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# Adaptive Circadian Strategies of Arctic Mammals Under Extreme Photoperiods

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**Abstract:**
Arctic mammals experience month of continuous daylight in summer and continuous darkness in winter, challenging conventional circadian regulation. While photoperiod is traditionally considered as the dominant zeitgeber, evidence shows that many Arctis species have evolved adaptations beyond reliance on light signals. The experiment show that polar bears show flexibility, adjusting their circadian clock depending on both prey availability and environmental constraints. Similarly, the experiment show Arctic ground squirrels and other resident mammals depend on non-photic cues such as temperature fluctuations, food availability and internal hormone cycles, ensuring that reproduction and survival act even when light is an unreliable zeitgeber. However rapid climate change is decreasing sea-ice and snow cover, animal population and damage cyclic dynamics of rodents and their predators, disturbing adaptive mechanisms. Understanding circadian adaptions under extreme environmnets is essential for predicting the resilience of Arctic animals under climate change. These insights highlight the urgency of integrating chronobiological perspectives into Arctic conservation strategies to mitigate biodiversity loss in a rapidly changing climate.

**Keywords:** Circadian rhythm; Arctic mammals; Climate change.

## 1. Introduction

Biological timing systems are essential for the survival of organisms across extreme environments. At temperate latitudes a rhythm that lasts roughly 24 hours, links physiology and behavior to regular daily and seasonal cycles. Seasonal changes in day length act as trustworthy indicators that links to internal and external clocks, allowing organisms to maximize energy balance, reproduction, and activity patterns. However, in the Arctic this is a big challenge where extreme seasonal variation leads to almost no normal light-dark cycles. Organisms experience months of continuous daylight in the summer and continuous darkness in the winter [1]. Light is no longer a reliable Zeitgeber in these conditions, which leads to the question of how Arctic mammals control their biological timing.

Recent work over the past two decades have revealed striking diversity in the circadian strategies of Arctic mammals. For example, reindeer show a weak or absent circadian rhythms under either continuous light or long periods of darkness, showing that their clock may be arrhythmically or only seasonal expressed [2]. On the other hand, Arctic ground squirrels maintain strong circadian control during the active season but abandon circadian patterns during hibernation, relying instead on endogenous circannual cycles [3]. Seals and polar bears show further flexibility, routinely adjusting their internal timing to match feeding opportunities [4]. Together these cases show that high-latitude mammals have a unique circadian rhythm allow survival to adapt to the special photoperiodism.

Even with these advances, there are still significant knowledge and understanding gaps remain. Most studies on circadian rhythms have been on photic entrainment in model organisms. The non-photic processes of circadian regulation in Arctic mammals have not been studied as thoroughly. It's still not clear how much temperature changes, food abundance, geomagnetic fields, or social cues can replace photoperiod in these species. Also, it's still very hard to figure out how Arctic mammals' circadian rhythms can change, whether it's by turning off, reprogramming, or decoupling standard clock genes. The interplay between genes and environment is still unclear. These questions need to be answered right away because the Arctic is changing quickly with climate change that is changing the seasonal patterns of ice cover, the supply of prey, and the stability of habitats.

This work aims to synthesize existing knowledge on the seasonal timing systems of Arctic mammals, focusing on circadian adaptations that function without photoperiodic entrainment. By examining behavioral, physiological, and genetic data, it explores how these animals preserve temporal organization when the primary cue of day length is weak. Understanding such adaptations sharpens insight into circadian biology and clarifies the resilience—and vulnerability—of Arctic fauna under swiftly changing climatic conditions.

## 2. Material and Methods

The AGS's annual cycle includes a short season of activity, with above-ground activities limited to 3–5 months. After the breeding season, animals enter frozen burrows called hibernation burrows. Individuals experience long periods of continuous dormancy, with short periods of normal body temperature (35–37 °C) during the intermittent awakening phase. Males use stored food for 2–3 weeks before their first exit, and females are not considered to store food and usually resume their daily activities within 4 days of exiting the cave [3]. Data were collected at the Toolik Field Station (68°38′N, 149°38′W) at the University of Alaska Fairbanks on ground squirrels in the North Slope of Alaska. In the spring of 2010, nine adult male ground squirrels (weighing 710 ± 91 g) were implanted, and on 9 August one juvenile (weighing 593 g) was implanted. In September 2010, all individuals were captured again using isoflurane (2%–5%, oxygen-assisted) and temperature and light loggers were installed. In the spring of 2011, 9 out of 10 were successfully recaptured, of which 1 lost its collar, 1 light recorder failed, and 1 body temperature recorder failed. In the end, the body temperature and light data of 6 individuals when they entered hibernation and heterothotherms in autumn were obtained, and only the body temperature data of 4 individuals were retained because the batteries of 2 light recorders ran out in the middle of hibernation. Body temperature data were performed in Clocklab software (Actimetrics, Evanston, IL) using Lomb–Scargle periodogram analysis (Ruf 1999) to detect the presence and significance of rhythms over a range of 5–30 hours. The cycle analysis was measured in 10 days, including: (1) the active period before entering hibernation in autumn, (2) the underground normal body temperature stage, (3) the first dormant stage after soil freezing, (4) the first return to normal body temperature after completing heterothermia, (5) the pre-exit stage, and (6) the post-exit stage. The results showed that before entering hibernation, the core body temperature of male ground squirrels in the natural state had a diurnal rhythm with an amplitude of 2–4 °C, and the rhythm maintained a diurnal rhythm pattern and was synchronized with 24.0–24.2 hours ($P < 0.01$). When wearing a light recorder, the results showed that the individual had an expected increase in body temperature of 1–2 °C before exiting the acupuncture point, followed by exposure to the light environment. The daily decrease in body temperature correlates with the time of day when individuals return to the dark burrow (Fig. 1) [5].

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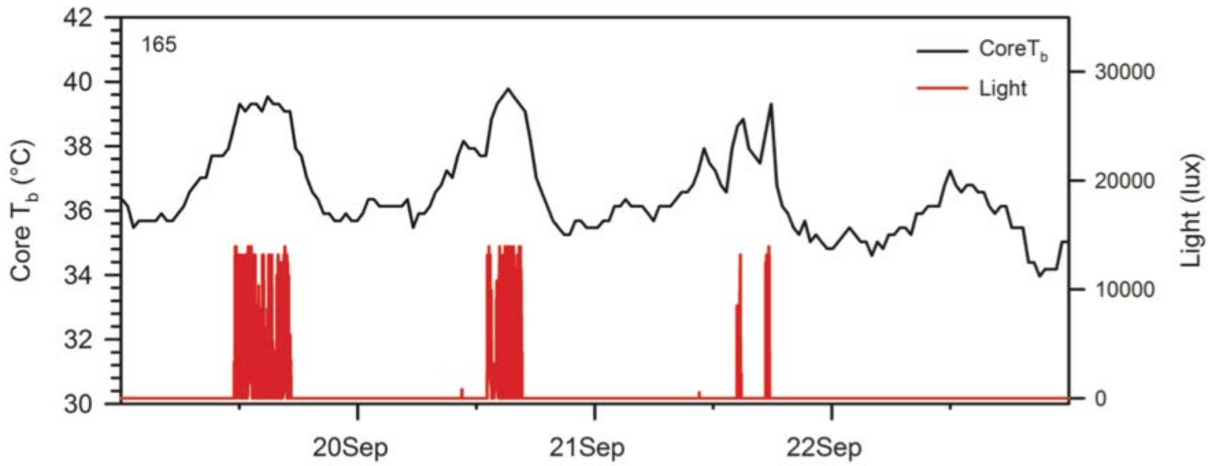


**Fig. 1 Core body temperature (T; black line) recorded each 34 min and exposure to light (red line) recorded each 30 s versus calendardate of a free-living male arctic ground squirel before entering the hibernacula in fall. Note that T, begins to rise before first exposure tolight, and the rhythm exhibits attenuated amplitude on the day the squirrel failed to emerge [5]**

Polar bears have a strong circadian rhythm. It averaged 24.40 ± 1.39 hours during the continuous light period (June–August) and 23.89 ± 1.72 hours during the continuous dark period (November–April, excluding the breeding period). It is relatively stable most of the year, but shifts occur during spring predation and seal littering. The results suggest that circadian rhythms are closely related to environmental photoperiod conditions, uncertainty in prey supply, and individual differences. Between 2009 and 2017, researchers monitored 147 female polar bears in the southern Beaufort Sea and the Chukchi Sea, and the United States Geological Survey (USGS) and the United States Fish and Wildlife Service (USFWS) collected data on 122 females at the same time. The study encoded the data on a monthly scale, and the results showed that the conclusions were basically the same whether it was weekly, biweekly or monthly. The activity level of individuals in the acupuncture period decreased significantly, but it is unclear whether their circadian rhythms are still functioning. Researchers combined seal population data to assess the potential impact of food availability on circadian rhythms. The results showed that April to June was the peak annual feeding period for polar bears, corresponding to the spring spawning period of seals. The rest of the months are considered non-farrowing and have fewer potential food resources. Reproductive status and hormonal fluctuations also affect activity patterns, but it remains unclear whether there are differences between females in different reproductive states. Further analysis and comparison were made between female individuals without cubs, with one-year-old cubs and with two-year-old cubs, and rhythm disturbances were modeled as binary variables, using the logit link function in the linear mixed model framework. The results showed that free-living polar bears were significantly less likely to experience rhythm disturbances than those who maintained their rhythms. When rhythm disorders occur, feeding period, habitat environment and burrowing status have significant effects on the probability of occurrence. Individuals were more likely to exhibit rhythm disturbances during peak feeding periods, and the probability of nursing females was higher than that of non-breeding females. Individuals who appeared on both ice and land in the same month were more likely to have rhythm disorders than individuals on the ice alone. However, there was no significant difference between individuals who were only active on land and those in ice or mixed ice and land environments. Photoperiod and reproductive status had no significant effect on the probability of rhythm disturbances (Fig. 2) [4]. Polar bears' circadian rhythms are driven by both light and food resources, as well as behavioral stages and habitats. The plasticity of its rhythm reflects the adaptability of polar bears to extreme environments and reveals that the regulation of species rhythms may face new challenges in the context of climate warming and sea ice reduction.

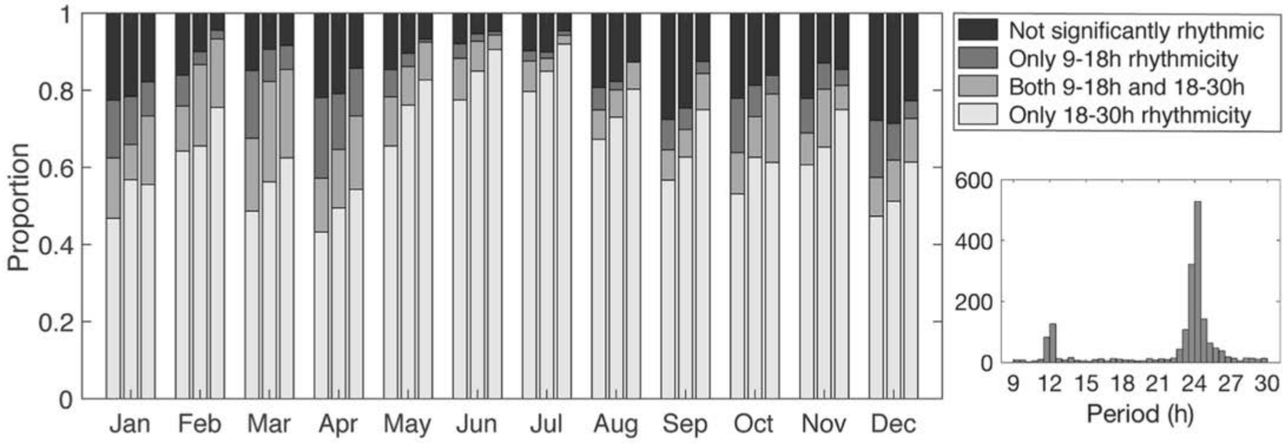


**Fig. 2 Proportion of rhythmic and arhythmic animals, in which each group of 3 stacked bars shows results from weekly (left)biweekly (middle), and monthly (right time windows of the data for the given month. Inset: histogram displaying the distribution ofsignificant periods for the entire data set, with counts of 2-week windows per 30-min period bin [4]**

Climate change could become an important factor affecting polar bears' circadian rhythms. Over the past 150 years, the global average surface temperature has risen by about 0.4 °C, while the Arctic has warmed two to three times as much as the world. In the past two or three decades, the extent of Arctic Sea ice has decreased at a rate of about 45,000 km² per year, with delayed freezing times and earlier melting times [6]. This presents a major challenge for Arctic marine mammals such as polar bears and seals, which rely heavily on sea ice [7]. It is also known that climate change can lead to shifts in animal population dynamics between stable and cyclic phases and has been proposed to modify the cyclic dynamics of rodents and their predators [8]. As previously stated, food availability – particularly seals, which serve as prey – is among the factors that impact the circadian rhythm of polar bears. To sum up, climate change may well be yet another vital factor affecting polar bears' circadian rhythms. The study indicates that Arctic mammals show a considerable level of flexibility in temporal regulation under extreme environments, with different species demonstrating distinct adaptive pathways in rhythm regulation. Comparisons between terrestrial rodents and large marine mammals underscore the driving impact of environmental factors such as temperature, food availability, and ice and snow cover on rhythm formation, further unveiling the coupling between physiological mechanisms and external conditions. These findings not only furnish critical evidence for comprehending life processes in extreme ecosystems but also provide valuable insights for prediction. Ground squirrels display prominent diurnal rhythms at high latitudes and exhibit different body temperature patterns during hibernation and non-hibernation stages. Polar bears make flexible rhythmic adjustments under continuous light and dark conditions, and their rhythmic changes are closely associated with feeding season, prey supply, and burrowing behavior. Further analysis reveals that environmental disturbances brought about by climate change are turning into a key factor affecting rhythm regulation, especially via sea ice reduction and food resource fluctuations on polar bear populations. Based on these outcomes, it can be inferred that circadian rhythm is not merely a reflection of physiological mechanisms, but also the intersection of environmental stress and adaptation strategies. Future studies need to further validate these laws at longer scales and cross-species comparisons to assess the evolution trends of animal rhythms and survival strategies in extreme ecosystems in the context of climate change [9, 10].

## 3. Analytical Perspective

Although previous studies have documented the diverse circadian rhythm regulation patterns of Arctic mammals under extreme light conditions, the overall understanding remains incomplete. Photoperiod is no longer a reliable external cue in these environments, which limits the applicability of traditional rhythm research frameworks that rely on light–dark alternation. Moreover, the influence of non-photoperiodic factors on rhythm formation has not been systematically clarified. Temperature fluctuations may alter energy allocation through metabolic load, food availability and predation pressure may directly shape activity patterns, and social signals and group interactions may provide additional internal temporal cues. Evidence is also lacking on how gene regulation and epigenetic mechanisms are reprogrammed under environmental stress. As Arctic ecosystems experience rapid climate change, with shrinking ice sheets, altered seasonal vegetation, and

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unstable food chain dynamics, the urgency to investigate circadian regulatory mechanisms has intensified. Building on existing findings, this study seeks to integrate behavioral, physiological, and ecological evidence to examine how Arctic mammals sustain chronobiological stability in the absence of reliable photoperiodic signals, thereby offering new perspectives on their adaptive strategies and ecological. This kind of research can deepen our understanding of the diversity of biological rhythm regulation. It also provides a theoretical basis for the assessment of species resilience in the context of climate change. An understanding of the rhythmic mechanism of polar mammals will provide reference for global biodiversity conservation and ecological management.

## 4. Conclusion

Arctic mammals have remarkably adaptable circadian and seasonal timing systems that allow them to survive for months in conditions devoid of regular light-dark cycles. While photoperiod is still an important signal, species like polar bear and Arctic ground squirrels demonstrate that non-photic signals, such as temperature, food availability, and internal hormone rhythms, are equally important in coordinating behavior, reproduction, and metabolism. Because of this adaptive plasticity, mammals can adapt to situations that would normally interfere with circadian organization, such as polar night and constant daylight. Ongoing climate change, however, is changing trophic interactions, vegetation growth, and snow cover, which may affect or destabilize the cues that these species rely on. Thus, it is important to comprehend how Arctic mammals control seasonal time in ways other than photic entrainment: It demonstrates the variety of ambient timekeepers, which promotes chronobiological theory. In-depth research on these mechanisms not only helps to reveal the coupling laws of physiological and ecological processes in extreme environments, but also provides important implications for understanding the evolution of biological rhythms in different latitudes and climate regions. As global environmental uncertainty continues to increase, this knowledge will have far-reaching implications for predicting changes in species fitness, guiding conservation strategies, and advancing ecological theories.

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