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Light-level geolocation as a tool to monitor polar bear (*Ursus maritimus*) denning ecology: a case study

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Abstract

Background Monitoring polar bears is logistically challenging and expensive. Traditionally, reproductive history has been assessed using permanent marks from physically captured individuals, which requires assumptions about reproductive history based on their status at the time of capture. This is often supplemented with economically costly satellite telemetry (ST) collars restricted to adult females, which yield data on space use and reproductive history.

Methods This study assesses the potential of adapting light-level geolocation (Global location sensing or GLS) tags, developed for birds and fish, to estimate life history metrics for polar bears. Traditionally, GLS uses light intensity and time of day to estimate approximate twice-daily locations. This information, combined with temperature data, can be used to assess approximate locations of maternity denning events, denning timing, general space use, and population connectivity.

Results Adult females ($n = 54$) were equipped, some several times, with a total of 103 GLS in Svalbard and Greenland from 2012 to 2021. Of these, 44 were also equipped with 80 ST collars during this period. This yielded GLS and ST data records for each individual up to 9.4 years (mean (\bar{O}) 4.0 years) and 5.1 years (\bar{O} 1.5 years), respectively. Combined with capture information, the GLS and ST collars were used to score reproductive history (determined presence or absence of maternity denning events) for 72–54% of bear winters during this period, respectively. Using GLS yielded on average 4.3 years of unbroken reproductive history records (up to 8 years for some individuals) including denning phenology and age at first reproduction. Additionally, geographic locations could be estimated during spring and autumn (when twilight was present) with an average daily accuracy of 93 km (4–1042 km) and 58 km (5–550 km) when aggregating by season.

Conclusions This study establishes GLS as a powerful, low-cost method for polar bear population monitoring that can provide data on reproductive history, including age at first reproduction, and maternity denning location and phenology in programs with ongoing recapture. GLS can also be used to monitor males and immatures that cannot wear ST collars.

Keywords Breeding phenology, Denning, GLS, Polar bear, Reproductive history, Space use, *Ursus maritimus*, Winter behaviour

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Introduction

Ecological monitoring is important for addressing fundamental questions related to the conservation and management of species which includes evaluating population trends [1]. For vertebrates, traditional direct (e.g., manual counts, captures) and indirect monitoring methods (e.g., fecal, snow track or burrow counts) are often limited by their cost and logistical challenges, and frequently provide only localized snapshot of data in space (where the fieldwork took place) and time (when the fieldwork took place). In recent years, technological advancements have ameliorated some of these challenges by allowing researchers to track wildlife with remote sensing (e.g., [2, 3]), tracking devices (e.g. [4,]) and camera traps (e.g., [5]). Cost-effective, scalable monitoring techniques are ever more important in light of global declines in biodiversity [6].

A particularly logistically challenging vertebrate species to study is the polar bear (*Ursus maritimus*). This arctic apex predator is a sea ice-associated species and particularly vulnerable to the effects of climate change due to the recent dramatic losses of Arctic sea ice and warming of their environment in general [7]. Since the 1980s, the use of satellite transmitter tracking devices (ST), in particular through deployment of collars on adult females, has led to invaluable knowledge about polar bear ecology, including demography and space use [4]. A critical aspect of polar bear life history is the use of over-winter maternity dens, typically dug into snow drifts, to give birth to and protect altricial cubs from the harsh environmental conditions [8–10]. Only pregnant females enter a den for a prolonged period, while males, subadults, or non-pregnant females might enter a shelter den for shorter periods often to avoid harsh conditions [11]. ST collars are a powerful but costly tool that allows for identifying the location of a den and the timing of entrance and emergence to monitor reproduction (e.g., [12–15]). However, ST collars do not fit adult males (neck is wider than the skull) and are not suited for subadults (still growing). Several alternative tag types have been used, including glue-on or ear-attachment with a smaller size and a smaller battery (40–70 g). These ST tags typically last only a few months and have, in some cases, led to tissue damage [4, 16].

ST devices require relatively large amounts of power compared to smaller environmental sensing archival data loggers because they must radio communicate with satellites. Hence, they require greater battery capacity and are larger and heavier. GLS data loggers (historically known as Global Location System, Global Location Service and Global Location Sensing as well as light-level geolocators) have been developed as small, archival, light-weight, and low-cost, but low accuracy global tracking devices [17]. The light intensity data recorded by these devices

are extracted upon retrieval and processed to reconstruct daily positions using astronomical equations. So far, this technology has primarily been used to determine movements of vertebrate species such as marine mammals [18], sea turtles [19], seabirds [20], passerine birds [21], waders [22], and fish [23]. In addition, some non-geolocating studies have used GLS to investigate animal behaviour [24] and phenological plasticity [25, 26] in small animals (for further comparison between tracking technologies see [27]).

Here, we illustrate the potential of GLS as a powerful, long-term, and low-cost monitoring tool for polar bears. Specifically, we develop methods to identify maternity denning events and their phenology, as well as seasonal space use using a specially adapted long life GLS design recording light intensity, time, temperature, and saltwater immersion events, built as a small ear-tag.

Method

Data collection

Fieldwork was conducted in the Archipelago of Svalbard (74–82°N, 10–35°E) and East Greenland (60–84°N, 74–12°W) in the European Arctic as part of the ongoing polar bear monitoring by the Norwegian Polar Institute and Greenland Institute of Natural Resources during 2012–2021 (Fig. 1). Capture of polar bears followed standard protocols [28]. Morphometric measurements and reproductive state (presence and age of cubs) were recorded. Age of bears was estimated reading cementum growth layers in an extracted vestigial premolar, unless age of the bear was known based on a first capture as a juvenile [29, 30]. Starting in 2012, all

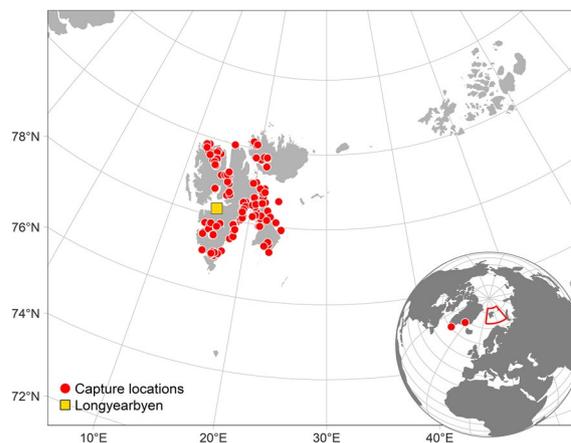


Fig. 1 Study area and its location globally (inset). Red dots illustrate capture locations of GLS-equipped polar bears in Svalbard and Greenland (inset). Location of the weather station in Longyearbyen shown in yellow. Projection: Azimuthal Equidistant centred on 78°N and 30°E

female bears in Svalbard except cubs of the year (COY) that were captured received an ear-tag GLS logger (Intigeo-PB, Migrate Technology Ltd, Cambridge, UK, Fig. 2). The GLS ear-tags weighed 5.9 g, with a diameter of 20 mm and a total length of 31 mm, not substantially bigger than the traditional ear-tag weighing 2.6 g, with a diameter of 16 mm and a total length of 28 mm, deployed on polar bears across the Arctic and used for harvest recoveries. They were also attached using the same methods as used for the traditional ear-tags [31]. The price tag of a single GLS tag was ~93% less than for a conventional ST collar. Most captures took place in March and April (88%), but some loggers were also deployed in September (12%). Tags were retrieved in subsequent years during opportunistic recaptures. Two GLS loggers were deployed and retrieved in southeast and northeast Greenland during 2016–2018 (Fig. 1). The loggers regularly measured and recorded light intensity, temperature, and saltwater immersion with time. Light data were interpreted directly to indicate shading by den cover, and to establish latitude (using day/night length) and longitude (using time of local noon/midnight) positioning twice daily when possible [17]. Compromises in the design of the GLS logger favoured long-term deployment such that many years of data could be recorded. Light intensity was sampled every minute with the maximum value recorded in each 10 min period (range 1 to 563 lx). Temperature (0.125 °C resolution, ± 0.5 °C accuracy) was sampled every 10 min with maximum and minimum recorded every four hours. In addition, every four hours, four

consecutive 10 min temperature samples were recorded in a 'burst'. The communication contacts on the logger had a second function to detect whether the logger was in saltwater or not (Fig. 2). This wet/dry saltwater immersion check was performed every 30 secs and a count of 'wets' recorded. Due to memory limitations, the maximum count of 'wets' in any four hours was three and not 120.

During the study period, several adult females in Svalbard were also fitted with ST collars (TGW-4678–3 and TGW-4678–4, Telonics, AZ, USA), recording GPS locations (accurate to within a few metres) every two hours. Further, these ST collars also recorded temperature (instantaneously every second hr) as well as bear activity (number of seconds a bear movement exceeded an accelerometer threshold, within each 2-h period). These data were transmitted via the Iridium satellite network. The two Greenland bears equipped with GLS loggers were also fitted with ST collars (TAW-4610, Telonics, AZ, USA) but, rather than recording GPS locations and transmitting the data via satellite, these were Argos PTTs (Platform Transmitter Terminals) and their location determined using the Doppler method every four days by the ARGOS satellite network (Collecte Localisation Satellites). In contrast to GPS, ARGOS locations are accurate to a few km [32]. In this manner, 22 adult females were double-tagged with both ST collars and GLS loggers during 2013–2020 (some several times) and, where GLS loggers were later retrieved, the collar data provided accurate location and reproductive history to compare with GLS derived data.

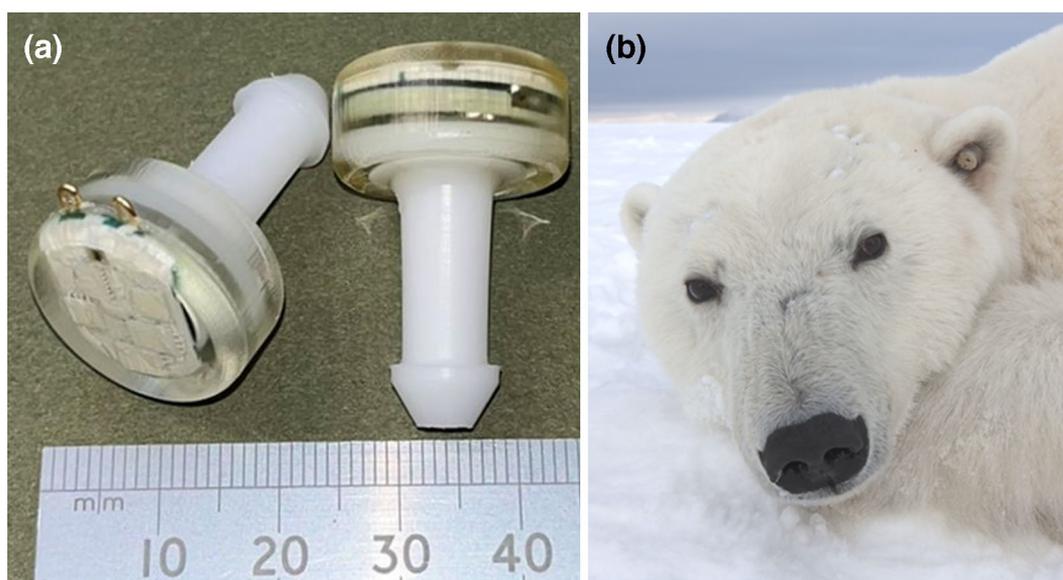


Fig. 2 **a** Intigeo-PB ear-tag GLS logger and **b** the GLS equipped on the ear of an adult female polar bear

Classifying reproduction and denning phenology

Reproduction events for female adult polar bears were systematically classified as maternity denning (hereafter “denning”, or D1) or non-denning (hereafter D0), for each winter period when data were available. We used three different data sources: (1) capture event information, (2) ST collars, and (3) GLS loggers. Maternity denning was assumed to occur sometime between 15 September and 15 May, based on earlier phenology studies across the Arctic [9, 11, 12, 14, 33–36]. Cubs are born in mid-winter, by mid-January [11, 37]. Short periods of up to a few weeks in a den were assumed to be temporary shelter denning, and thus unless denning events were longer than 2 months, we assumed no reproduction (D0) for that winter.

The presence of COYs or yearlings during capture was used to classify recent reproductive history of adult females as maternity denning or non-denning [38]. Females have an assumed 3-year reproductive cycle, weaning cubs at the age of 2 years and 3–4 months in most Arctic areas, including Svalbard [11]. They are assumed to not enter a den for a prolonged period when with older cubs. The presence of COYs signifies that the female was in a maternity den the previous winter (D1), while the presence of yearlings signifies that the female was in a maternity den two winters ago (and therefore did not den (D0) last winter). If a female was lactating and alone in spring when captured, proving she nursed cubs at some stage, but at the same time capture or sensor data proves she never reproduced until a year before capture, we know she gave birth (and lost COYs) the winter before capture (and was denning, D1). The typical age of first reproduction for female polar bears in Svalbard is 6 years [39].

Denning history estimation using ST collars followed methods in previous studies [9, 12–15, 40]. Denning events as well as denning phenology (timing of den entry and exit) were assessed using movement behaviour as well as temperature and activity profiles throughout the winter months [41].

A similar approach was used to identify denning events using GLS loggers. Here, light, temperature and saltwater immersion data were used to classify winter behaviour and denning phenology. The light data signature of a denning bear (entering a dark den) is characterized by an early abrupt seasonal drop and/or late abrupt increase in estimated daylength and mean and max daily light intensity recorded compared to the expected seasonal light curve at the last capture latitude (Fig. 3). This was supplemented with daily mean 4-h minimum temperature data. A denning event could be clearly identified by an increase (at start) and later decrease (at emergence) in recorded temperature and concurrent diversion from ambient

temperature as recorded at Longyearbyen airport (yellow square in Fig. 1). Temperature profiles for Longyearbyen airport have been downloaded from the Norwegian Meteorological Institute (frost.met.no, accessed 23 June 2022). Further, saltwater immersion records corroborated light and temperature information as bears showed no indications of being in saltwater when denning but did so during other times of the year, likely because of occasional swimming and diving (head and thus GLS submerged) in the sea (Fig. 3). Other causes might also produce a “wet” signal such as sweat, saliva or other conductive liquids deposited between the contacts of the logger. The ‘burst’ mode temperature record in the logger was analysed but did not yield more information than using daily mean 4-h minimum temperature records to establish denning information and was not used in further analyses.

Scored denning events (D1 or D0) using ST collars and GLS information were validated with each other, and by visual observation of bears during subsequent capture (e.g., presence of COYs), where possible (Additional file 1: Fig. S1).

Location estimation

Location estimation using light-level geolocators requires the determination of discrete twilight events as defined by dawn and dusk light thresholds. Initial twilight event timings for all bears were determined from log-transformed recorded light intensities and time using the function `twilightCalc` and a threshold of 3.1 lx (GeoLight package [42]). This threshold value was used for all deployments. During several autumn (August to November) and spring seasons (February to April) identification of these twilight transitions was challenging due to noisy light data, likely as a consequence of the bears’ behaviour (e.g., in den, dirty). These instances of noisy data were identified using `twilightEdit` (TwGeos package [43]), a function designed to identify likely erroneous events in consecutive days, using a 4 day window, a 30 min outlier threshold and a 15 min stationary site variation.

Locations based on twilight transitions were calculated with the threshold method [44] using the `thresholdLocation` function (SGAT package [45]), a calibrated solar angle of -3.5° , and a tolerance of 0.18. The tolerance chosen relates to the strength of the rejection of latitude results close to the equinoxes when the solar declination is near zero and hence latitude estimates are extremely sensitive to errors. The solar angle corresponding to the twilight light threshold was determined using “in-habitat” calibration of all 2533 sets of twilight transitions in seasons with less than 30% likely erroneous seasonal data (as identified with `twilightEdit`, Additional file 1: Fig. S2) and during days at which ST collar GPS locations were

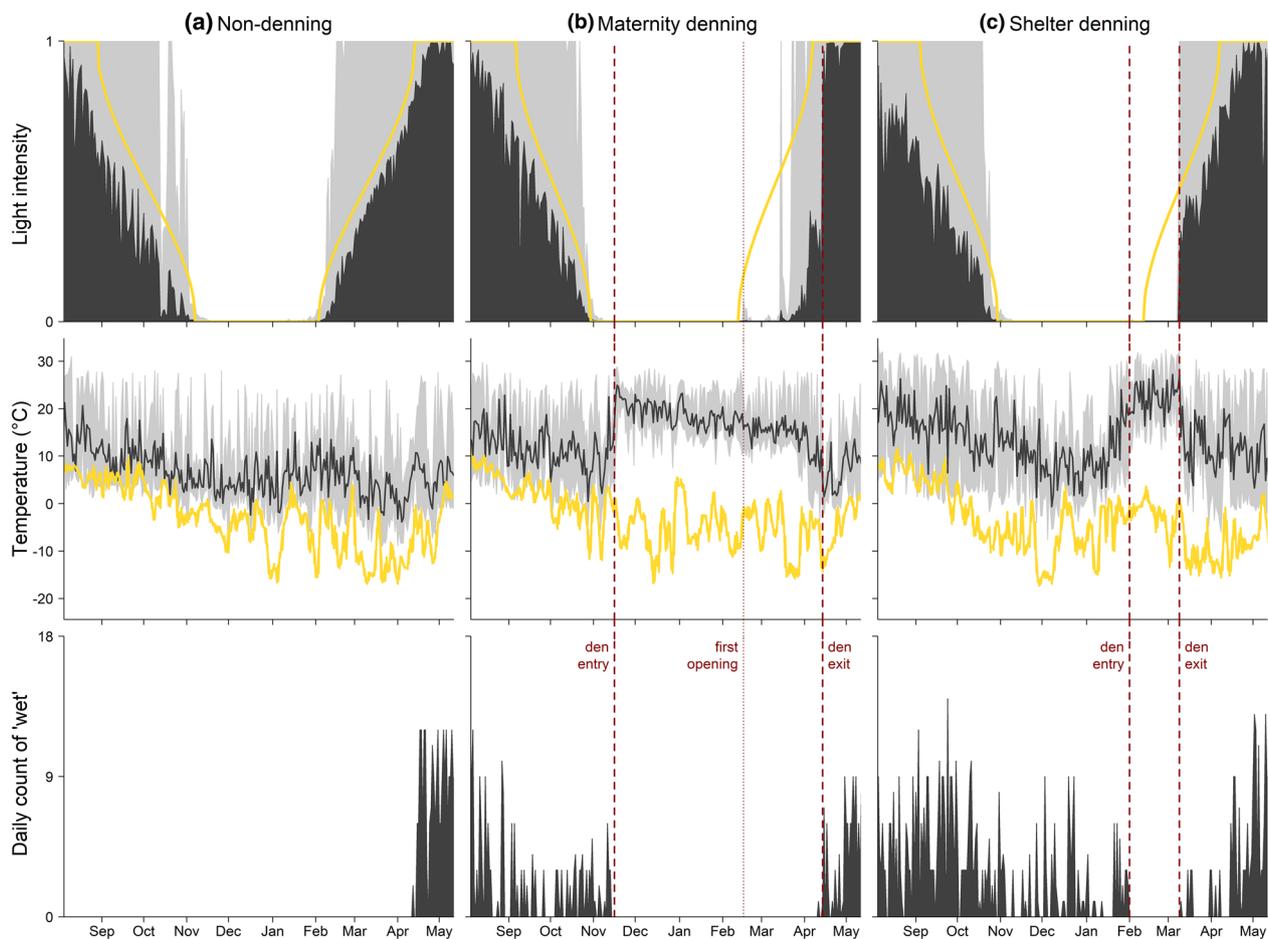


Fig. 3 Examples of GLS data signatures for three winters: **a** non-denning (D0), **b** maternity denning (D1), and **c** short shelter denning (D0). Top: Daily mean (black) and maximum (grey) light intensity (on an arbitrary scale of 0 to 1) as measured by the GLS is shown with ideal day length at the last capture location (yellow, scaled to 0 to 1). Middle: Mean daily in-ear logger temperature (as minimum record every 4 h; black) is plotted together with its daily range (grey) and surface air temperature at Longyearbyen airport, Svalbard (yellow, Fig. 1). Bottom: Daily count of 'wet' recordings (maximum of 18 = count of 3 during all six 4-h periods during a day) the logger registered using a conductivity switch (black). Vertical stippled and dotted red lines denote behaviour classified as den entry, first den opening and den exit

also available across all individuals (Additional file 1: Fig. S3 [44]). Location accuracy of GLS logger derived positions was quantified for all double tagged individuals as great circle distance to ST collar derived positions twice daily as well as between seasonal median locations. All analyses were conducted in R 4.1.2 [46].

Results

In total, 271 GLS loggers were deployed in Svalbard from 2012 to 2019 (33 on immature bears 1–4 years of age). Of these, 117 were retrieved in 2013 to 2021 (43% recovery rate, 4 from immature bears), while 7 were identified to have been lost upon recapture (3%, 0 from immature bears). We retrieved on average 1.8 years of data (range 0.2–5.4 years) from 103 recovered GLS

loggers (88% of retrieved tags) equipped to 54 different adult females (several were fitted with ear-tags multiple times). Two GLS tags deployed in Greenland were retrieved and also yielded data. During the study period, we also collected data from 80 ST collars equipped to 44 adult females (several of the bears were fitted with collars multiple times). Of these, 25 individuals were double tagged with GLS and ST collars simultaneously for a period. The periods with GLS data for adult females varied from 0.9 to 9.4 years (mean (\bar{O}) 4.0 years), compared to 0.2–5.1 years (\bar{O} 1.5 years) for ST collars. Individual GLS loggers and ST collars collected data over a period of 0.1–5.0 years (\bar{O} 1.6 years), and 0.1–2.2 years (\bar{O} 0.8 years), respectively.

Classifications of winter denning

All tagged individuals in Svalbard combined were known to be alive for 265 winters during 2012/13 to 2019/20. A third (32%) of these winters could be classified as denning (D1) or non-denning (D0) events using capture event information such as the presence of cubs of the year (COY) or yearlings (Table 1). Similarly, 28% of winters could be classified as D0 or D1 using ST collar only and 61% of winters could be classified as D0 or D1 using GLS logger data only. Winter classifications reached 54%, 72% and 84%, when ST data were combined with capture data, GLS data with capture data, and all three data sources combined, respectively (Table 1). Depending on data sources (captures, ST collars or GLS loggers), on average, 1.2–4.3 years of unbroken reproductive history records were collected, while 8-year unbroken records were obtained for 7 individuals (Table 1, Fig. 4). Similarly, age at first reproduction was determined for four females where the age was certain based on first capture as dependent cubs (Table 2). In total, 19 (25%) and 56 winters (35%) classified using ST collars and GLS loggers respectively, could be confirmed with capture event information with no inconsistencies. Similarly, for all 26 winters where classification was made using both ST collars and GLS logger independently (but without capture information) there were no contradictions (D1 $n=9$, D0 $n=17$).

Locations

In Svalbard, twilight transitions were only registered during spring (February – April) and autumn (August – November) at times of the year when the archipelago was not in polar night or midnight sun (Fig. 5). This resulted in ~80 days of twilight transitions during each spring or autumn season. Of those, the latitudinal aspect of location estimation was not affected by equinox periods for ~38 days. This resulted in, on average, 100 longitude (range: 2–251) and 19 latitude (range: 0–56) estimates per bear per season. Fewer latitudes

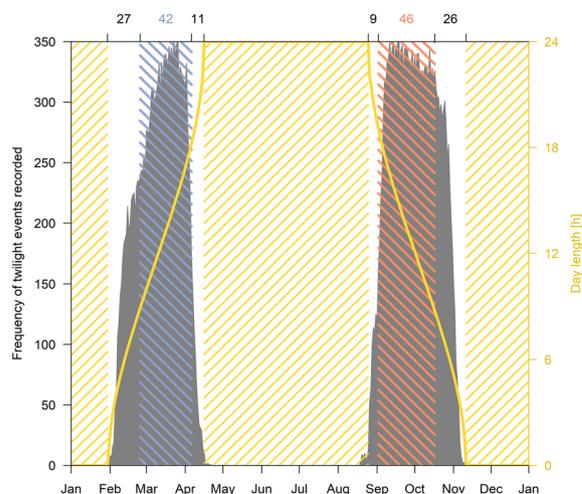


Fig. 4 Frequency of twilight events recorded by all GLS in Svalbard throughout the year (grey). Yellow line denotes day length at 76°N (southern edge of Spitsbergen). Hatched areas illustrate times of the year without twilight events (i.e., polar night or midnight sun; yellow) as well as times when latitude estimation is affected by spring (blue) or fall (orange) equinox. Number of days when location estimation is possible (and potentially affected by equinoxes) throughout the year are shown on top

could be estimated during spring seasons following maternity denning events with, on average, 5 estimates (range: 0–35). At the more southerly locations in Greenland, positions could be estimated also during summer and, in parts, during winter (Additional file 1: Fig. S4). Consequently, a bear’s general space use could be quantified during up to 11% (38% using only longitudes, Fig. 5) and 43% (68% using only longitudes) of the year in Svalbard and Greenland, respectively. Median twice daily as well as median seasonal location accuracy in Svalbard was estimated at 90 km (range: 4–2943 km, $n=818$) and 48 km (range: 1–516 km, $n=61$), respectively. Similar accuracies are found for the two females tagged in Greenland (twice daily accuracy:

Table 1 Reproductive events (D1 = maternity den, D0 = not in maternity den) classified for all 52 adult females in Svalbard which at some point had a GLS logger during winter seasons 2012/13 to 2019/20

Data source	Denning classified n (D1/D0)	Percent classified of all 265 bear winters during this period%	Mean (max for n ind) years with unbroken record
Capture events	86 (45/41)	32	1.5 (5, $n=2$)
ST collars	75 (36/39)	28	1.2 (4, $n=1$)
GLS	162 (76/86)	61	3.1 (8, $n=2$)
Capture events + ST Collars	142 (72/70)	54	2.4 (8, $n=2$)
Capture events + GLS	192 (90/102)	72	3.8 (8, $n=3$)
Capture Events + GLS + ST COLLARS	222 (108/114)	84	4.3 (8, $n=7$)

Table 2 Four instances where data from GLS ear-tags together with capture data (CAP) enabled the determination of age at first reproduction. These females were captured first as COYs, providing known age. The first reproduction attempt is highlighted in bold for each individual. D1 = denning, D0 = non-denning

Age	Bear A	Bear B	Bear C	Bear D
4	(GLS) D0	(GLS) D0	No information	No information
5	(GLS) D1	(GLS) D0	(CAP) Never lactated	(CAP) Never lactated
6	(GLS) D0	(CAP) Lactating	(GLS) D0	(GLS) D0
7	(GLS) D1	No information	(GLS) D1	(GLS) D0
8	No information	No information	(GLS) D0	(GLS) D1

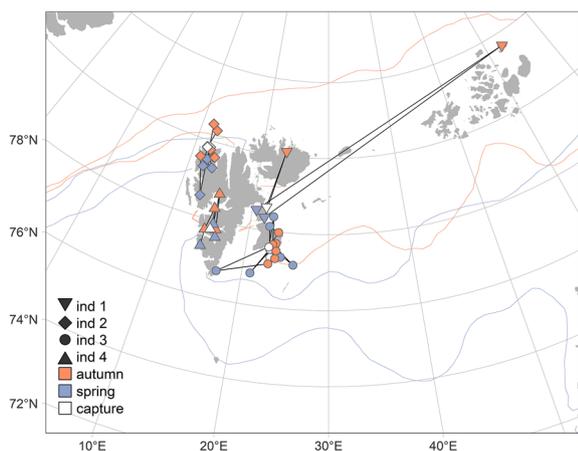


Fig. 5 Examples of multi-year tracks, based on GLS data, of consecutive seasonal centroids and capture locations of four females denoted with different symbols. Lines illustrate extreme sea ice extends during autumn (2014 & 2018, orange) and spring (2016 & 2020, blue). Projection: Azimuthal Equidistant centred on 78°N and 30°E

median = 83 km, range = 12–366 km, $n = 65$; seasonal accuracy: median = 43 km, range = 9–1609 km, $n = 8$). This way, seasonal centroids accurately inform about overall female space use and seasonal movement (Fig. 6). This includes general denning locations with a median accuracy of 215 km (range = 18–516 km, $n = 6$, Additional file 1: Fig. S5).

(See figure on next page.)

Fig. 6 Example of eight years of unbroken reproductive history information, general space use and yearly light profiles for an adult female polar bear in Svalbard. Reproductive history: Winter classification as maternity denning (D1) or non-denning (D0) was based on capture information (CAPTURE), ST collar (ST) and GLS logger data (GLS). Captures with cubs of the year are shown as COY (indicating D1). This female was tagged with her first GLS at capture in 2012, and a new one at each subsequent capture. Thus, the data shown are from three GLS tags, with 4, 1, and 3 years of data. She received a ST collar in 2017 that provided data for one year. General space use: Seasonal centroids (autumn (Aug–Nov) in orange and spring (Feb–Apr) in blue) and capture locations (white diamond) are plotted for each winter on a longitude–latitude grid. Stippled vertical and horizontal lines denote mean seasonal longitudes and latitudes while density plots on each axis correspond to distribution from estimated twice daily light locations. ST collar GPS tracks are added when available (color-coded by season and black if outside these seasons). Yearly light profile: Black and white denote time of day with recorded darkness and light, respectively. Rug plots at the bottom of each panel depict successful location estimates. Hatched areas illustrate latitudes affected by equinox periods during spring (blue) and autumn (orange). Curved yellow lines illustrate the change in timing of twilight (approx. sunrise and sunset) at the most recent capture location throughout the year. Capture event timings are depicted as ‘C’ in white diamonds and with additional arrows if they occurred outside the plotting region

Discussion

In this study, we established the use of small GLS ear-tags as a powerful and low-cost method for long-term monitoring of polar bear populations, with the ability to provide data on polar bear reproduction and general space use. We demonstrated that GLS loggers can even be applied in the high Arctic Archipelago of Svalbard as well as in lower latitudes in eastern Greenland. At more southerly latitudes, due to the nature of light-level geolocation, location data can be acquired for significantly longer periods compared to higher latitudes. This is the case for most of the 19 Arctic polar bear populations, being located further south than Svalbard [11].

Reproductive history (denning/no denning) could be determined for more than 72% of bear winters during an eight-year period among adult females where GLS tags were retrieved. This presents a significant improvement in estimating actual reproductive history of polar bear females compared to traditional methods such as capture-recapture and ST collars alone. Thus, we show that in populations with a capture–recapture programme, GLS can be an important asset in studies on reproductive success, and reproductive ecology in general, e.g., to identify deviations from, or showing variation in, the reproductive cycle. Using capture and GLS ear-tag data, we also identified a specific case of a female mating when having yearlings alive, rather than one year later, as is the assumed norm in most polar bear populations [11]. Thereby, we could show that

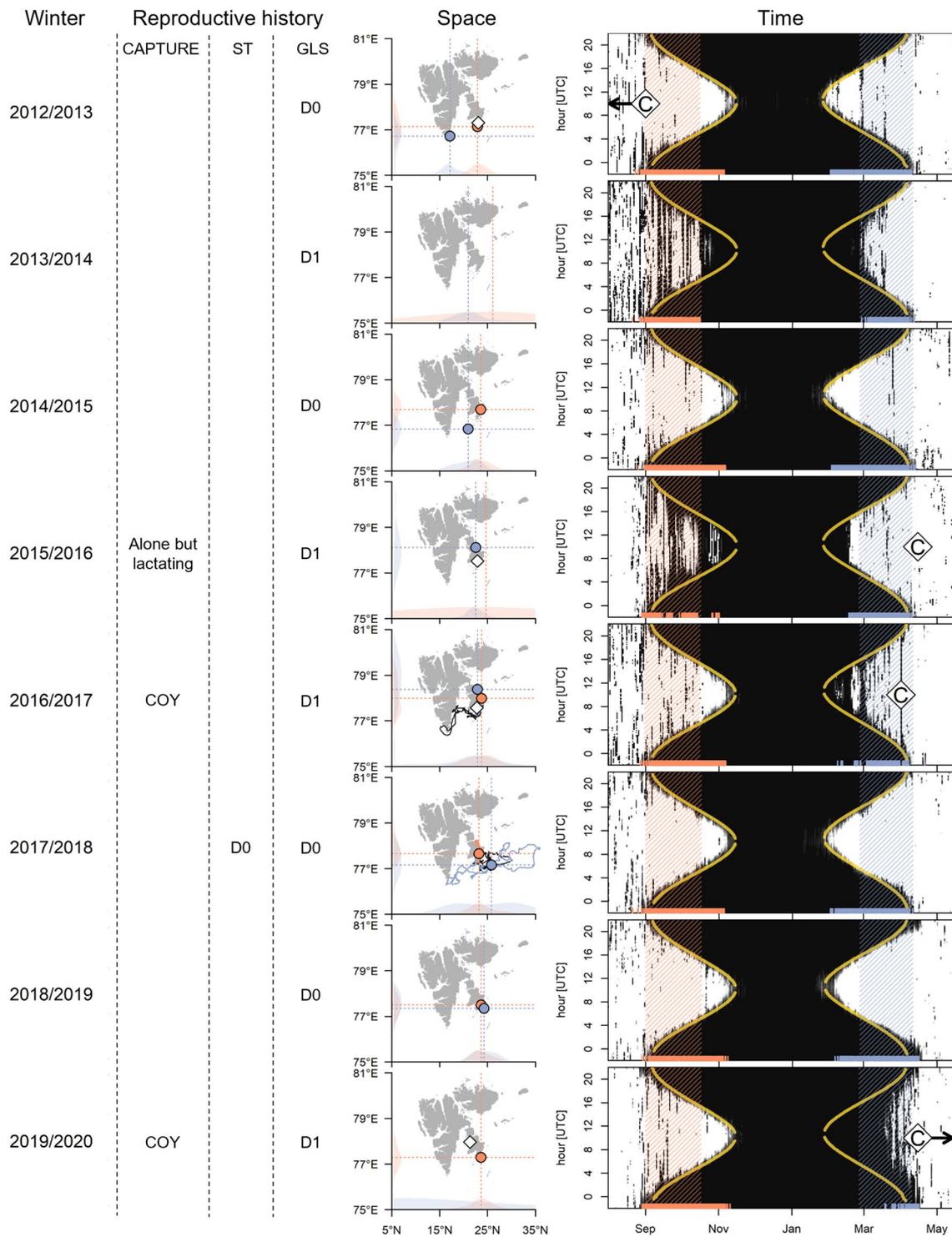


Fig. 6 (See legend on previous page.)

required assumptions about reproductive history based on an adult female’s status at the time of capture are not always valid and more complete records of reproductive history are necessary. While ST collars can only

be deployed safely on adult females [4], we deployed GLS ear-tags on all females one year or older. Thus, we can also obtain reproductive data for the early years

of females recaptured as adults, including age at first reproduction.

We showed that GLS loggers, like ST collars, provide data on denning phenology and general space use. Because these small GLS ear-tags can be deployed also on adult males and all younger bears of both sexes, they are well suited for studies on shelter denning behaviour, dispersal and movement behaviour and how this may vary among age classes, sexes and individuals [11]. Although smaller ST devices (at 40 – 70 g; still considerably larger than the 5.9 g ear-tags used here) with varying attachment methods have been used for males and young bears earlier, these have in several cases been less optimal both due to tissue damage and short battery life [16]. Based on deviations and break points in measured light levels and temperatures, and supplemented with an activity proxy, our approach could be widely generalized to other challenging to monitor denning species such as wolverines (*Gulo gulo*) [47] or arctic foxes (*Alopex lagopus*) [48].

The GLS loggers also come with disadvantages. Being archival, they must be retrieved during a subsequent physical recapture of the tagged individual as there is no remote data telemetry, unlike with ST collars. Hence, this approach will be less useful for roaming or pelagic bears inhabiting the pack ice [49], or in subpopulations where there is less monitoring effort. Also, spatial location accuracy and precision using GLS is far lower than using ARGOS PTT [50] or GPS tracking [51] due to the inherent nature of location estimation using ambient light [52]. However, our calculated median 43–90 km error rate for estimated polar bear location was significantly lower than that reported for flying birds (~100 s of kms) [50, 51, 53]. Potential reasons for this include, lower spatial density of location fixes for fast moving birds compared to walking bears, and increased variability in ambient light attenuation with birds due to the attachment method, the animal's behaviour as well as its habitat. Another disadvantage is that GLS have only sparse positional coverage at high latitudes. The twilight events required to estimate locations are not available during times of midnight sun and polar night, while latitude cannot be estimated during spring and fall equinox [52]. Consequently, location estimation is often not possible after maternity den emergence at high latitudes, where females may exit dens during spring equinox or in midnight sun conditions [9, 11, 12, 14, 33–36]. With recent advances in location estimation using GLS incorporating both new sensors (e.g., pressure [54]) and new methods (geolocation in 24-h daylight [55]) positional coverage and accuracy may improve.

Conclusion

We have shown that GLS loggers are a powerful method to monitor polar bear populations, even at high Arctic latitudes, which are the extreme limit for light-level geolocation. In long-term monitoring programs with ongoing capture-recapture, this approach provides valuable knowledge on polar bear reproductive history and general space use. In studies that span only a few years, requiring accurate location estimates, or those with low recapture probability, use of ST collars would be a better tool. Of note, GLS ear-tags record data up to about 5 years and can be retrieved years after that, making them a valuable long-term monitoring tool also in areas with low recapture probability as long as monitoring is ongoing. The use of GLS may also lead to new knowledge about immature polar bears and adult males, which cannot be tracked with any other currently available method.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s40317-023-00323-4>.

Additional file 1. Supplementary figures supporting the approach detailed.

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Author contributions

All authors conceived the idea and designed the study; JF and JA designed the logger; JA and KL collected the data; BM and JA analysed the data; BM led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication. All authors read and approved the final manuscript.

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Availability of data and materials

The R scripts used for the analyses presented in this study are available at <https://github.com/benjamin-merkel/Polar-bear-GLS>. The Svalbard GLS ear-tag dataset supporting the conclusions of this article are available at the Norwegian Polar Data Centre, <https://data.npolar.no>, <https://doi.org/10.21334/npolar.2023.f361dff9>.

Declarations

Ethics approval and consent to participate

All animal handling was approved by the Norwegian Animal Research Authority, the Government of Greenland and with permits from the Governor of Svalbard and Government of Greenland.

Competing interests

JF is employed by Migrate Technology Ltd, which developed and produced the loggers.

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References

- Honrado JP, Pereira HM, Guisan A. Fostering integration between biodiversity monitoring and modelling. *J Appl Ecol*. 2016;53:1299–304.
- Fretwell PT, Scofield P, Phillips RA. Using super-high resolution satellite imagery to census threatened albatrosses. *Ibis*. 2017;159:481–90.
- Stapleton S, LaRue M, Lecomte N, Atkinson S, Garshelis D, Porter C, Atwood T. Polar Bears from Space: assessing satellite imagery as a tool to track Arctic Wildlife. *PLoS ONE*. 2014;9: e101513.
- Laidre KL, Durner GM, Lunn NJ, Regehr EV, Atwood TC, Rode KD, Aars J, Routti H, Wiig Ø, Dyck M, Richardson ES, Atkinson S, Belikov S, Stirling I. The role of satellite telemetry data in 21st century conservation of Polar Bears (*Ursus maritimus*). *Front Marine Sci*. 2022. <https://doi.org/10.3389/fmars.2022.816666>.
- Wearn OR, Glover-Kapfer P. Snap happy: camera traps are an effective sampling tool when compared with alternative methods. *Royal Soc Open Sci*. 2019;6: 181748.
- Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, Venail P, Narwani A, Mace GM, Tilman D, Wardle DA, Kinzig AP, Daily GC, Loreau M, Grace JB, Larigauderie A, Srivastava DS, Naeem S. Biodiversity loss and its impact on humanity. *Nature*. 2012;486:59–67.
- Laidre KL, Stern H, Kovacs KM, Lowry L, Moore SE, Regehr EV, Ferguson SH, Wiig Ø, Boveng P, Angliss RP, Born EW, Litovka D, Quakenbush L, Lydersen C, Vongraven D, Ugarte F. Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. *Conserv Biol*. 2015;29:724–37.
- Ramsay MA, Stirling I. On the mating system of polar bears. *Can J Zool*. 1986;64:2142–51.
- Messier F, Taylor MK, Ramsay MA. Denning ecology of Polar Bears in the Canadian Arctic archipelago. *J Mammal*. 1994;75:420–30.
- Stirling I. Polar Bears: The Natural History of a Threatened Species. Ontario: Fitzhenry and Whiteside; 2011.
- Amstrup SC. The Polar Bear, *Ursus maritimus*. In: Feldhamer GA, Thompson BC, Chapman JA, editors. *Wild mammals of North America: biology, management, and conservation*. Baltimore: Johns Hopkins University Press; 2003. p. 587–610.
- Wiig Ø. Survival and reproductive rates for polar bears at Svalbard. *Ursus*. 1998;10:25–32.
- Fischbach AS, Amstrup SC, Douglas DC. Landward and eastward shift of Alaskan polar bear denning associated with recent sea ice changes. *Polar Biol*. 2007;30:1395–405.
- Escajeda E, Laidre KL, Born EW, Wiig Ø, Atkinson S, Dyck M, Ferguson SH, Lunn NJ. Identifying shifts in maternity den phenology and habitat characteristics of polar bears (*Ursus maritimus*) in Baffin Bay and Kane Basin. *Polar Biol*. 2018;41:87–100.
- Rode KD, Olson J, Eggett D, Douglas DC, Durner GM, Atwood TC, Regehr EV, Wilson RR, Smith T, Martin MST. Den phenology and reproductive success of polar bears in a changing climate. *J Mammal*. 2018;99:16–26.
- Wiig Ø, Born EW, Laidre KL, Dietz R, Jensen MV, Durner GM, Pagano AM, Regehr E, Martin MST, Atkinson S, Dyck M. Performance and retention of lightweight satellite radio tags applied to the ears of polar bears (*Ursus maritimus*). *Animal Biotelemetry*. 2017;5:9.
- Wilson RP, Ducamp JJ, Rees WG, Culik BM, Niekamp K. Estimation of location: global coverage using light intensity. *Wildlife telemetry - Remote Monitoring and Tracking of Animals*. 1992:131–134.
- DeLong RL, Hill RD. Documenting migrations of northern elephant seals using day length. *Mar Mammal Sci*. 1992;8:155–9.
- Fuller WJ, Broderick AC, Phillips RA, Silk JRD, Godley BJ. Utility of geolocating light loggers for indicating at-sea movements in sea turtles. *Endang Species Res*. 2008;4:139–46.
- Croxall JP, Silk JRD, Phillips RA, Afanasyev V, Briggs DR. Global circumnavigations: tracking year-round ranges of nonbreeding albatrosses. *Science*. 2005;307:249–50.
- Stutchbury BJM, Tarof SA, Done T, Gow E, Kramer PM, Tautin J, Fox JW, Afanasyev V. Tracking long-distance songbird migration by using geolocators. *Science*. 2009;323:896–896.
- Niles LJ, Burger J, Porter RR, Dey AD, Minton CD, González PM, Baker AJ, Fox JW, Gordon C. First results using light level geolocators to track Red Knots in the Western Hemisphere show rapid and long intercontinental flights and new details of migration pathways. *Wader Study Group Bulletin*. 2010;117:123–30.
- Block BA, Dewar H, Blackwell SB, Williams T, Prince E, Boustany AM, Farwell C, Dau DJ, Seitz A. Archival and Pop-up Satellite Tagging of Atlantic Bluefin Tuna. In: Sibert JR, Nielsen JL, editors. *Electronic Tagging and Tracking in Marine Fisheries: Proceedings of the Symposium on Tagging and Tracking Marine Fish with Electronic Devices*, February 7–11, 2000, East-West Center, University of Hawaii. Dordrecht: Springer; 2001.
- Williams CT, Wilsterman K, Kelley AD, Breton AR, Stark H, Humphries MM, McAdam AG, Barnes BM, Boutin S, Buck CL. Light loggers reveal weather-driven changes in the daily activity patterns of arboreal and semifossorial rodents. *J Mammal*. 2014;95:1230–9.
- Refsnider JM, Qian SS, Streby HM, Carter SE, Clifton IT, Siefker AD, Vazquez TK. Reciprocally transplanted lizards along an elevational gradient match light environment use of local lizards via phenotypic plasticity. *Funct Ecol*. 2018;32:1227–36.
- Williams CT, Wilsterman K, Zhang V, Moore J, Barnes BM, Buck CL. The secret life of ground squirrels: accelerometry reveals sex-dependent plasticity in above-ground activity. *Royal Society Open Science*. 2016;3: 160404.
- Bridge ES, Thorup K, Bowlin MS, Chilson PB, Diehl RH, René W. Technology on the move: recent and forthcoming innovations for tracking migratory birds. *Bioscience*. 2011. <https://doi.org/10.1525/bio.2011.61.9.7>.
- Stirling I, Spencer C, Andriashek D. Immobilization of polar bears (*Ursus maritimus*) with TELAZOL in the Canadian Arctic. *J Wildl Dis*. 1989;25:159–68.
- Calvert W, Ramsay MA. Evaluation of age determination of polar bears by counts of cementum growth layer groups. *Ursus*. 1998;1:449–53.
- Christensen-Dalsgaard S, Aars J, Andersen M, Lockyer C, Yoccoz N. Accuracy and precision in estimation of age of Norwegian Arctic polar bears (*Ursus maritimus*) using dental cementum layers from known-age individuals. *Polar Biol*. 2010;33:589–97.
- Stirling I, Jonkel C, Smith P, Robertson R, Cross D. The ecology of the polar bear (*Ursus maritimus*) along the western coast of Hudson Bay. Occasional paper Canadian Wildlife Service. 1977;33:1–64.
- Lowther AD, Lydersen C, Fedak MA, Lovell P, Kovacs KM. The Argos-CLS Kalman filter: error structures and state-space modelling relative to fastloc GPS Data. *PLoS ONE*. 2015. <https://doi.org/10.1371/journal.pone.0124754>.
- Derocher AE, Andersen M, Wiig Ø, Aars J, Hansen E, Biuw M. Sea ice and polar bear den ecology at Hopen Island. *Svalbard Marine Ecol Progress Series*. 2011;441:273–9.
- Laidre KL, Born EW, Heagerty P, Wiig Ø, Stern H, Dietz R, Aars J, Andersen M. Shifts in female polar bear (*Ursus maritimus*) habitat use in East Greenland. *Polar Biol*. 2015;38:879–93.
- Olson JW, Rode KD, Eggett D, Smith TS, Wilson RR, Durner GM, Fischbach A, Atwood TC, Douglas DC. Collar temperature sensor data reveal long-term patterns in southern Beaufort Sea polar bear den distribution on pack ice and land. *Mar Ecol Prog Ser*. 2017;564:211–24.
- Amstrup SC, Gardner C. Polar bear maternity denning in the Beaufort Sea. *J Wildl Manag*. 1994;58:1–10.
- Harington CR. Denning habits of the polar bear (*Ursus maritimus* Phipps). *Canadian Wildlife Service Rep*. 1968;5:1–30.
- Stirling I, Andriashek D. Terrestrial maternity denning of polar bears in the Eastern Beaufort Sea Area. *Arctic*. 1992;45:363–6.
- Derocher A. Population ecology of polar bears at Svalbard. *Norway Population Ecol*. 2005;47:267–75.

40. Messier F, Taylor MK, Ramsay MA. Seasonal activity patterns of female polar bears (*Ursus maritimus*) in the Canadian Arctic as revealed by satellite telemetry. *J Zool.* 1992;226:219–29.
41. Andersen M, Derocher AE, Wiig O, Aars J. Polar bear (*Ursus maritimus*) maternity den distribution in Svalbard. *Norway Polar Biology.* 2012;35:499–508.
42. Lisovski S, Hahn S. GeoLight—processing and analysing light-based geolocator data in R. *Methods Ecol Evol.* 2012;3:1055–9.
43. Lisovski S, Wotherspoon S, Michael S. TwGeos: Basic data processing for light-level geolocation archival tags. R package version 0.1.2. 2016 <https://github.com/slisovski/TwGeos> Accessed 13 Dec 2022.
44. Lisovski S, Bauer S, Briedis M, Davidson SC, Dhanjal-Adams KL, Hallworth MT, Karagicheva J, Meier CM, Merkel B, Ouwehand J, Pedersen L, Rakhimberdiev E, Roberto-Charron A, Seavy NE, Sumner MD, Taylor CM, Wotherspoon SJ, Bridge ES. Light-level geolocator analyses: a user's guide. *J Anim Ecol.* 2020;89:221–36.
45. Sumner MD, Wotherspoon SJ, Hindell MA. Bayesian estimation of animal movement from archival and satellite tags. *PLoS ONE.* 2009;4: e7324.
46. Team RD. A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing; 2021.
47. Magoun AJ, Copeland JP. Characteristics of wolverine reproductive den sites. *J Wildl Manag.* 1998;62:1313–20.
48. Tannerfeldt M, Moehrenschrager A, Angerbjörn A. Den ecology of swift, kit and arctic foxes: a review. ecology and conservation of swift foxes in a changing world. Edited by MA Sovada and LN Carbyn. Canadian Plains Research Center, Regina, Sask. 2003:167–181.
49. Mauritzen M, Derocher AE, Wiig Ø. Space-use strategies of female polar bears in a dynamic sea ice habitat. *Can J Zool.* 2001;79:1704–13.
50. Phillips RA, Silk JRD, Croxall JP, Afanasyev V, Briggs DR. Accuracy of geolocation estimates for flying seabirds. *Mar Ecol Prog Ser.* 2004;266:265–72.
51. Halpin LR, Ross JD, Ramos R, Mott R, Carlile N, Golding N, Reyes-González JM, Militão T, De Felipe F, Zajková Z, Cruz-Flores M, Saldanha S, Morera-Pujol V, Navarro-Herrero L, Zango L, González-Solís J, Clarke RH. Double-tagging scores of seabirds reveals that light-level geolocator accuracy is limited by species idiosyncrasies and equatorial solar profiles. *Methods Ecol Evol.* 2021;12:2243–55.
52. Lisovski S, Hewson CM, Klaassen RHG, Korner-Nievergelt F, Kristensen MW, Hahn S. Geolocation by light: accuracy and precision affected by environmental factors. *Methods Ecol Evol.* 2012;3:603–12.
53. Merkel B, Phillips RA, Descamps S, Yoccoz NG, Moe B, Strøm H. A probabilistic algorithm to process geolocation data. *Mov Ecol.* 2016;4:26.
54. Nussbaumer R, Gravey M, Briedis M, Liechti F. Global positioning with animal-borne pressure sensors. *Methods Ecol Evol.* 2023;00:1–14.
55. Lisovski S. Light-level geolocation in polar regions with 24-hour daylight. *Wader Study Gr Bull.* 2018;125:129–34.

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