,539 km^2 (Mauritzen et al. 2001) and dietary differences were postulated to explain the different space use patterns (Mauritzen et al. 2001). In particular, Mauritzen et al. (2001) suggested that near-shore bears relied more on the landfast ice and preyed largely on ringed seals during spring, while pelagic bears preyed more on bearded and harp seals over a longer period. Paper 3 and Paper 7 support this suggestion, because ringed seal kills were most numerous in landfast ice areas in spring and bearded and harp seal kills were mainly found in pack ice areas in summer.

6.1.6. Levels of different pollutants in Svalbard polar bears; consequences of a polluted diet

The relevance of feeding in explaining levels of contaminants in wildlife is often discussed (see Paper 8 and Andersen et al. 2006, hereafter Paper 9). McKinney et al (2009) linked diet, sea ice changes and changes in contaminant levels in Hudson Bay polar bears. They documented how the change in diet, as a result of sea ice change and prey availability, increased the levels of several contaminants in bear tissue(s). Thus, prey composition is an important element in understanding the ecotoxicology of polar bears. If climate change alters the distribution and abundance of prey (Stirling and Derocher 1993), documentation of the current predation patterns is essential for understanding how exposure to environmental pollutants might vary as a result of climate change (McKinney et al. 2009).

A wide range of manmade environmental pollutants have been transported by air and ocean currents from southern industrialised areas to the Arctic during the last decades, among them organochlorines (OCs)(Oehme 1991; Barrie et al. 1992; De March et al. 1998). These compounds are highly lipophilic and persistent to biological degradation; they accumulate in the marine environment and biomagnify up food chains (Muir et al. 1988; Barrie et al. 1992). Arctic organisms are adapted to dealing with short periods of high production during which lipid energy stores are built, resulting in high dependence on fat at most trophic levels (Barrie et al. 1992). Polar bears have the capacity to metabolize several organic pollutants (Letcher et al. 2000), but the metabolites resulting from this process are believed to have an even more negative effect than the original compounds (Cheek et al. 1999; Marchesini et al. 2008; Gutleb et al. 2010).

PCBs were first identified in polar bears in the 1970s (Bowes and Jonkel 1975). Svalbard polar bears have shown PCB levels comparable to those found in ringed seals from the Baltic Sea, where reproductive disorders were reported (Norheim et al. 1992; Olsson et al. 1992;

Bernhoft et al. 1997). In polar bears at Svalbard, a possible immunotoxic effect (Bernhoft et al. 2000) and negative association between OCs and retinol and thyroid hormones have been reported (Skaare et al. 2000). Studies indicate that negative effects of organic pollutants on immune response and metabolism exist in polar bears (Lie et al. 2004, 2005; Braathen et al. 2004; Villanger et al. 2011). Contaminants in polar bears have been studied in most parts of the species range (Norstrom et al. 1998). However, limited data from most parts of the Russian Arctic have precluded an understanding of circumpolar PCB patterns.

Paper 8 demonstrated regional variation in PCB contamination in polar bear blood between the European, Russian and western North American Arctic regions. We found the PCB levels to be highest in the western part of the Russian Arctic, and that the relative contribution of the low chlorinated congeners increasing while the higher chlorinated congeners decrease from west to east. Further, the study showed that the proportion of the PCB congeners 118 and 156 were higher in the Chukchi Sea compared to Svalbard. These two congeners represent the most acutely toxic congeners in this study.

We believe that the variation observed in the study is due to different PCB exposure between the regions. Variation in PCB congener levels and patterns could be explained by regional prey differences. Polar bears are typically considered to be predators of ringed and bearded seals (Stirling and Archibald 1977; Smith 1980), which feeds on sympagic and benthic species (Gjertz and Lydersen 1986; Hjelset et al. 1999). However, in some populations, polar bears feed on pelagic feeding harp seals (Lønø 1970), and benthic feeding white whales (*Delphinapterus leucas*), narwhals (*Monodon monoceros*) (Lowry et al. 1987; Smith and Sjare 1990) and walruses (Calvert and Stirling 1990; Ovsyanikov 1995). It is known from satellite tracking of individuals, that polar bears in the Kara and Laptev seas spend considerable amounts of time in multiyear ice (Belikov et al. 1998). This is also the case for parts of the population in Svalbard and Franz Josef Land (Wiig 1995). If the structure of the ice-associated food web in these areas causes greater bioaccumulation of contaminants compared to other areas, this could result in higher levels of PCB in these polar bears.

Our findings are based on analyses of blood samples from polar bears captured in five different geographic regions. Our data are homogenous in that only samples from adult females were included. Further, all females were captured in spring. However, there are differences in age, body condition and reproductive status at capture. Females emerging from dens with young cubs are very lean (Derocher and Stirling 1998), while others who might have lost their cubs or have older cubs would have been feeding for a longer period before capture and may have been in better condition. Both long- and short-term differences in feeding history (and thus body condition) presumably influence the concentrations and patterns of organochlorines, and this can be a problem, particularly when considering blood sample analyses (Lydersen et al. 2002). In addition, females with offspring can shed PCBs through milk and this also complicates interpretation of the results of contaminant analyses (Bernhoft et al. 1997; Polischuk 1999; Bytingsvik et al. 2012). Movement behaviour further complicates the issue. For example, Olsen et al. (2003) explained differences in contaminant levels as a result of varying activity seen in small versus large home range sizes in Barents Sea polar bears.

As mentioned earlier, geographic variation in feeding habits may not only result in geographic variation in contaminant levels, it may also affect the relative patterns observed in the compounds. Since different species have a varying ability to metabolise contaminants in their food (Wolkers et al. 2004), the path these compounds travel up the food web will determine the pattern seen in the upper trophic levels.

Organic pollutants are typically lipophilic and are accumulated in fatty tissues. Other groups of contaminants, for example radionuclides, use other pathways, but nevertheless end up at higher levels in top predators. The tendency for Arctic marine food chains to be dependent on benthic and sea ice associated systems provides an efficient mechanism for biomagnification of contaminants, and in combination with the longevity of marine mammals this results in high uptake rates of radionuclides (e.g. Pentreath et al. 1982; Aarkrog et al. 1997; Brown et al. 1999; Carroll et al. 2002).

^{137}Cs makes its way into the Arctic marine environment via global fallout from atmospheric weapon testing, discharges from European reprocessing and power facilities and fallout from the Chernobyl accident in 1986. The monitoring of radioactivity in Arctic marine mammals is important for a number of reasons. Information on current levels of contamination is required for monitoring, for the understanding of impacts and behaviour of radionuclides in arctic ecosystems and in the evaluation of potential consequences of future contamination on specific species.

The low ^{137}Cs levels observed in the marine mammals studied in Paper 9 reflect the current low ^{137}Cs activity in sea water in the European Arctic, following the reduction in discharges from reprocessing facilities at Sellafield, UK in the mid-1970s. Recently reported ^{137}Cs activities in sea water from the study area ranged from 2.0 to 3.4 Bq/m^3, compared to peak values of 20 to 45 Bq/m^3 for the Svalbard area and Barents Sea in the 1980s (Hallstadius et al. 1982; Kershaw and Baxter 1995; Strand et al. 2002). A large number of potential local sources of radionuclide contamination are known in the region (e.g. nuclear reactor dump sites and radioactive waste, atmospheric nuclear bomb testing sites on Novaya Zemlya). It appears from our data in Paper 9 that these potential sources currently have little impact on marine mammals in the European Arctic.

A number of studies have shown that ^{137}Cs biomagnifies through marine food chains (e.g. Calmet et al. 1992; Kasamatsu and Ishikawa 1997; Watson et al. 1999; Heldal et al. 2003), but that this happens mostly at lower trophic levels (Brown et al. 2004). Paper 9 has shown that ^{137}Cs contamination of marine mammals in the European Arctic region is low at present. Comparison of concentration factors suggests that ^{137}Cs is biomagnified through marine food chains through to seal species, while the situation with regard to further trophic transfer to polar bears remains unclear.

In general, pollution is acting across large temporal and spatial scales, potentially having negative effects on polar bear reproduction and survival in several populations. The ban on PCB usage is an example of how positive results can be achieved, as the decreasing trends of these contaminant in arctic biota show (Wolkers et al. 2008). New compounds are, however, being detected in polar bear tissues, calling for new research and management initiatives. While most sources of organic pollutants are found outside the Arctic, and output is continuous but slow, radioactive contaminant sources are found many places in the Arctic and the potential for acute and significant contamination is present. Nuclear power plants and waste disposal sites represent potential sources of contamination and comprehensive plans for managing and monitoring such sources are needed.

6.2. The multiple stressor issue and perspectives on future monitoring and management

A stressor has been defined as a variable (biotic or abiotic) that adversely affects individual physiology or population performance (Barrett et al. 1976; Vinebrooke et al 2004). Stressors can be both natural and anthropogenic, and they often interact to produce a combined impact, which can be synergistic, additive or antagonistic towards the organism. Stressors are synergistic when their combined effect is larger than the effect of their individual effects added together (additive) and antagonistic describes when the combined effect is smaller (Vinebrook et al. 2004).

In this thesis I have shown how sea ice changes, disturbance and pollution are threats to polar bears that act on different spatial and temporal scales. Consequently, they are linked to different aspects of polar bear population biology as stressors. The multiple stressor perspective is currently receiving progressively more attention from management authorities and the scientific community (for example Vinebrooke et al. 2004; Jenssen 2006; Obbard et al. 2010; Vongraven and Peacock 2011; UNEP/AMAP 2011; Vongraven et al. 2012; Dietz et al. 2013). A recent AMAP report (AMAP 2011) concluded that "the complex processes involving transport pathways, intercompartmental distribution, bioaccumulation, and transformation of anthropogenic contaminants will be affected by the recently observed climate change in the Arctic environment". They describe how the behaviour of pollutants can change with regard to both abiotic and biotic properties as the climate changes. Further, they noted that climate change is expected to result in increased human development and increased contaminant discharge in the Arctic. A number of knowledge gaps with regard to the combined effects of climate change and pollution were identified, and it is clear that further research is needed.

Jenssen (2006) pointed out that pollutants with endocrine-disruptive properties are the second most serious anthropogenic threat in the Arctic, after climate change, and that the combination of these two stressors may be a "worst-case combination for Arctic marine mammals and birds". Dietz et al. (2013) stated that different contaminants (for example various POPs and heavy metals) can act together making it difficult to determine the effect of individual compound in free-ranging animals. Further, they noted that confounding factors such as age, sex, reproductive status, body condition, and presence of diseases or other stressors further complicates analyses. They suggested nevertheless that increasing trends of mercury (Hg) in polar bears from northeast Canada and East Greenland might represent a health risk to the most susceptible animals when stress from climate change, shifts in pathogen organisms, decreased access to food and other contaminations are simultaneously taken into account (Dietz et al. 2013).

It has been documented that contaminants have negative effects on thyroid hormones, sex steroid homeostasis and the immune system of marine mammals, including polar bears (Haave et al. 2003; Olsen et al. 2003; Oskham et al; 2003, 2004, Braathen et al. 2004; Lie et al. 2004, 2005; Letcher et al. 2010). Both sea ice changes and human disturbance, although acting on quite different scales, may reduce access to food or increase energy expenditure through less effective hunting (including less prey) or longer walking or swimming distances. In combination with a generally weaker state of health, the net effect of the stressors might affect survival significantly, especially for very young or old animals. The effect of a longer ice-free period in Hudson Bay lowered survival in these two age groups (Regehr et al. 2007). The Hudson Bay population is not considered to have problems with pollution, and disturbance from humans is limited to the period when bears are fasting on land. However, there is reason to believe that there will be an increase in disturbance and human-bear conflicts as climate change progresses, both in this population and elsewhere in the Arctic.

Lowered survival as a result of sea ice changes was also found in polar bears in the Southern Beaufort Sea (Regehr et al. 2010). For Svalbard, analyses of the effect of sea ice reduction on survival have not yet been conducted. However, the contamination issue has been suggested as a possible explanation for the slow population recovery after the heavy harvest stopped in 1973 (Derocher 2005). In addition, polar bear habitat in this region is projected to be significantly reduced in the decades to come. The reduction of available habitat will probably lead to decreasing population size (Amstrup et al. 2008, 2010, Durner et al. 2009). Sea ice in the Svalbard region is characterized by active drift ice combined with stable landfast ice. Even if ringed seal breeding has been documented in the drift ice, the landfast ice is thought to be essential to normal pup production levels (Smith and Lydersen 1991). During recent years, pup production in Svalbard has been very low in several important ringed seal breeding fjords (Kovacs et al. 2011). It is reasonable to believe that polar bear females with small cubs might be particularly vulnerable to the loss of this potential prey, because these females are the most nutritionally stressed group of bears at this time of the year (Watts and Hansen 1987; Atkinson and Ramsay 1995). Since fat-soluble contaminants are released into blood circulation when stored fat is metabolized, the mothers experience high levels of contaminants carried to vital organs during the first months of lactation, which causes transfer of pollutants to the foetuses *in utero* and to the cubs through the milk (Polischuk et al. 2002). It is reasonable to believe that the combined effect of pollution and sea ice reductions in the Barents Sea population acts in an additive, or synergistic, negative fashion (Derocher 2005; Jenssen 2006). Further research and monitoring is needed to increase our understanding of the effects of these stressors on reproduction and survival in this population.

Recently, a paradigm shift has been suggested in the field of biological monitoring, with the introduction of the term adaptive monitoring (Lindenmayer and Likens 2009). The key feature of adaptive monitoring is that a monitoring process should evolve as an iterative process as new knowledge emerges or as new questions arise. The need for a conceptual model and the importance of choosing the relevant monitoring parameters is also highlighted by Lindenmayer and Likens (2009).

Monitoring of polar bear populations is a perfect example of why adaptative monitoring is so important because knowledge about important sources of impacts on this species have changed through time. The need for better monitoring programs for polar bears that seek to understand processes related to the population level effects of a range of stressors has recently been identified (Vongraven and Peacock 2011; Vongraven et al. 2012). The idea of an adaptive monitoring program also includes the concept of adaptive management (Lindenmayer and Likens 2009; Vongraven et al. 2012). When changes occur in a population, management regimes should change accordingly. In this context it is important to realise that population changes might be rapid as thresholds are crossed, and that plans for how to deal with such changes should be made early (Andrew E. Derocher personal communication).

Management regimes and strategies might be challenged as new threats appear. One must ask - what is the ultimate aim of polar bear circumpolar management? Is maximising harvest the goal or is it conservation of the species. Aims are obviously different among different management jurisdictions. Currently some stakeholders believe that polar bears are not in danger of extinction and that proper resource management is sufficient to ensure the survival of populations (see Wiig 2005; Vongraven 2009). In other words, it has been argued that more powerful conservation measures, such as lowered quotas or total protection of animals and their habitats are not needed at this time (see Vongraven et al. 2012 for discussion). This may currently be true for some polar bear populations, but for others the status is far more uncertain. Some populations are declining (Hunter et al. 2010; Regehr et al. 2007, 2010), for others data is unavailable (Obbard et al. 2010). Therefore a more careful conservation approach should be taken. The Barents Sea population is currently one of few populations that is totally protected and some critical habitat has varying degrees of protection, but this is restricted to areas inside Norwegian territorial waters. In this population, the precautionary principle has been used as a conservation tool.

Overharvesting and poaching were the main conservation concerns when the work on the Polar Bear Agreement was initiated in the 1960s (Anon 1965; Prestrud and Stirling 1994). From 1870 to 1970, several polar bear populations were overharvested, which lead to the implementation of quota systems in some populations and total protection in others (Prestrud and Stirling 1994). The on-going and future large-scale habitat losses in combination with other threats such as pollution and human development are much more serious challenges, which require a broad management approach. It is generally agreed that the rapid climate change seen during the last century is caused mainly by human activity (IPCC 2007), but whether changes in climate are reversible is still under discussion. Amstrup et al. (2010) argued that a significant reduction in the emission of CO_2 to the atmosphere could reduce the rate of sea ice loss, and consequently increase polar bear population persistence.

It has been suggested that strict conservation measures must be initiated to secure the survival of the species (Vongraven and Peacock 2011; Vongraven et al. 2012), and that this can only be made possible through a coordinated effort from all Range States. Similar more general advice has been given to the international community with regard to conservation of mammals globally (Rondinini et al. 2011). Rondinini et al. (2011) identified key elements for a successful large scale conservation strategy to include an institution with recognised authority, clear goals and objectives, relevant species data, a priority list and well developed indicators. The cooperation around the Convention on Biological Diversity (http://www.cbd.int) was proposed as a possible starting point for a new global initiative for the conservation of mammals. Rondinini et al. (2011) further suggested that an expanded version of the International Union for the Conservation of Nature (IUCN) Red List (http://www.iucnredlist.org/) would be a suitable future tool. Wilson et al. (2011) pointed out that one of the main challenges in mammal conservation is prioritizing what to focus on, since “we cannot do everything, everywhere, all the time”.

However, Rondinini et al. (2011) stressed that a global mammal conservation strategy is urgent, and although there are still significant knowledge gaps, the work cannot be delayed. The recent initiatives taken internationally to improve knowledge and monitoring of polar bear populations throughout the range of the species (e.g. Anon 2009; Vongraven et al. 2012) are in line with these views. Work on the international Action Plan for polar bears is ongoing, and a framework for improved research and monitoring has been developed.

It is the responsibility of researchers, management authorities and other stakeholders to cooperate in gaining the necessary knowledge to provide sound management advice and conservation action. It is important for management strategies to be based on the best available scientific knowledge to ensure best practice with respect to preserving the global population of polar bears.

7. Concluding remarks

7.1. Specific conclusions

1. **The population size of polar bears in the Svalbard and Barents Sea area**

We estimated that the Barents Sea polar bear population contained approximately 2,650 (95% CI approximately 1,900–3,600) bears in August 2004. The estimated size of the Barents Sea polar bear population is much smaller than the minimum size that must have been present prior to the high hunting pressure from 1870 to 1970. This indicates that, historically, the population was much larger and that the population acted as a sink for animals from other areas.

2. **Activity and habitat use of female polar bears in Svalbard**

We found both monthly and diurnal patterns in fine scale polar bear movements, with maximum movement rates above 4 km/h during 4 hour periods. Simulations showed that a commonly used sampling regime of one location every 6th day would have significantly underestimated the movement rates and the home range sizes compared to our estimates, thus GPS collars with high accuracy and high sampling frequency are essential for fine scale analyses of habitat use. Using this technology, we found that space use patterns differed according to reproductive state; females with COYs had smaller home ranges and used fast-ice areas close to glacier fronts more frequently than lone females. The eventual disappearance of these important habitats might become critical for the survival of polar bear cubs in Svalbard and other regions with similar habitat characteristics.

3. **Denning distribution and the effect of sea ice variability on denning behaviour**

The highest number of dens was recorded on the islands in the eastern and northern parts of the Svalbard Archipelago with fewer dens found further west on the island Spitsbergen. The majority of dens (62%) in Svalbard were located on land within ca. 1 km of the shore. Our observations of den distribution indicates that denning is now more widespread in the archipelago compared to 40-50 years ago and reflects a reestablishment of denning areas following decades of protection. The arrival of sea ice at Hopen Island in autumn shifted from late October to mid-December during the period 1979 to 2010. Fewer maternity dens were found on the island in years when sea ice arrived later in the autumn. Later arrival of sea ice in the autumn was correlated with lower body mass of adult females and their cubs at emergence. Timing of arrival and departure of sea ice is already affecting the denning ecology of polar bears at the southern extent of their range in Svalbard.

4. The effect of disturbance on polar bears in important landfast ice habitats

Females with cubs and single medium sized bears tended to show more intense responses to motorized vehicle disturbance in landfast ice habitats than adult males or lone adult females. On average, bears were alerted to snowmobiles at 1,164 m, and showed locomotive responses at 843 m. There was a statistically significant difference in reaction distance between sex and age classes. The response intensity was affected by wind direction. Female polar bears with COYs may be at greater risk via disturbance, since they react at greater distances with amplified responses.

5. Diet of polar bears in Svalbard and the Barents Sea

Prey composition was dominated numerically by ringed seals (63%), followed by bearded (13%), harp seals (8%) and unknown species (16%). When known prey were converted to biomass, the total diet composition was dominated by bearded seals (55%), followed by ringed seals (30%) and harp seals (15%), which indicated that bearded seals are an important dietary item for polar bears in the western Barents Sea. Different patterns of space use by different bears may result in geographic variation of diet within the same population.

6. Levels of anthropogenic contaminants (persistent organic and radionuclide pollutants)

Our results indicate that polar bears from Franz Josef Land and the Kara Sea have the highest PCB levels in the Arctic. Decreasing trends were seen eastwards and westwards from this region. Of the congeners investigated in the present study, the lower chlorinated PCBs increase and the high chlorinated compounds decrease from Svalbard eastward to the Chukchi Sea. Different pollution sources, compound transport patterns and regional prey differences could explain variation in PCB congener levels and patterns seen in polar bears. The results of our radionuclide study indicated low specific activities of ^{137}Cs in Arctic marine mammals in the Barents and Greenland Seas. Concentration factors (CF) of ^{137}Cs from seawater were determined for polar bears, ringed, bearded, harp and hooded seals. Mean CF values were higher than those reported for fish and benthic organisms in the literature, suggesting bioaccumulation of ^{137}Cs in the marine ecosystem.

7.2. Overall conclusion

The biological traits that make polar bears well adapted to the Arctic environment are problematic in the context of encounters with human activity, pollution and significant changes to their sea ice habitat. This thesis has described how polar bears in Svalbard have been negatively affected by human activity in the last century, but that the threats have changed through time. There are clear linkages between population biology and current anthropogenic threats, and it is reason to believe that the combination of several stressors have significant negative effects on polar bears. It seems clear, however, that the processes involved and the population level effects are not well understood. An international Action Plan for polar bears is under construction and a comprehensive monitoring program that aims to understand the consequences of multiple stressors, has been recommended by an international expert group. Norway is obliged to manage the Norwegian population based on the best available scientific data, as stated by Article VII of the Agreement, and thus should follow the advice given by the group. Improving future management of the species requires relevant research and monitoring through increased scientific effort in the Barents Sea population. The arctic environment as a whole should be managed in such a way that the combined effects of stressors on populations, including polar bears, are minimized.

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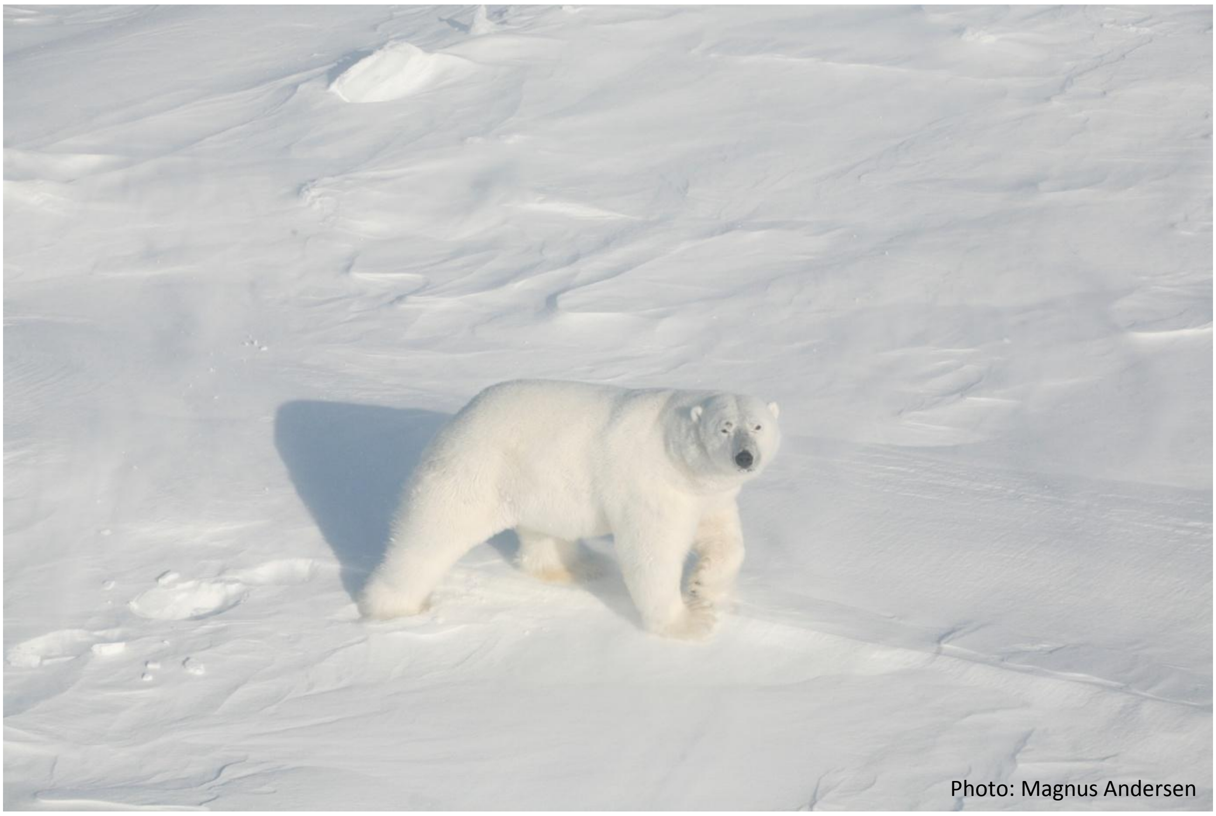
Paper 1



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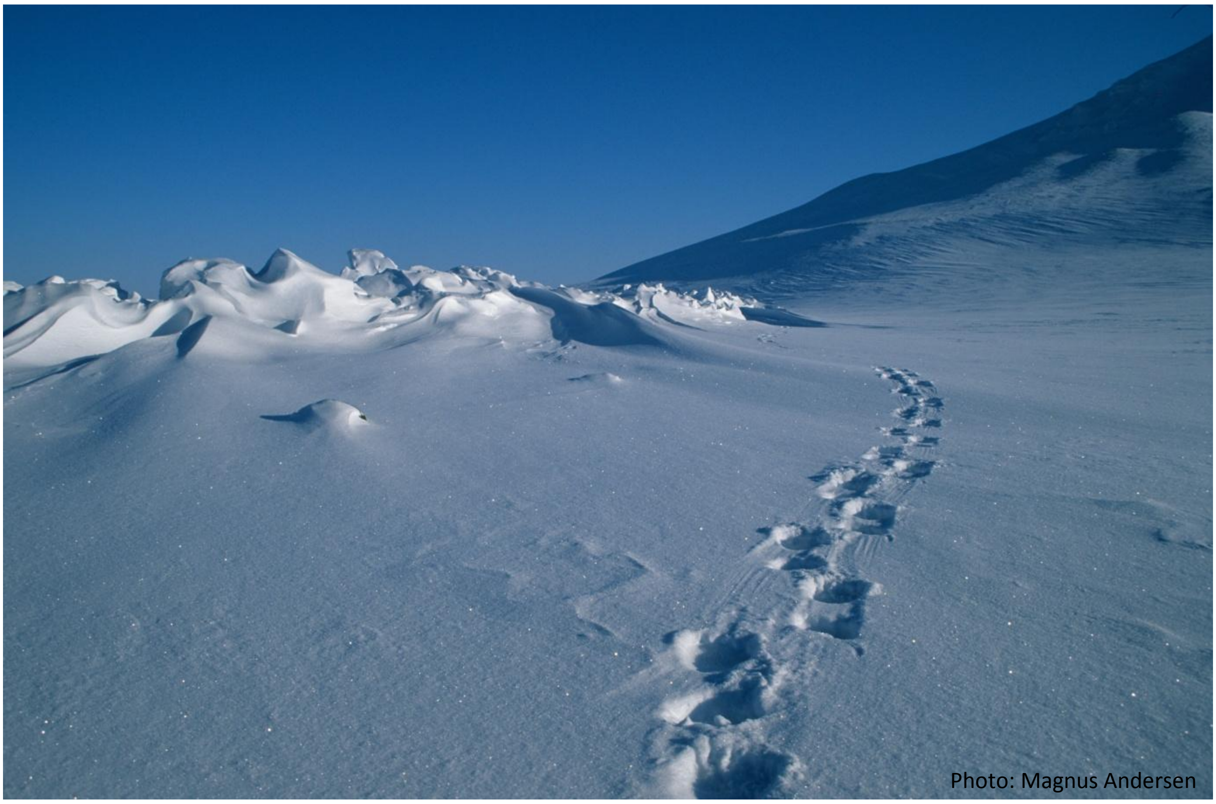

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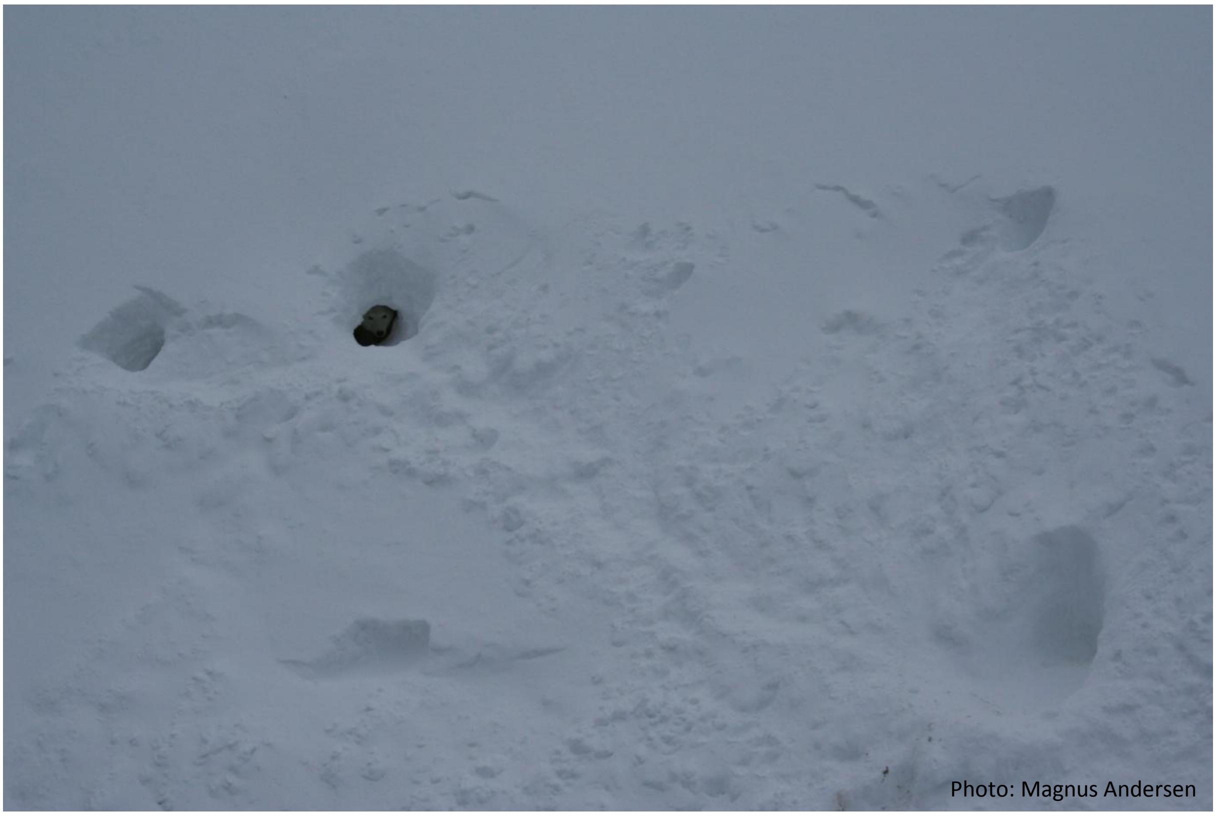

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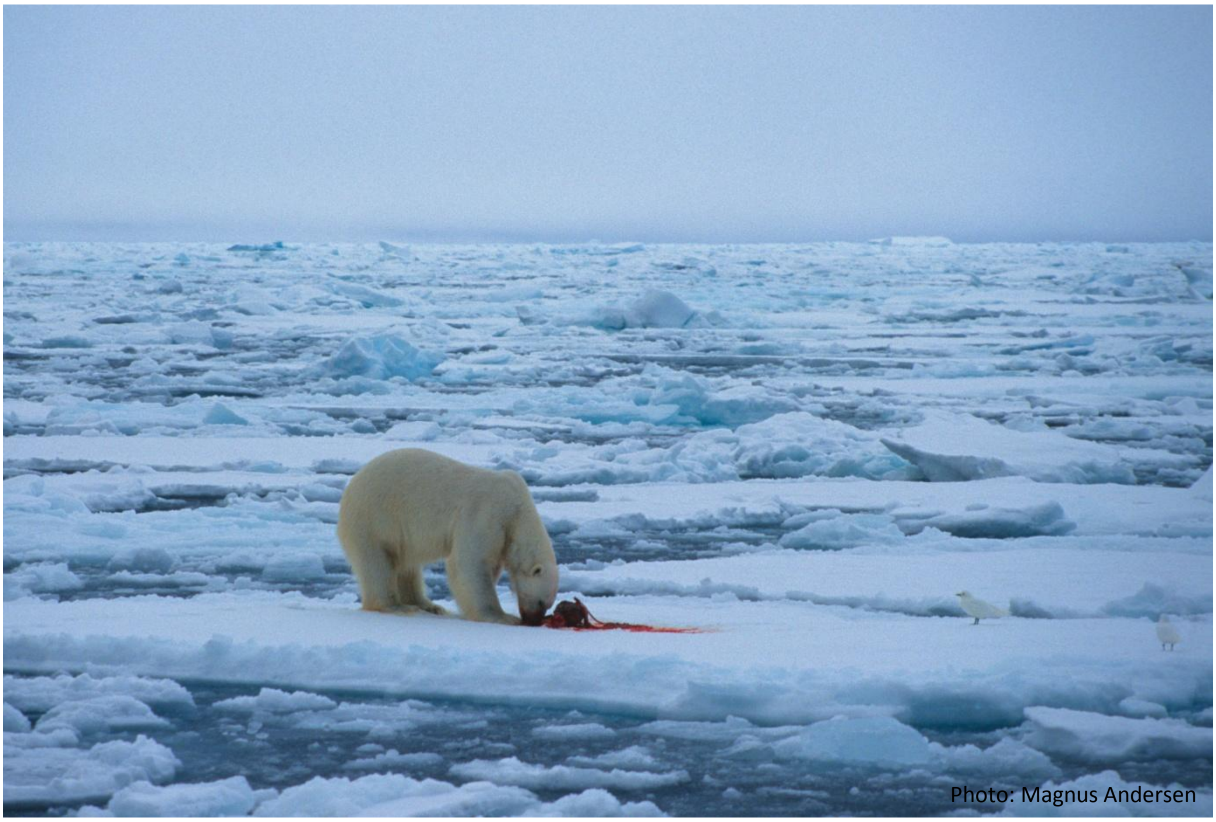
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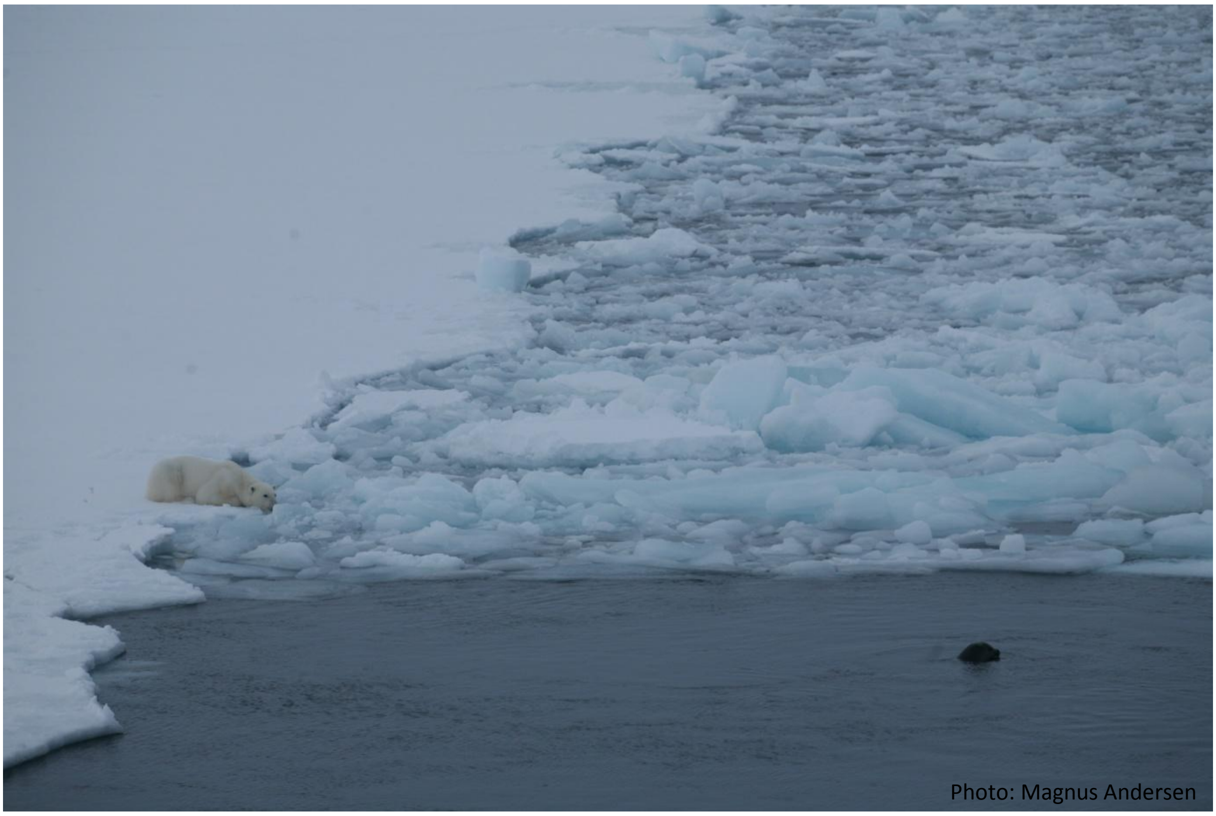

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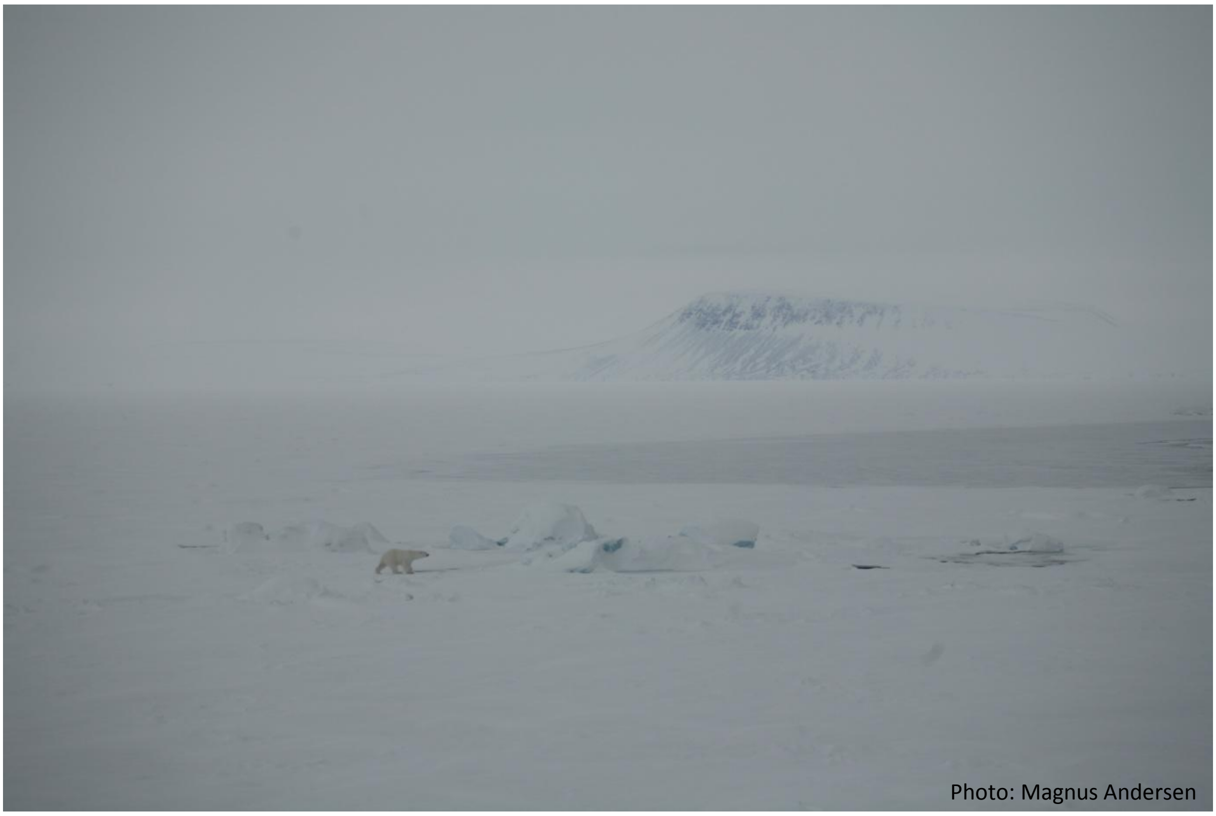

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