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Sea ice and polar bear den ecology at Hopen Island, Svalbard

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ABSTRACT: The maternity denning of polar bears *Ursus maritimus* was studied at Hopen Island, Svalbard, Norway, using information collected by direct observation and live-capture of females and cubs during den emergence in spring of 1994 to 2008. The number of maternity dens observed annually varied from 0 to 36. 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 Hopen Island in years when sea ice arrived later in the autumn. There were no significant differences in body mass or litter size between female polar bears denning on Hopen Island and females caught elsewhere in Svalbard; however, females denning on Hopen Island were significantly younger than females denning elsewhere in Svalbard. Later arrival of sea ice in the autumn at Hopen Island was correlated with lower body mass of adult females and their cubs at emergence. The timing of arrival and departure of sea ice is highly variable but a trend of later arrival in autumn may be affecting the denning ecology of polar bears at the southern extent of their range in Svalbard.

KEY WORDS: Polar bear · *Ursus maritimus* · Climate change · Sea ice · Denning · Reproduction

INTRODUCTION

The Arctic is warming (IPCC 2007) and the Arctic sea ice system has shown a rapid and dramatic decrease in sea ice extent, ice thickness, and ice age, with more first-year and less multi-year ice (Rothrock et al. 1999, Parkinson & Cavalieri 2002, Nghiem et al. 2007, Comiso et al. 2008, Walsh 2008, Kwok & Rothrock 2009). These changes affect Arctic marine ecosystems and may affect species distribution and persistence (e.g. Laidre & Heide-Jorgensen 2005, Bluhm & Gradinger 2008, Greene et al. 2008). How species respond to climate change is influenced by population structure and changes in habitat (Keith et al. 2008). Given the highly dynamic nature of sea ice habitats and directional change in sea ice, understanding the effects of climate warming is a priority for conservation of many Arctic marine species. One important characteristic of concern due to diminishing sea ice is habitat connectivity (Weins 1995, Lindenmayer et al. 2008). Sea-ice-dependent species, such as polar bears *Ursus maritimus*, are at risk of habitat fragmentation that may limit migration, feeding, and reproduction and thus species' persistence (Mauritzen et al. 2003b, Derocher et al. 2004, Laidre et al. 2008, Moore 2008). Shifting phenology due to climate change is an emerging concern for many wildlife species, and the disruption of timing of key life-history events can have negative consequences on population trajectory and distribution (Easterling et al. 2000, Stenseth & Mysterud 2002, Johnston et al. 2005, Gaston et al. 2009).

Polar bears are particularly vulnerable to the effects of climate change due to their close association with sea ice, which is their primary habitat and the platform from which they hunt their prey (e.g. ringed

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seals *Pusa hispida* and bearded seals *Erignathus barbatus*) (Stirling & Derocher 1993, Derocher et al. 2004, Amstrup et al. 2008, 2010, Durner et al. 2009). Shifts in the distribution of polar bears related to changing sea ice conditions have been documented and are projected to continue with time (Schliebe et al. 2008, Durner et al. 2009). One critical element of the life history of polar bears is the use of over-winter maternity dens to protect cubs from the harsh conditions of the Arctic during their first few months of life (Harington 1968, Blix & Lentfer 1979). Polar bears breed in the spring and exhibit delayed implantation so that active gestation is limited to the 2 mo before parturition (Wimsatt 1974, Derocher et al. 1992, Rosing-Asvid et al. 2002). Dens are typically created by pregnant females in the autumn or early winter in snow drifts (Harington 1968, Durner et al. 2003). Pregnant females can spend up to 8 mo in dens, where they give birth and rear their young until they have matured sufficiently to leave the den (Watts & Hansen 1987, Amstrup & Gardner 1994). At birth, polar bear cubs are altricial, weighing 600 to 800 g; are sparsely haired; and have a limited capacity for metabolic heat production (Blix & Lentfer 1979, Ramsay & Dunbrack 1986). Dens provide a warmer microclimate for females to raise their cubs (Harington 1968). Cubs are born from mid-November to January (Harington 1968, Derocher et al. 1992) and emerge from the den between February and May, when they weigh about 10 kg (Derocher & Stirling 1998).

Polar bears are distributed over the circumpolar Arctic in 19 populations (Bethke et al. 1996, Mauritzen et al. 2002, Obbard et al. 2010). Maternity dens are typically distributed at low densities, with the majority located on land, except near Alaska, where sea ice denning is common (Harington 1968, Larsen 1985, Ramsay & Stirling 1990, Stirling & Andriashek 1992, Amstrup & Gardner 1994, Andersen et al. in press). Suitable habitat for maternity dens is determined by topographic features that accumulate sufficient snow cover and sea ice patterns that allow access to and from land at appropriate times (Jonkel et al. 1972, Durner et al. 2003, Richardson et al. 2005). Female polar bears show fidelity to den areas but not to specific den sites (Schweinsburg et al. 1984, Ramsay & Stirling 1990, Garner et al. 1994, Zeyl et al. 2010).

Polar bears living in the Norwegian Arctic near Svalbard are part of the Barents Sea population that is shared with Russia (Mauritzen et al. 2002). The distribution and movement patterns of this population are highly variable, with annual home range sizes for adult females varying 2000-fold from 185 to 373 539 km^2 (Mauritzen et al. 2001). Sea ice in the Barents Sea is dynamic and influences seasonal movements of female bears (Mauritzen et al. 2003b). Although the role of sea ice dynamics on the facultative use of shelter dens has been investigated (Ferguson et al. 2000), the relationship between sea ice and maternity denning has not. The timing of arrival in maternity denning areas varies among populations, but depending on sea ice dynamics, pregnant females arrive months or weeks before entering maternity dens (Ramsay & Stirling 1990, Van de Velde et al. 2003, Fischbach et al. 2007). We predicted that the abundance of dens at the southern edge of the range of polar bears in the Svalbard area would be largely determined by the timing of arrival of sea ice in the autumn when pregnant females would be seeking terrestrial habitats for suitable den sites. To test this prediction, we examined the denning ecology, the abundance of dens, and characteristics of female polar bears emerging from dens with cubs (<4 mo old) on Hopen Island, the southernmost denning area in Svalbard, in relation to sea ice arrival. We also examined the date of departure of sea ice cover because sufficient sea ice is necessary for females with young cubs to leave the denning area. The age, body mass, and litter size of the females and body mass of cubs on Hopen Island were compared to females and cubs in other parts of Svalbard. We also examined relationships between cub mass and maternal characteristics (e.g. female age and mass) and the relationship of these characteristics with the timing of sea ice arrival at Hopen Island.

MATERIALS AND METHODS

The core study area consisted of Hopen Island in the Svalbard Archipelago (76° 35′ N, 25° E), Norway, and adjacent areas in the western Barents Sea (74–81° N, 15–45° E) (Fig. 1). Hopen Island, about 90 km from the main archipelago, is 37 km long and up to 2 km wide, with 8 plateaus with the highest elevation at 385 m. Polar bears and their maternity dens were located by helicopter by searching for den openings and tracks in the snow while flying at 25 to 100 m above ground in spring (March to May). Den positions (latitude and longitude) were recorded by GPS. Hopen Island was surveyed from 1995 to 2003 and in 2008 to assess the influence of sea ice dynamics on the distribution and abundance of dens. From 1995 to 2002, the island was surveyed at least 5 times yr^{-1} because it was the main base for polar bear research. The survey period varied between years and

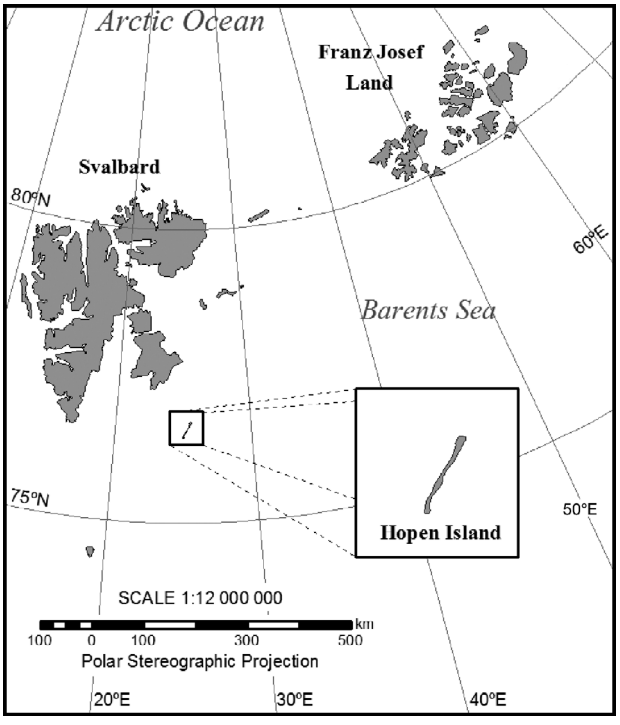

Fig. 1. Svalbard and Hopen Island, Norway

ranged from March 23 to May 1. In 2003, the island was surveyed once (April 26), and in 2008 it was visited twice (April 8 and 19). Variation in weather conditions affected our survey intervals and den visibility, so it was not possible to determine when dens first opened or whether the entrances to dens from which females had already departed were no longer visible. Thus, we consider our observations an index of denning activity. Hopen Island den habitat is restricted to areas that accumulate sufficient snow for den construction, and dens and associated activity are easily observed from the air. Therefore, we are confident that the observed dens reflect the relative abundance of dens on the island.

We attempted to sample all females with cubs sighted from 1994 to 2002 across the Svalbard Archipelago as a part of a research program on the ecology of the Barents Sea population. Bears caught at Hopen Island were compared to bears caught in other areas of Svalbard. Adult bears were caught by remote injection of a dart (Palmer Cap-Chur Equipment) containing the drug Zoletil® (Virbac), fired from a helicopter (Stirling et al. 1989). Cubs were caught by hand and immobilized by hand injection. Bears were permanently marked with a tattoo on the inside upper lip and a numbered plastic tag placed in each ear. Animal handling methods were approved by the National Animal Research Authority (Oslo) and complied with Norwegian law.

Ages were determined from a vestigial premolar tooth extracted from bears >1 yr old (Calvert & Ramsay 1998). A series of standardized morphometric measures were collected from each bear while they were lying sternally recumbent with the back legs straight behind and the forelegs flexed forward at the elbows parallel to the body. Body length (cm) was measured as the dorsal straight-line distance from the tip of the nose to the caudal end of the last tail vertebrae. Axillary girth (cm) was measured as the circumference around the chest at the axilla with a rope (0.4 cm in diameter) tightened with a tension of 0.5 kg. Body mass for adults was estimated from a regression model developed for the study population using axillary girth and body length (Derocher & Wiig 2002). Body mass for cubs was determined by spring scale (Chatillon IN-060, Ametek). To assess variation in female reproduction, we examined the relationship between cub mass and maternal age, maternal mass, and date of autumn ice arrival at Hopen Island in a multiple regression.

Because polar bears avoid sea ice cover <50% (Stirling et al. 1999, Mauritzen et al. 2003a, Durner et al. 2009), we used 60% ice cover at Hopen Island as an index of ice arrival and departure. Sea ice arrival and departure was determined from passive microwave SSM/I (Special Sensor Microwave Imager) remote sensing data (NASA's Earth Observing System Distributed Active Archive Center, National Snow and Ice Data Center, University of Colorado, Boulder). These data are available at ftp://sidads.colorado.edu. We used the daily weighted mean percent cover in the four 25 × 25 km cells closest to the position 76° 36′ N, 25° 12′ E at Hopen Island, 2 centered around points close to the northern and southern point of the island, and the others directly west and east, thus forming a 50 × 50 km square with Hopen Island in the center. The weighting was an inverse function of the distance of each cell center to the reference point at Hopen Island. To assess longer-term trends in sea ice near Hopen Island, we examined sea ice arrival and departure trends from 1979 to 2010 (the period for which ice data are available) using linear regression.

Ice data extraction and analysis functions were custom-written using the R package (2009 version, R Development Core Team). We used SAS statistical software (SAS Institute) to perform linear regressions, polynomial regressions, multiple regression, *t*-tests, and Kruskal-Wallis tests. Means are presented with ±1 SE. Statistical significance was $p \leq 0.05$.

RESULTS

Dens were found throughout the survey period (March 23 to May 1). Some dens had already been opened before our surveys began, but the pattern of our observations suggests that April 7 (SE = 1 d, n = 97) was the peak of den emergence (Fig. 2). There was no trend in the date of first observations over time (linear regression: p = 0.25). The dens were distributed widely over Hopen Island from the southern to northern tip, with 58% of the dens found in the northern half of the island.

From 1979 to 2010, the date of arrival of 60% sea ice cover in the Hopen Island area varied among years from October 18 to February 28 (Fig. 3). The mean date was December 2 (SE = 5.8 d, n = 33) and there was a trend for the sea ice to arrive later over time (linear regression: $F_{1,30}$ = 7.36, p = 0.011, R^2 = 0.20). The date at which sea ice cover dropped below 60% in spring varied from April 3 to July 13, with a mean of June 2 (SE = 4.4 d, n = 32), and showed no significant trend over time ($F_{1,29}$ = 3.23, p = 0.083). Ice cover dropped below 60% before the mean date of den emergence in only 1 yr (2006). The number of dens found in a year varied from 0 to 36, with a mean of 10.5 (SE = 3.7 dens, n = 10). A 3rd-order polynomial regression ($F_{2,7}$ = 5.69, p = 0.034, R^2 = 0.62) showed that the number of dens observed decreased with later arrival of 60% sea ice cover (Fig. 4). Of the 51 females caught on Hopen Island, 3 had denned there previously.

There was no significant difference (*t*-test: p = 0.42) in the mean litter size on Hopen Island (mean = 1.78 ± 0.07 cubs, n = 51) compared to other areas at Svalbard during the same period (mean = 1.68 ± 0.07 cubs, n = 60). The age of females with cubs on Hopen Island (mean = 9.0 ± 0.5 yr, n = 51) was lower (Kruskal-Wallis test: p =0.0003) than the age of females with cubs in other areas of Svalbard (mean = 12.0 ± 0.6 yr, n = 60). Females with cubs on Hopen Island had a mean body mass (176 ± 2.7 kg, n = 49) that was not significantly different (*t*-test: p = 0.56) from that of females with cubs from other areas in Svalbard (173 ± 3.6 kg, n = 60). The body mass of females with cubs on Hopen Island, however, was negatively related to the date of arrival of 60% sea ice cover the previous year (linear regression: $F_{1,47}$ = 7.03, p = 0.011, R^2 = 0.13).

The mean body mass of cubs on Hopen Island (9.9 ± 0.2 kg, n = 86) was lower (*t*-test: p = 0.0055) than that of cubs born elsewhere in Svalbard (13.7 ±

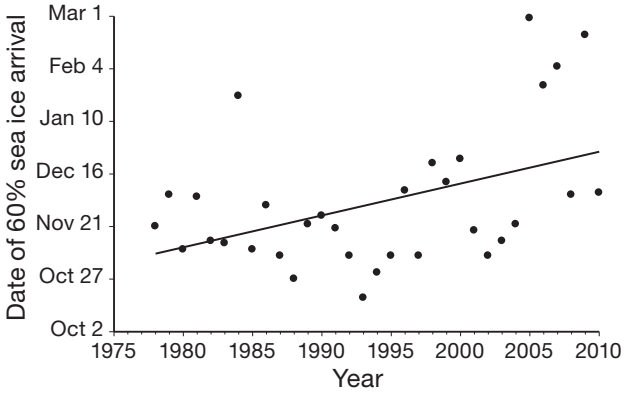

Fig. 3. Date of arrival of 60% sea ice cover determined by Special Sensor Microwave Imager (SSM/I) imagery in the area near Hopen Island from 1978 to 2010. The straight line represents a linear regression (see 'Results')

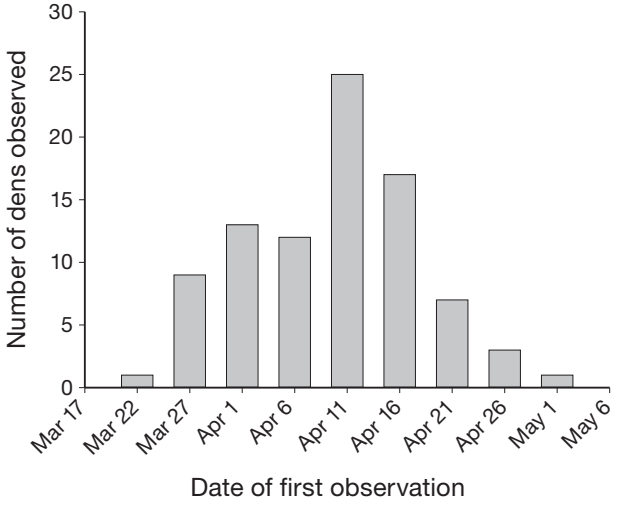

Fig. 2. *Ursus maritimus*. Date of first observation of polar bear maternity dens on Hopen Island from 1994 to 2002

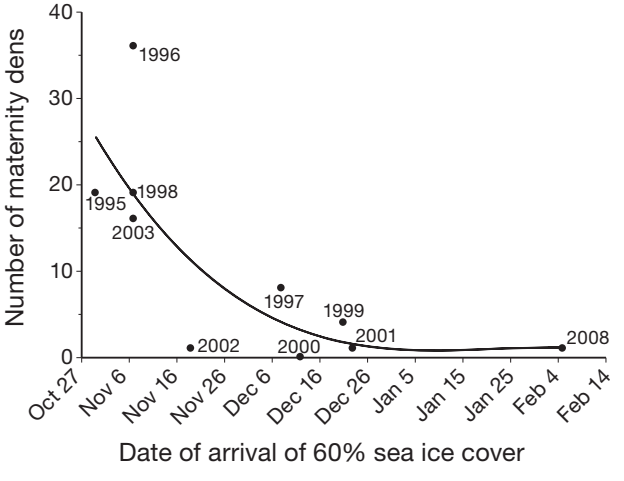

Fig. 4. *Ursus maritimus*. Number of polar bear maternity dens observed on Hopen Island in relation to the date of arrival of 60% sea ice the previous autumn. The curved line represents a 3rd-order polynomial (see 'Results')

1.3 kg, n = 74). Multiple regression of cub mass with maternal body mass, maternal age, and date of sea ice arrival revealed that only date of sea ice arrival was negatively related to cub mass (multiple regression: $F_{1,84} = 7.35$, p = 0.0081, $R^2 = 0.080$).

DISCUSSION

The dates of arrival and departure of sea ice near Hopen Island varied substantially over time and likely reflect its location near the southern edge of where sea ice exists in the Barents Sea (Shapiro et al. 2003). The trend towards later arrival of sea ice coincides with a reduction in sea ice thickness observed over the last 4 decades at Hopen Island (Gerland et al. 2008).

During the period from 1900 to ~1950, before the effects of climate change on sea ice, only 2 dens were recorded on Hopen Island (Lønø 1970). The reason for the larger number of dens on Hopen Island during our study than earlier 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 Barents Sea polar bear population. Between 1945 and 1970, an average of 320 bears, including females with offspring, were killed each year in the Svalbard Archipelago, including an average of 41 bears yr^{-1} from Hopen Island (total reported harvest on Hopen Island 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 & Stirling 1994) and protection allowed the population to recover over the next 30 yr (Derocher 2005). The larger number of maternity dens we observed may be a result of the re-establishment of Hopen Island as a denning area as the population has increased. The distribution of maternity dens in the Beaufort Sea was similarly restricted spatially by hunting that occurred before 1972 that depleted the number of bears denning on land (Stirling & Andriashek 1992, Amstrup & Gardner 1994).

The younger age of females on Hopen Island, compared to other areas in Svalbard, may be related to recent recolonization from other areas by females giving birth for the first time. The low recapture rate of bears, however, suggests low den-area fidelity, and this may be related to sea ice conditions. It is likely that bears that were unable to reach Hopen Island in the autumn denned on other nearby islands in Svalbard given that the sea ice distribution allowed them to reach alternative denning areas. The mean date of den emergence on Hopen Island (April 7) was similar to that previously reported for Svalbard (April 5) using satellite telemetry (Wiig 1998). Similar emergence dates, body mass, and litter size of adult females on Hopen Island compared to other areas of Svalbard indicate that Hopen Island provided suitable denning habitat. The correlation between the later dates of sea ice arrival at Hopen Island and the lower body mass of mothers in spring, however, suggests that recent environmental conditions 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 gestation and nursing until cubs can leave the den (Watts & Hansen 1987, Molnár et al. 2011). Maternal body mass in spring was correlated with body mass of cubs and with cub survival (Derocher & 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 be a component of reproductive success.

Our results showed a relationship between the timing of arrival of sea ice at Hopen Island and the number and body mass of female polar bears denning there. As the sea ice north of Alaska has become less suitable for denning, maternity den distribution has shifted from stable multi-year sea ice to land (Fischbach et al. 2007). Fischbach et al. (2007) concluded that a longer melt season, reduction in stable old ice, and increases in unconsolidated ice were responsible for the shift to denning on land. A smaller-scale shift in den areas was noted in western Hudson Bay, where maternity dens shifted northwards between 2 periods, and changes in the sea ice were thought to be involved (Ramsay & Stirling 1990).

After leaving the den, young polar bear cubs are vulnerable to hypothermia when exposed to cold water (Blix & Lentfer 1979). In most years, it was evident that there was sufficient sea ice for females with young cubs to leave Hopen Island without having to cross open water. However, the suitability of a maternity denning area for raising cubs is in part determined by the timing of sea ice arrival and sea ice departure. The reproductive success of any females that manage to den on Hopen Island could be negatively affected if the sea ice departs earlier in spring in the future.

Climate change is the most pressing conservation concern for polar bears due to the declining area, connectivity, and suitability of sea ice habitats (Stirling & Derocher 1993, Derocher et al. 2004, Amstrup et al. 2008, Wiig et al. 2008, Durner et al. 2009). 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. Our results show that although Hopen Island is at the southern extent of the range of polar bears in the Barents Sea, it can provide appropriate maternal denning habitat. When the sea ice arrives later, Hopen Island is less available, fewer dens are found there, and cub mass is lower. Later arrival of sea ice is a form of habitat fragmentation that results in reduced connectivity. 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, respond as sea ice patterns change in the Arctic.

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