Exploring the effects of ice-free season length on polar bear (*Ursus maritimus*) age acceleration

by

Nina Eilberg

A thesis submitted to the Department of Biological Sciences, University of Manitoba,

in partial fulfilment of the requirements for the course

BIOL 4100 (Honours Thesis)

for the degree of

Bachelor of Science (Honours)

©April, 2026

Abstract

The Arctic is warming four times faster than the global average, causing the ice-free season to lengthen, and pushing species to new extremes. Polar bears (*Ursus maritimus*) rely on the presence of sea ice for hunting and turn to fasting during the ice-free season. During longer ice-free seasons, bears must increase their expenditure of stored energy for survival. Lifetime adversity – the cumulative total of the hardships experienced by an individual – has been seen to increase with the warming climate, however, the time periods during which bears are most vulnerable to environmental changes have yet to be explored. The Western Hudson Bay (WHB) polar bear population lives in the south of the species range, near Churchill, Manitoba, Canada, and has been sampled for tissues yearly since 1980. This extensive dataset has been used to create an epigenetic clock, a tool based on DNA methylation patterns that can calculate age acceleration. As an influential factor of behaviour and lifespan, age acceleration can provide insights into the overall health condition of individuals and populations. This study explores developmental stages during which WHB polar bears may be more susceptible to longer ice-free seasons. Using simple linear regressions, I found that age acceleration was significantly affected by ice-free season length during fetal development, the year of independence, and male sexual maturation. Maternal effects may be affecting offspring age acceleration, yet further investigation is needed. Improving our understanding of aging in the face of environmental stressors and monitoring age acceleration in wild populations could become crucial aspects of future conservation strategies.

Acknowledgements

I would like to thank Evan S. Richardson and Climate Change Canada for contributing data from the Western Hudson Bay polar bear population and for their continued commitment to the study of polar bears.

I would also like to thank both of my committee members, Dr. Meaghan J. Jones and Dr. John Markham for their time and detailed attention to the project.

I am deeply grateful to my supervisor, Dr. Colin J. Garroway, and my mentor, Dr. Levi Newediuk, for their support and guidance. I could not imagine a better introduction to the field of research than my experience thanks to you.

I appreciate the helpful feedback and encouragement throughout the process of writing and presenting my honours thesis from members of the Population Ecology & Evolutionary Genetics Group.

To my friends and family, both near and far, thank you for asking questions and challenging my knowledge, for listening to my endless answers, and for celebrating every milestone with me through positive messages, late-night phone calls, coffee, boardgames, and polar bear parties.

Table of Contents

Abstract i
Acknowledgements ii
List of Tables iv
List of Figures v
Introduction 1
Methods 6
Results 11
Discussion 16
Literature Cited 20
Appendix A: Sample Sizes 28
Appendix B: Simple Linear Regression Models 29
Appendix C: Linear Regression Models with Interaction Terms 33

List of Tables

Table 1. 5
Table 2. 8
Table 3. 10
Table 4. 15
Table A1 28
Table B1 29
Table B2 31
Table C1 33
Table C2 35
Table C3 37

List of Figures

Figure 1.....9
Figure 2.....12
Figure 3.....13
Figure 4.....14

Introduction

Species on our planet are threatened by the impacts of climate change (Urban 2015; Spooner et al. 2018). Since 1979, global temperatures have risen rapidly, with the Arctic warming four times faster than the global average (Rantanen et al. 2022). This temperature shift has caused environmental changes, such as the lengthening of the Arctic ice-free season, which are pushing species to new extremes (Hoffmann and Sgrò 2011; Lunn et al. 2016; Harris et al. 2018; Spooner et al. 2018). Polar bears (*Ursus maritimus*) depend on sea ice for hunting and fast during the ice-free season (Stirling et al. 1977). Longer ice-free periods force bears to increase their energy expenditure for survival (Lunn et al. 2016; Pagano et al. 2024). Biological age serves as a biomarker of cumulative lifetime adversity and has been proposed as an indicator of mortality risk (Marioni et al. 2016). Therefore, it could act as an early warning for conservation concerns in populations. Individual biological aging appears to increase with the warming climate (Newediuk et al. 2025). Yet, the specific life stages during which polar bears are most vulnerable to environmental change remain to be studied.

The most extensively studied polar bear population is the Western Hudson Bay (WHB) population, which inhabits the southern part of the species' range near Churchill, Manitoba, Canada, and has been sampled for tissue annually since 1980 (Malenfant et al. 2016). This comprehensive dataset has been used to measure biological age (Newediuk et al. 2025), based on the epigenetic process of DNA methylation – the addition or removal of methyl groups covalently attached to cytosine-guanine dinucleotides (CpG sites) (Horvath 2013; Jones et al. 2015). DNA methylation can occur with the passage of time or under pressures like environmental stressors (Horvath 2013; Jones et al. 2015; Bateson

and Poirer 2019). Changes in some CpG site methylation occur predictably as the organism ages, enabling the development of age-estimation tools (epigenetic clocks) across large taxonomic groups, specific species, or even individual populations (Horvath 2013; Jones et al. 2015; Horvath and Raj 2018; Newediuk et al. 2025).

Chronological age – the total time from birth to observation – can be compared with biological age using linear regression (Horvath 2013; Moqri et al. 2023). The residuals from this regression serve as estimates of age acceleration, indicating how much an individual diverges from the average pace of aging in the population; large positive values suggest individuals aging faster than expected (Horvath 2013; Newediuk et al. 2025). As an important factor influencing behaviour and lifespan, age acceleration may offer insights into an individual's overall experience of adversity (Jones et al. 2015; Pearce et al. 2022). For instance, humans who faced early life adversity – such as abuse, neglect, or other threats and violence outside typical childhood and adolescent experiences – have been linked to accelerated aging and negative physical and mental health outcomes (Sumner et al. 2019). Because age acceleration reliably reflects the cumulative effects of adversity in response to environmental changes (Bateson and Poirier 2019), it is possible to examine the connection between a warming Arctic climate and polar bears' cumulative lifetime adversity. This project seeks to enhance our understanding of how environmental changes impact both individuals and populations.

Polar bear behaviour patterns are strongly tied to the seasons. During the winter, close to 100% of the surface of Hudson Bay is covered with sea ice (Danielson 1971). Polar bears acquire most of their energy using the sea ice to prey on seals in late spring and early summer (Stirling et al. 1977; Pagano et al. 2024). The ice cover begins to melt

in spring, slowly forcing polar bears to move onto land until Hudson Bay freezes up again at the beginning of winter – this period when the ice cover is below 50% is called the ice-free season (Stirling et al. 1977; Lunn et al. 2016; Castro de la Guardia et al. 2017). During the ice-free season, polar bears lose access to energy-rich seals and are forced to fast, scavenge, or turn to lower energy food sources – such as berries and other vegetation – often needing to spend stored energy from the hunting season (Atkinson and Ramsay 1995; Lunn et al. 2016; Pagano et al. 2024). When the ice-free season is longer than usual, stored energy that may have otherwise been allocated to mating, gestation, or lactation, is tapped into for survival (Atkinson and Ramsay 1995; Lunn et al. 2016; Hutchings 2021; Pagano et al. 2024). Due to increased energy expenditure while on land, polar bears experience greater body-mass loss, increasing the risk of starvation (Pagano et al. 2024).

Adverse experiences can be more influential on an individual's phenotypic development during critical developmental periods than during other life stages (Fawcett and Frankenhuis 2015). It may be during these developmental periods that environmental stressors have a greater impact on an individual's long-term health (Stearns 1992; Knudsen 2004; Fawcett and Frankenhuis 2015; Jones et al. 2015). As suggested by studies on red deer (*Cervus elaphus*) and wild sheep (*Ovis aries*), males of highly sexually dimorphic species can be more susceptible to lower energy intakes than females due to larger body sizes (Clutton-Brock et al. 1985; Drake et al. 2025). Both polar bear sexes have similar growth rates, but they are dimorphic in size, with males growing to be larger than females (Kingsley 1979). Identifying during which life periods polar bears are most vulnerable and whether there is a difference in vulnerability associated with sex can

deepen our understanding of the relationships between the environment and the individual.

Polar bears have a life history similar to that of other mammals, with developmental periods of significant organismal change that require substantial energy, such as prenatal development, infancy, and sexual maturation (Fawcett and Frankenhuis 2015; Kong et al. 2025). Pregnancy is an especially energetically demanding period because females rely on stored energy from the past year, as they fast through the ice-free season and continue fasting as they den through the winter for gestation, birth, and lactation (Stirling et al. 1977; Atkinson and Ramsay 1995). Pregnant females may therefore be more susceptible to environmental changes during the period leading up to pregnancy. The prenatal and perinatal environments that are created by females may affect offspring DNA methylation (Eapen et al. 2026). Early-life adversity of the parents may also lead to paternal or maternal effects affecting the offspring (Coslovsky and Richner 2011; Merril et al. 2021; Hamlat et al. 2025).

Another period when polar bears may be more vulnerable to stressors is during their first year of independence, as they are inexperienced and unaccustomed to living on their own, and may not be as efficient as adults at acquiring energy (Pagano et al. 2024). Life stages such as late adulthood and cubs in their first two years (who are still reliant on their mothers) might be less affected by longer ice-free seasons, either through gained skills and experience or protection, respectively.

My objective is to examine the relationship between the duration of ice-free seasons in Hudson Bay and the age acceleration of WHB polar bears to assess cumulative lifetime adversity. I hypothesize that polar bear age acceleration is most strongly

influenced by the length of the ice-free season during key developmental stages (**Table 1**, **Hypothesis 1**). I expect that polar bears experiencing longer ice-free seasons during crucial developmental stages (fetal development, year of birth, independence, and sexual maturity) will show greater age acceleration than those with shorter ice-free seasons in the same stages (**Table 1**, **Predictions A**, **B**, **C** and **D**).

Table 1. Hypothesis and predictions of the different ways in which the age acceleration in polar bears, as a measure of cumulative lifetime adversity, is affected by the length of the ice-free season during various developmental stages. Age refers to the year of life being assessed, with negative numbers indicating years before birth, 0 indicating the year of birth, and positive numbers indicating years since birth.

Hypothesis	Prediction	Ice-Free Season Length	Time Period	Age	Age Acceleration
Polar bears are affected by the ice-free season length during developmental periods	**A**	↑	Fetal Development	-1	↑
	B	↑	Year of Birth	0	↑
	C	↑	Year of Independence	3	↑
	D	↑	Sexual Maturation	*	↑

Note: *Sexual maturation occurs at age 6 in males, and age 4 in females.

This work will expand our understanding of the relationship between the ice-free season and the cumulative lifetime adversity faced by polar bears, offering insights into how environmental changes in the Arctic affect the life histories of species dependent on the sea ice.

Methods

My project examines the life stages of polar bears during which the impact of the ice-free season length may be greatest. The WHB polar bear population lives in the southern edge of the species range in Canada and has been sampled yearly since 1980 through a standardized sampling program by Environment and Climate Change Canada (Malenfant et al. 2016; Biddlecombe et al. 2025). Sampled bears were uniquely fitted with ear tags and tattooed on their upper lips for identification upon recapture (Malenfant et al. 2016).

The chronological age of polar bears was recorded based on known birth years or through age estimation using cementum-ring deposits from the removal of a third molar (Malenfant et al. 2016). Three tissue types were collected: rump fat, skin from leftover pinnal ear tissue obtained during ear-tagging or rump fat sampling, and blood from a femoral vein (Malenfant et al. 2016). DNA was extracted from these tissue samples, creating an extensive dataset used to measure DNA methylation, develop an epigenetic clock, and evaluate the fitness and adaptive potential of polar bears (Malenfant et al. 2016; Newediuk et al. 2025). Linear regression models were developed using both chronological and biological ages, with residuals indicating age acceleration (Newediuk et al. 2025). Using the same approach, a universal polar bear clock was created, incorporating samples from other populations and allowing for the measurement of age acceleration (Newediuk 2025). I used the age acceleration dataset from Newediuk (2025) to explore my **Hypothesis** (**Table 1**).

To calculate the breakup date, freeze-up date, and overall ice-free season in the Hudson Bay, I used the ice-concentration dataset from DiGirolamo et al. (2022). The ice-free season occurs from spring to autumn (Stirling et al. 1977), defined by Lunn et al.

(2016) and Castro de la Guardia et al. (2017) as the period of time between the first day of the year that ice coverage falls below 50% (breakup) until the first day that it reaches over 50% coverage again (freeze-up). I measured the ice-free season in number of days.

I used RStudio with R version 4.5.2 and eight packages – bayestestR (Makowski et al. 2019), brms (Bürkner 2017, 2018, and 2021), broom (Robinson et al. 2025), broom.mixed (Bolker and Robinson 2024), car (Fox and Weisberg 2019), htmltools (Cheng et al. 2024), knitr (Xie 2014, 2015, and 2025), and tidyverse (Wickham et al. 2019) – to assess the relationship between the ice-free season and age acceleration. I constructed a data frame including the following information for all the available samples from the WHB population: bear identification number, sex, year of birth, corrected age, and age acceleration.

For each polar bear individual, I retained only samples from the most recent year. For multiple samples from the most recent year, I computed the average age acceleration value. After filtering for the most recent samples, the sample size comprised 257 individuals, with 112 males and 145 females (See **Appendix A: Table A1**). Since polar bears are born in the winter, their age at sampling has been corrected to follow true years rather than calendar years (Newediuk et al. 2025) (**Table 2**). Polar bears sampled before the ice-free season, in March to April, were labelled ending in ".25" (as a quarter of a year has elapsed since their day of birth) and were assessed using the ice-free season of the previous year. Any polar bears sampled in August to September were labelled ending in ".75", as they would have experienced three-quarters of a year since their day of birth, and were assessed using the ice-free season of the previous year, as the ice-free season of the sampling year had not ended before sampling occurred. However, since polar bears

sampled in late September to November experienced the complete ice-free season of their sampling year, they were labelled with an age ending in ".00" and were assessed up to the sampling year. No polar bears were sampled from May to July, or from December to February.

Table 2. Age labels given to polar bears sampled during three different seasons (March-April, August-September, or Late September-November) based on how much of a year has elapsed since their day of birth, and what ice-free season they were assessed with.

Sampling Time	Time Since Day of Birth	Age Label (x = # of years)	Ice-Free Season Used for Assessment
March-April	¼ of a year	$x.25$	Year before sampling
August-September	¾ of a year	$x.75$	Year before sampling
Late September-November	1 year	$x.00$	Sampling year

To test my **Hypothesis**, I fitted a linear model for each year in a 14-year range, starting 5 years prior to the year of birth and ending at age 8 (ages -5 to 8, see **Appendix A: Table A1** for sample size by age group). I expected this timeframe would allow us to identify the years that are more impactful on age acceleration and compare models from those years with those from years I expected would be less impactful. I assessed the polar bears in years before they were conceived as a form of control – I expected to see no effect of the ice-free season length on age acceleration in ages -5 to -2. Individuals were included in a model only if they were confirmed to have lived to that age and had experienced the full ice-free season of that year (i.e. individuals that were sampled at any time after an age was completed). For example, an individual sampled at age 4.75 was only included in models from ages -5 to 3.

I calculated relative years – the calendar year an individual would be at each age in the 14-year range (see **Figure 1**) – and grouped individuals by age. Then, I added the ice-concentration data from DiGirolamo et al. (2022) by matching the breakup and freeze-up dates to each year, and I calculated the total length of the ice-free season in days for each year. I retained only the years for which ice-concentration data were available.

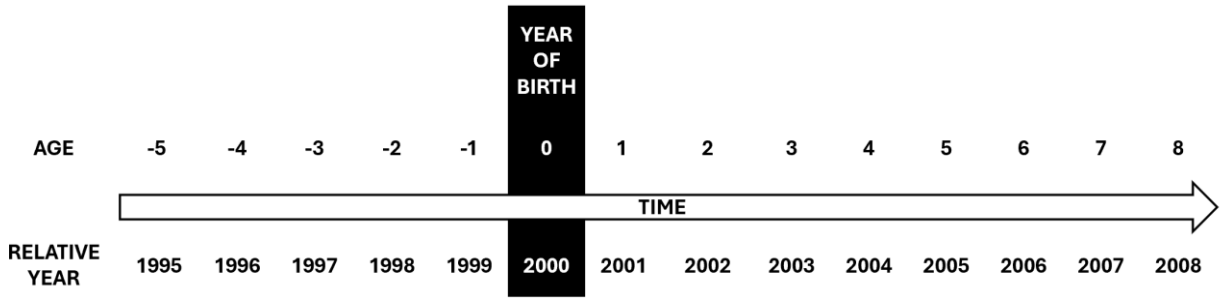


Figure 1. The age and relative year of a polar bear born in the year 2000, ranging 14 years (from 5 years prior to birth to 8 years of age).

I fitted three different model types (**Table 3**). First, a simple linear regression was used to assess the effect of ice-free season length on age acceleration in ages from -5 to 8 in groups of combined sexes, males, and females. The split of polar bears into sex-based groups was done to account for differences in age at sexual maturation (age 4 for females, and age 6 for males). Second, a linear regression with sex as an interaction term was used to assess whether the relationship between ice-free season length and age acceleration varies by sex. To account for drastic temperature changes due to climate change, the third linear regression included the year 1995 as an interaction term and was used to assess whether the relationship between ice-free season length and age acceleration depended on whether the year being assessed was before or after 1995. This interaction term was based on an analysis of ice-free seasons in the Arctic by Castro de la Guardia et al. (2017),

which found that the year 1995 marked a turning point in ice-free season lengths, with ice-free seasons significantly shorter before 1995 than after 1995. Each model included the ice-free season length as the independent variable and the age acceleration as the dependent variable and was created using the function brms() (Bayesian Regression Models) using Stan.

Table 3. The linear regression models for each **Prediction** of the **Hypothesis**. Within the models, x is the ice-free season length in days, y is the age acceleration in years, β_{Sex} is an interaction term that splits polar bears into males and females, and β_{1995} is an interaction term that splits polar bear ages into before and after the year 1995. For each age within a group, 1 model is fitted.

Age Acceleration (y) ~ Ice-Free Season Length (x)	**Model Type**	**# of Models**	**# of Models per Group**
$y \sim x_{Age}$	Simple Linear Regression	42	14 for combined sexes 14 for males 14 for females
$y \sim x_{Age} * \beta_{Sex}$	Linear Regression with Interaction Term	14	14 for combined sexes
$y \sim x_{Age} * \beta_{1995}$	Linear Regression with Interaction Term	28	14 for males 14 for females

After fitting the models, I extracted the following values at the 95% confidence level for tables (see **Appendices B** and **C**): the estimates, the standard error, and the lower and upper bounds of the confidence interval. I also extracted the probability of the effect direction for each model, indicating the probability that the effect is negative or positive. If the probability of the effect's direction exceeded 0.89, I considered the effect meaningful, as using 0.89 credible intervals is recommended by McElreath (2020). I created plots showing both 0.89 and 0.95 credible intervals (**Figures 2**, **3**, and **4**). Any

credible intervals that did not cross over 0 were considered to be significant (i.e. polar bears in that age group that experienced longer ice-free seasons than other polar bears in the same age group had higher age accelerations). I also calculated the R^2 values for each model as a measure of goodness of fit. R^2 values range from zero to one and show how well the independent variable in the linear model explains the variation in the dependent variable. R^2 values closer to one show that the variation in the dependent variable is better explained by the independent variable than models with R^2 values closer to zero.

Results

Simple Linear Regression Models

I fitted 14 simple linear regression models for males (**Figure 2**, **Appendix B: Table B1**) and 14 for females (**Figure 3**, **Appendix B: Table B2**). In the year of fetal development (age -1), males show a significant positive relationship between ice-free season length and age acceleration, but not in the year of birth (age 0), year of independence (age 3), or reaching sexual maturity (age 6) (**Figure 2**, **Appendix B: Table B1**). Females show a significant positive relationship between ice-free season length and age acceleration in their year of sexual maturity (age 4), but not during the other developmental periods of interest (**Figure 3**, **Appendix B: Table B2**). I also fitted 14 models with the two sexes combined, in which there was significance for the year of fetal development, year of independence, and year of males' sexual maturity, but not in for year of birth (**Figure 4**, **Table 4**). Other models that had a significant positive relationship include age -2 for males, age 6 for females, and the following ages for the combined-sex models: -2, 2, 5, 7, and 8.

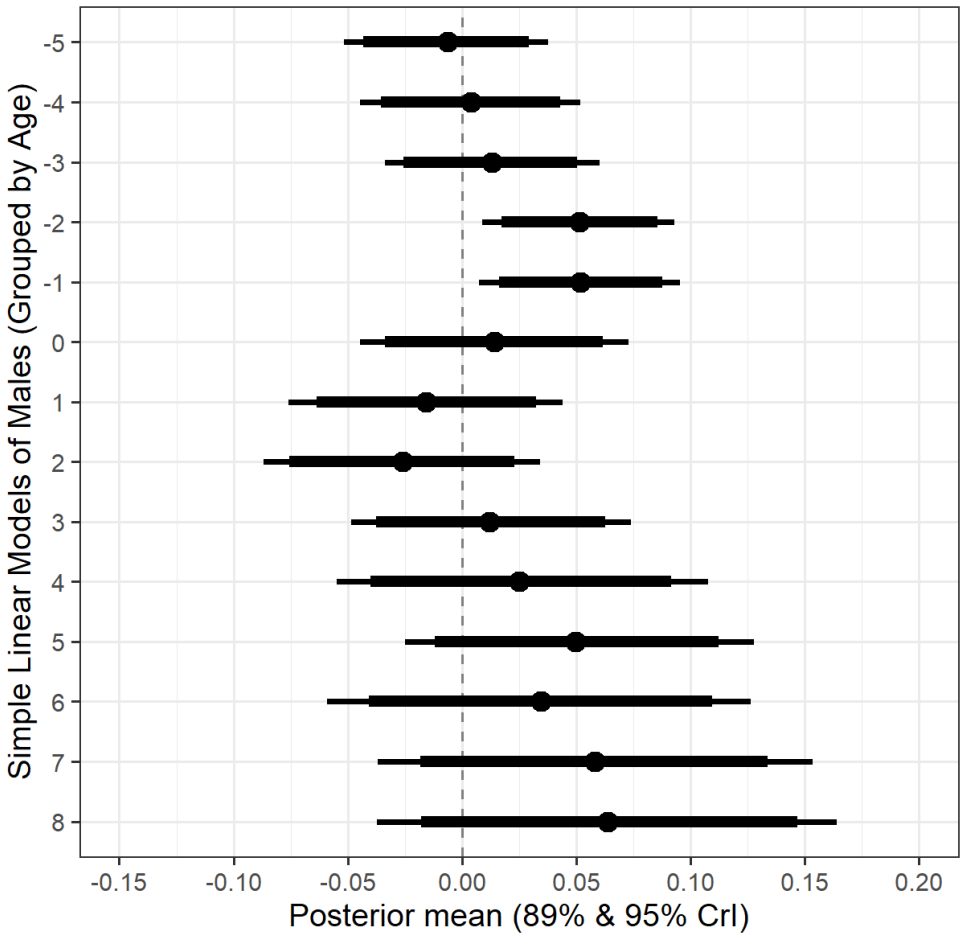


Figure 2. Model summaries of 14 simple linear regression models of ice-free season length on age acceleration for male polar bears by age group (from 5 years before birth to the age of 8, where 0 is the year of birth). Black circles are estimates of the overall mean effect of ice-free season length, with 89% (thick lines) and 95% (thin lines) credible intervals. Credible intervals that overlap 0 (dashed vertical line) suggest no significant effect of ice-free season length.

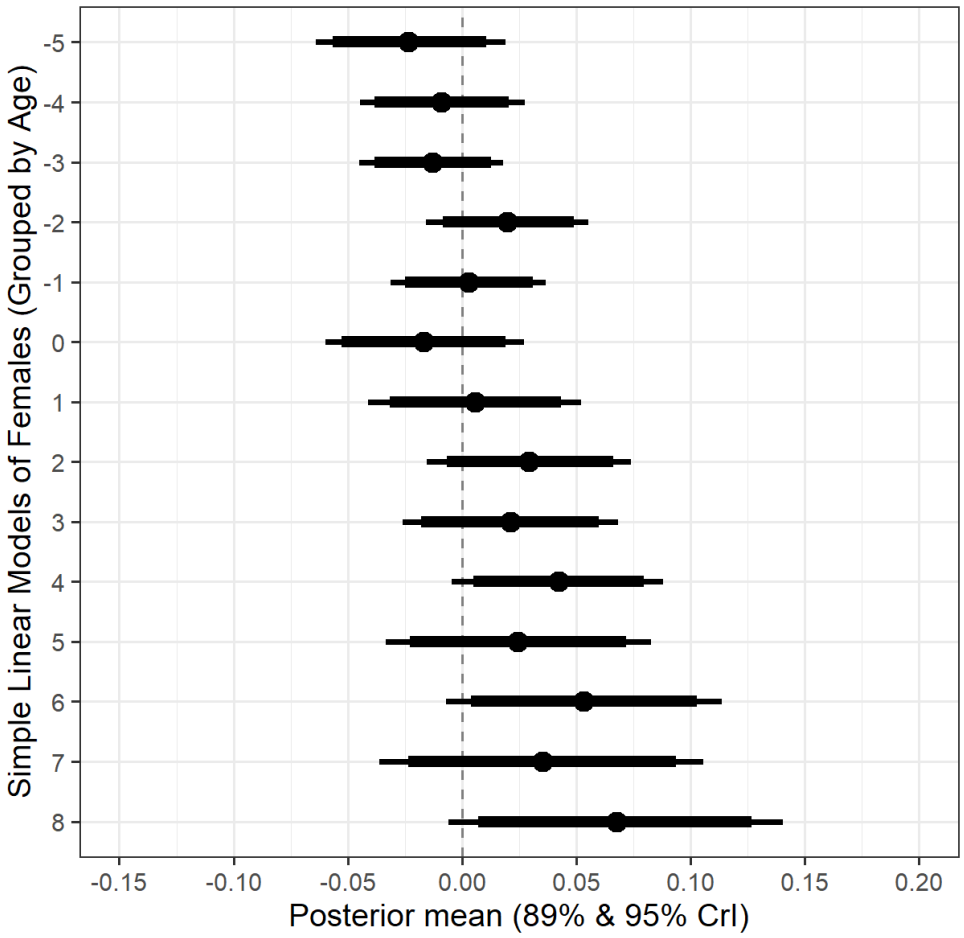


Figure 3. Model summaries of 14 simple linear regression models of ice-free season length on age acceleration for female polar bears by age group (from 5 years before birth to the age of 8, where 0 is the year of birth). Black circles are estimates of the overall mean effect of ice-free season length, with 89% (thick lines) and 95% (thin lines) credible intervals. Credible intervals that overlap 0 (dashed vertical line) suggest no significant effect of ice-free season length.

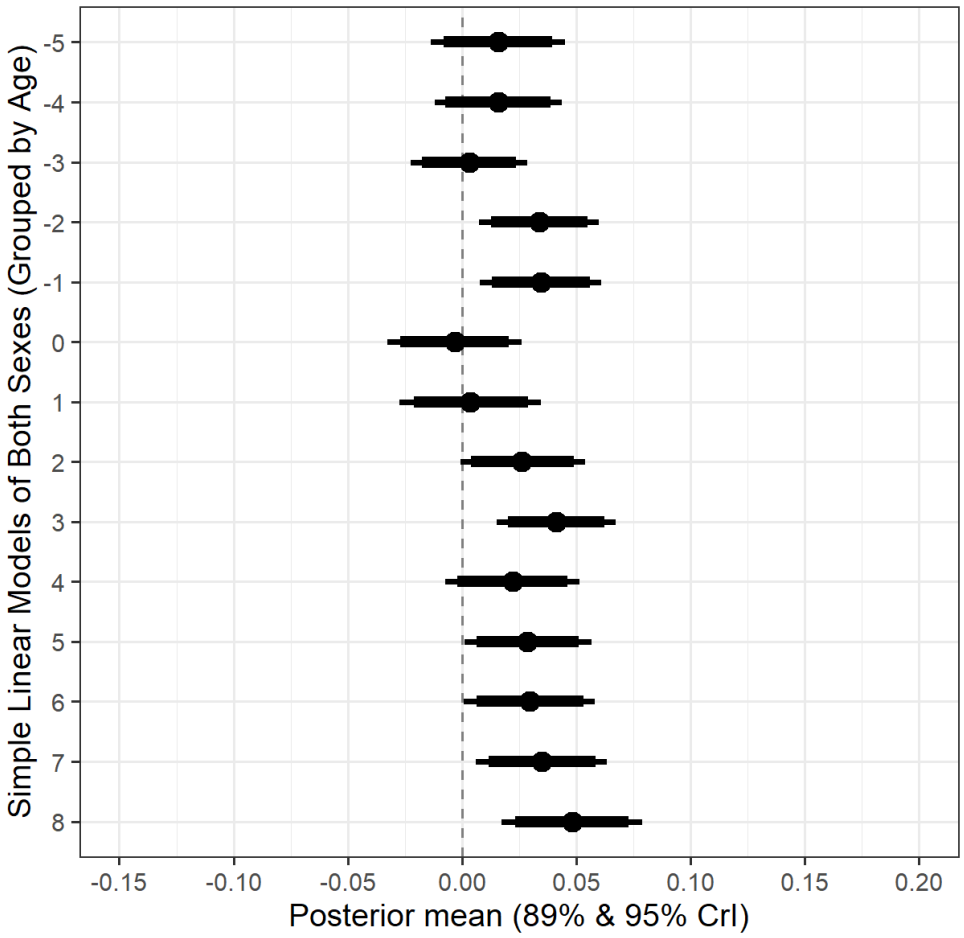


Figure 4. Model summaries of 14 simple linear regression models of ice-free season length on age acceleration for polar bears of both sexes by age group (from 5 years before birth to the age of 8, where 0 is the year of birth). Black circles are estimates of the overall mean effect of ice-free season length, with 89% (thick lines) and 95% (thin lines) credible intervals. Credible intervals that overlap 0 (dashed vertical line) suggest no significant effect of ice-free season length.

Table 4. Estimates, standard errors, confidence interval lower and upper bounds, and probabilities of direction for 14 simple linear regression models (age acceleration ~ ice-free season length) in polar bear males and females grouped by age from 5 years before birth until the age of 8. Year of birth (age 0) is highlighted with a dark background.

Age	Term	Estimate	Standard Error	Confidence Interval Lower Bound	Confidence Interval Upper Bound	Probability of Direction
	Intercept	-2.31	2.37	-6.96E+00	2.37	0.84
-5	Ice-Free	0.02	0.01	-1.36E-02	0.04	0.86
	R^2	0.03	0.03	1.26E-03	0.06	NA
	Intercept	-2.35	2.31	-6.83E+00	2.11	0.84
-4	Ice-Free	0.02	0.01	-1.19E-02	0.04	0.87
	R^2	0.02	0.03	1.22E-03	0.06	NA
	Intercept	-0.31	2.12	-4.43E+00	3.87	0.56
-3	Ice-Free	0.00	0.01	-2.25E-02	0.03	0.60
	R^2	0.01	0.02	6.09E-04	0.04	NA
	Intercept	-5.19	2.15	-9.36E+00	-0.94	0.99
-2	Ice-Free	0.03	0.01	7.34E-03	0.06	0.99
	R^2	0.06	0.06	5.01E-03	0.13	NA
	Intercept	-5.39	2.20	-9.65E+00	-0.96	0.99
-1	Ice-Free	0.03	0.01	7.81E-03	0.06	0.99
	R^2	0.06	0.06	5.21E-03	0.13	NA
	Intercept	0.75	2.46	-4.07E+00	5.60	0.62
0	Ice-Free	0.00	0.01	-3.26E-02	0.03	0.58
	R^2	0.01	0.02	5.66E-04	0.04	NA
	Intercept	-0.41	2.64	-5.54E+00	4.79	0.56
1	Ice-Free	0.00	0.02	-2.75E-02	0.03	0.59
	R^2	0.01	0.02	5.83E-04	0.04	NA
	Intercept	-4.05	2.33	-8.61E+00	0.44	0.96
2	Ice-Free	0.03	0.01	-8.19E-04	0.05	0.97
	R^2	0.04	0.04	2.37E-03	0.10	NA
	Intercept	-6.49	2.19	-1.08E+01	-2.18	1.00
3	Ice-Free	0.04	0.01	1.51E-02	0.07	1.00
	R^2	0.07	0.07	1.21E-02	0.16	NA
	Intercept	-3.38	2.48	-8.25E+00	1.50	0.91
4	Ice-Free	0.02	0.01	-7.28E-03	0.05	0.93
	R^2	0.03	0.04	1.74E-03	0.08	NA
	Intercept	-4.55	2.36	-9.27E+00	0.10	0.97
5	Ice-Free	0.03	0.01	1.03E-03	0.06	0.98
	R^2	0.04	0.05	2.54E-03	0.10	NA
	Intercept	-4.74	2.45	-9.48E+00	0.06	0.97
6	Ice-Free	0.03	0.01	6.95E-04	0.06	0.98

	R^2	0.04	0.04	2.58E-03	0.10	NA
	Intercept	-5.78	2.44	-1.06E+01	-0.94	0.99
7	Ice-Free	0.03	0.01	6.10E-03	0.06	0.99
	R^2	0.05	0.05	3.81E-03	0.12	NA
	Intercept	-8.21	2.61	-1.34E+01	-2.99	1.00
8	Ice-Free	0.05	0.02	1.72E-02	0.08	1.00
	R^2	0.07	0.07	1.17E-02	0.16	NA

Linear Regression Models with Year 1995 as an Interaction Term

I fitted 14 linear regression models with the year 1995 before/from as an interaction term for males (**Appendix C: Table C1**) and 14 for females (**Appendix C: Table C2**). The only models that had a significant relationship between ice-free season length and age acceleration that depended on whether the relative year was before or after 1995 were ages -5, -2, and 1 for males – none of the female models were significant. Since the interaction term was not consistently significant, none of these models are interpreted further.

Linear Regression Models with Sex as an Interaction Term

I fitted 14 linear regression models, including sex as an interaction term, for both sexes combined (**Appendix C: Table C3**). None of the models showed a significant relationship between ice-free season length and age acceleration that varied by sex. Therefore, these models are not interpreted further.

Discussion

Among the four developmental stages explored using combined-sex models, polar bears that experienced longer ice-free seasons during fetal development, independence, and males' sexual maturity showed accelerated aging (**Figure 4**, **Table 4**). However, models that assessed males and females separately found significant effects only on the

year of fetal development and on females' sexual maturity, respectively (**Figures 2** and **3**, **Appendix B**: **Tables B1** and **B2**), suggesting that sex may play a role in age acceleration. All models had low R^2 values, suggesting that ice-free season length is predictive of age acceleration, bust has a small effect at any particular age. Many other factors may be influencing age acceleration, such as maternal effects, sex, interactions with other species, and random environmental events.

In the combined-sex simple linear regression, both models for the year of fetal development and the year before (ages -1 and -2, **Figure 4** and **Table 4**) had a significant effect of ice-free season length on age acceleration. This finding suggests that there are parental effects affecting the age acceleration of the offspring, as supported by previous studies in humans, which found that there is an association between the age acceleration of mother and child, and that early life adversity in mother and father affects child DNA methylation (Merril et al. 2021; Hamlat et al. 2025). The prenatal and perinatal environments also affect DNA methylation (Eapen et al. 2026); therefore, maternal condition in the years leading up to offspring birth may be more strongly associated with offspring age acceleration than either maternal or paternal early-life adversity.

Maternal effects can influence early development (Coslovsky and Richner 2011) which may beneficially or detrimentally affect offspring. A human study suggests that accelerated aging in the womb may improve the chances of postnatal survival (Polinski 2023). However, detrimental effects can also occur as trade-offs for beneficial effects (Coslovsky and Richner 2011). As found in multiple studies on great tit (*Parus major*) offspring parasites, maternal stress from perceived predatory risk affects offspring phenotypes, with increased parasite survival as a side-effect (Tschirren et al. 2004;

Coslovsky and Richner 2011; Basso et al. 2014). The context in which maternal effects arise may provide insights into a species' ecological relationships, evolutionary history, and selective pressures.

Fetal development is a highly energetically demanding period for the mother, especially for polar bears, as the mother fasts through the ice-free season and then dens, continuing to fast through implantation, fetal development, birth, and the first few months of lactation until emerging with their cub(s) in the spring (Stirling et al. 1977; Atkinson and Ramsay 1995). To further investigate the relationship between maternal condition and offspring age acceleration, future studies may assess the effect of an early breakup date in the year before birth, rather than the overall ice-free season length. Relationships between parents and offspring may also be explored using pedigree data of the WHB polar bear population created by Degreef (2024).

The combined sex models showed a significant effect of ice-free season length on age acceleration later into life (ages 5, 7, 6 and 8, **Figure 4** and **Table 4**), which was unexpected, as age acceleration is mainly associated with adverse experiences in early childhood (Sumner et al. 2019; Arzu et al. 2024). Age acceleration may be additive throughout an individual's lifetime since it is observed later in life. To explore whether the accumulation persists into late adulthood, models could be extended into even later years using bears sampled at older ages.

I was not expecting to see significant differences in age patterns across the 14-year range between the sexes. A study of a wild population of sheep suggests that early-life adversity may be sex-specific (Drake et al. 2025), which may explain why male and female models show different effects. Although the linear models with sex as an

interaction term did not show a significant relationship between ice-free season length and age acceleration that depended on sex, I think there may still be a sex difference that would be observed if models were run again with a larger sample size. Kingsley (1979) determined that male polar bears grow larger than females, but because both sexes grow at a similar rate, males reach their mature weight at a later age than females. The difference in final organism size and the energetic input required to reach and maintain that size may lead to differences in DNA methylation. Associations between body size and susceptibility to low energy intakes have previously been found in other sexually dimorphic mammals (Clutton-Brock et al. 1985; Drake et al. 2025) and may also exist in polar bears.

Identifying the periods in polar bears' life history when they are most affected by their environment can help guide conservation efforts for many species reliant on sea ice. Age acceleration might serve as an early warning sign of conservation issues, as it reflects cumulative lifetime adversity and correlates with lower life expectancy. Tracking age acceleration in wild populations could become an essential part of conservation strategies to monitor population health. Improving our understanding of how aging interacts with environmental stressors during various developmental and life stages may assist in medical and biological assessments of individual health. By learning more about how epigenetic changes influence ecological and evolutionary processes, we can increase awareness of the impacts of climate change on global biodiversity.

Literature Cited

Arzu, J. L., Kelsey, K. T., Papandonatos, G. D., Cecil, K. M., Chen, A., Langevin, S. M., Lanphear, B. P., Yolton, K., Bucklet, J. P., and Braun, J. M. 2024. Associations of epigenetic age acceleration at birth and age 12 years with adolescent cardiometabolic risk: the HOME study. Clin. Epigenetics. **16**(163): 1–14. doi: 10.1186/s13148-024-01779-8.

Atkinson, S. N., and Ramsay, M.A. 1995. The effects of prolonged fasting of the body composition and reproductive success of female polar bears (*Ursus maritimus*). Funct. Ecol. **9**(4): 559–567. doi: 10.2307/2390145.

Basso, A., Coslovsky, M., and Richner, H. 2014. Parasite- and predator-induced maternal effects in the great tit (*Parus major*). Behav. Ecol. **25**(5): 1105–1114. doi: 10.1093/beheco/aru088.

Bateson, M., and Poirier, C. 2019. Can biomarkers of biological age be used to assess cumulative lifetime experience? Anim. Welf. **28**(1): 41–56. doi: 10.7120/09627286.28.1.041.

Biddlecombe, B. A., Derocher, A. E., Krebs, E., Lunn, N. J., McGeachy, D., and Richardson, E. S. 2025. Building the foundation for polar bear science: fifty years of research on polar bears in Western Hudson Bay. Arctic Sci. **11**(1): 1–12. doi: 10.1139/as-2024-0056.

Bolker, B., and Robinson, D. 2024. broom.mixed: tidying methods for mixed models. doi: 10.32614/CRAN.package.broom.mixed.

Bürkner, P-C. 2017. brms: an R package for Bayesian multilevel models using stan. J. of Stat. Softw. **80**(1): 1–28. doi: 10.18637/jss.v080.i01.

Bürkner, P-C. 2018. Advanced Bayesian multilevel modeling with the R package brms. The R J. **10**(1): 395–411. doi: 10.32614/RJ-2018-017.

Bürkner, P-C. 2021. Bayesian item response modeling in R with brms and stan. J. of Stat. Softw. **100**(15): 1–54. doi: 10.18637/jss.v100.i05.

Castro de la Guardia, L., Myers, P. G., Derocher, A. E., Lunn, N. J., and Terwisscha van Scheltinga, A. D. 2017. Sea ice cycle in western Hudson Bay, Canada, from a polar bear perspective. Mar. Ecol. Prog. Ser. **564**(1): 225–233. doi: 10.3354/meps11964.

Cheng, J., Sievert, C., Schloerke, B., Chang, W., Xie, Y., and Allen, J. 2024. htmltools: tools for HTML. doi: 10.32614/CRAN.package.htmltools.

Clutton-Brock, T. H., Albon, S. D., and Guinness, F. E. 1985. Parental investment and sex differences in juvenile mortality in birds and mammals. Nature. **313**(10): 131–133. doi: 10.1038/313131a0.

Coslovsky, M. and Richner, H. 2011. Increased predation risk on mothers affects survival of parasites feeding on the offspring. Anim. Behav. **81**(5): 1071–1075. doi: 10.1016/j.anbehav.2011.02.023.

Danielson, E. W. Jr. 1971. Hudson Bay ice conditions. Arctic. **24**(2): 90–107. doi: 10.14430/arctic3119.

De Greef, E. 2024. [Unpublished raw data on polar bear (*Ursus maritimus*) pedigree relationships.] University of Manitoba.

DiGirolamo, N., Parkinson, C. L., Cavalieri, D. J., Gloersen, P., and Zwally, H. J. 2022. Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data. (NSIDC-0051, Version 2). [Data Set]. Boulder, Colorado USA.

NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: 10.5067/MPYG15WAA4WX.

Drake, E. D., Ravindran, S., Bal, X., Pemberton, J. M., Pilkington, J. G., Nussey, D. H., and Froy, H. 2025. Sex-specific effects of early-life adversity on adult fitness in a wild animal. Proc. R. Soc. B. **292**(2043): 1–12. doi: 10.1098/rspb.2025.0192.

Eapen, A. A., Loveless, I. M., Pan, M., Liang, X., Urquhart, A., Straughen, J. K., Cassidy-Bushrow, A. E., Sitarik, A. R., Simmerman, N., Thompson, E., Kottyan, L., Ober, C., Johnson, C. C., Zoratti, E., and Levin, A. M. 2026. Immune pathways and prenatal/perinatal environmental exposures contribute to epigenetic gestational age prediction and acceleration. Epigenetics. **21**(1): 1–16. doi: 10.1080/15592294.2025.2610521.

Fawcett, T. W., and Frankenhuis, W. E. 2015. Adaptive explanations for sensitive windows in development. Front. Zool. **12**(1): 1–14. doi: 10.1186/1742-9994-12-S1-S3.

Fox, J., and Weisberg, S. 2019. An R companion to applied regression. 3rd edition. Sage, Thousand Oaks, California.

Hamlat, E. J., Mayer, S. E., Laraia, B., Moffitt, T. E., Surachman, A., Dutcher, E. G., Zhang, J., Lu, A. T., Yang, T. T., Mashah, M., Slavich, G. M., and Epel, E. S. 2025. Maternal childhood adversity accelerates epigenetic aging of children. Health Psychol. **44**(5): 479–488. doi: 10.1037/hea0001427.

Harris, R. M. B., Beaumont, L. J., Vance, T. R., Tozer, C. R., Remenyi, T. A., Perkins-Kirkpatrick, S. E., Mitchell, P. J., Nicotra, A. B., McGregor, S., Andrew, N. R., Letnic, M., Kearney, M. R., Wernberg, T., Hutley, L. B., Chambers, L. E., Fletcher,

M. -S., Keatly, M. R., Woodward, C. A., Williamson, G., Duke, N. C., and Bowman, D. M. J. S. 2018. Biological responses to the press and pulse of climate trends and extreme events. Nat. Clim. Change. **8**(1): 579–587. doi: 10.1038/s41558-018-0187-9.

Hoffmann, A.A., and Sgrò, C.M. 2011. Climate change and evolutionary adaptation. Nature. **470**(7335): 479–485. doi: 10.1038/nature09670.

Horvath, S. 2013. DNA methylation age of human tissues and cell types. Genome Biol. **14**(10): 3156. doi: 10.1186/gb-2013-14-10-r115.

Horvath, S., and Raj, K. 2018. DNA methylation-based biomarkers and the epigenetic clock theory of ageing. Nat. Rev. Genet. **19**(6): 371–375. doi: 10.1038/s41576-018-0004-3.

Hutchings, J. A. 2021. A primer of life histories. Ecology, evolution, and application. 1st edition. Oxford University Press, New York.

Jones, M. J., Goodman, S. J., and Kobor, M. S. 2015. DNA methylation and healthy human ageing. Aging Cell. **14**(6): 924–932. doi: 10.1111/acel.12349.

Kingsley, M. C. S. 1979. Fitting the von Bertalanffy growth equation to polar bear age-weight data. Can. J. Zool. **57**(5): 1020–1025. doi: 10.1139/z79-130.

Knudsen, E. I. 2004. Sensitive periods in the development of the brain and behaviour. J. Cognitive Neurosci. **16**(8): 1412–1425. doi: 10.1162/0898929042304796.

Kong, A.Y., Ortiz-Ross, X., and Blumstein, D. T. 2025. Is early life adversity associated with adult stress in a wild rodent? Ecol. Evol. **15**(4): 1–10. doi: 10.1002/ece3.71065.

Le Clercq, L.-S., Kotzé, A., Grobler, J.P., and Dalton, D.L. 2023. Biological clocks as age estimation markers in animals: a systematic review and meta-analysis. Biol. Rev. **98**(6): 1972–2011. doi: 10.1111/brv.12992.

López-Otín, C., Blasco, M.A., Partridge, L., Serrano, M., and Kroemer, G. 2013. The hallmarks of aging. Cell. **153**(6): 1194–1217. doi: 10.1016/j.cell.2013.05.039.

Lunn, N.J., Servanty, S., Regehr, E.V., Converse, S.J., Richardson, E., and Stirling, I. 2016. Demography of an apex predator at the edge of its range: impacts of changing sea ice on polar bears in Hudson Bay. Ecol. Appl. **26**(5): 1302–1320. doi: 10.1890/15-1256.

Makowski, D., Ben-Shachar, M., and Lüdecke, D. 2019. bayestestR: describing effects and their uncertainty, existence and significance within the Bayesian framework. J. of Stat. Softw. **4**(40): 1541. doi: 10.21105/joss.01541.

Malenfant, R. M., Coltman, D. W., Richardson, E. S., Lunn, N. J., Stirling, I., Adamowicz, E., and Davis, C. S. 2016. Evidence of adoption, monozygotic twinning, and low inbreeding rates in a large genetic pedigree of polar bears. Polar Biol. **39**(1): 1455–1465. doi: 10.1007/s00300-015-1871-0.

Marioni, R. E., Harris, S.E., Shah, S, McRae, A. F., von Zglinicki, T., Martin-Ruiz, C., Wray, N. R., Visscher, P. M., and Deary, I. J. 2016. The epigenetic clock and telomere length are independently associated with chronological age and mortality. Int. J. Epidemiol. **45**(2): 424–432. doi: 10.1093/ije/dyw04.

McElreath, R. 2020. Statistical rethinking. 2nd edition. Chapman and Hall/CRC, New York. doi: 10.1201/9780429029608.

Merrill, S. M., Moore, S. R., Gladish, N., Giesbrecht, G. F., Dewey, D., Konwar, C., MacIsaac, J. L., Kobor, M. S., and Letourneau, N. L. 2021. Paternal adverse childhood experiences: associations with infant DNA methylation. Dev. Psychobiol. **63**(6): 1–22. doi: 10.1002/dev.22174.

Moqri, M., Herzog, C., Poganik, J.R., Justice, J., Belsky, D.W., Higgins-Chen, A., Moskalev, A., Fuellen, G., Cohen, A.A., Bautmans, I., Widschwendter, M., Ding, J., Fleming, A., Mannick, J., Han, J.-D.J., Zhavoronkov, A., Barzilai, N., Kaeberlein, M., Cummings, S., Kennedy, B.K., Ferrucci, L., Horvath, S., Verdin, E., Maier, A.B., Snyder, M.P., Sebastiano, V., and Gladyshev, V.N. 2023. Biomarkers of aging for the identification and evaluation of longevity interventions. Cell. **186**(18): 3758–3775. doi: 10.1016/j.cell.2023.08.003.

Newdiuk, L. 2025. [Unpublished universal polar bear (*Ursus maritimus*) epigenetic clock.] University of Manitoba.

Newediuk, L., Richardson, E. S., Biddlecombe, B. A., Kassim, H., Kathan, L., Lunn, N., Rivkin, R., Salama, O. E., Schmidt, C., Jones, M. J., and Garroway, C. J. 2025. Climate change, age acceleration, and the erosion of fitness in polar bears. bioRxiv [Preprint]. doi: 10.1101/2024.01.05.574416.

Pagano, A. M., Rode, K. D., Lunn, N. J., McGeachy, D., Atkinson, S. N., Farley, S. D., Erlenbach, J. A., and Robbins, C. T. 2024. Polar bear energetic and behavioral strategies on land with implications for surviving the ice-free period. Nat. Commun. **15**(947): 1–15. doi: 10.1038/s41467-023-44682-1.

Pearce, E.E., Alsaggaf, R., Katta, S., Dagnall, C., Aubert, G., Hicks, B.D., Spellman, S.R., Savage, S.A., Horvath, S., and Gadalla, S.M. 2022. Telomere length and epigenetic

clocks as markers of cellular aging: a comparative study. GeroScience **44**(3): 1861. doi: 10.1007/s11357-022-00586-4.

Rantanen, M., Karpechko, A.Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., and Laaksonen, A. 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Commun. Earth Environ. **3**(1): 1–10. doi: 10.1038/s43247-022-00498-3.

Robinson, D., Hayes, A., and Couch, S. 2025. broom: convert statistical objects into tidy tibbles. doi: 10.32614/CRAN.package.broom.

Spooner, F.E.B., Pearson, R.G., and Freeman, R. 2018. Rapid warming is associated with population decline among terrestrial birds and mammals globally. Glob. Change Biol. **24**(10): 4521–4531. doi: 10.1111/gcb.14361.

Stearns, S. C. 1992. The evolution of life histories. 1st edition. Oxford University Press Inc., New York.

Stirling, I., Jonkel, C., Smith, P., Robertson, R., and Cross., D. 1977. The ecology of the polar bear (*Ursus maritimus*) along the western coast of Hudson Bay. Occas. Pap. Can. Wildl. Serv. Minister of Supply and Services, Ottawa.

Sumner, J. A., Colich, N. L., Uddin, M., Armstrong, D., and McLaughlin, K. A. 2019. Early experiences of threat, but not deprivation, are associated with accelerated biological aging in children and adolescents. Soc. Biol. Psychiat. **85**(3): 268–278. doi: 10.1016/j.biopsych.2018.09.008.

Tschirren, B., Richner, H., and Schwabl, H. 2004. Ectoparasite-modulated deposition of maternal androgens in great tit eggs. P. Roy. Soc. B-Biol. Sci. **271**(1546): 1371–1375. doi: 10.1098/rspb.2004.2730.

Urban, C.M. 2015. Accelerating extinction risk from climate change. Science. **348**(6234): 571–573. doi: 10.1126/science.aaa4984.

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T. L., Miller, E., Bache, S. M., Müller, K., Ooms, J., Robinson, D., Seidel, D. P., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., and Yutani, H. 2019. Welcome to the tidyverse. J. of Open Source Softw. **4**(43): 1686. doi: 10.21105/joss.01686.

Xie, Y. 2014. knitr: a comprehensive tool for reproducible research in R. *In* Implementing reproducible computational research. *Edited by* Stodden, V., Leisch, F., and Peng, R. D. Chapman and Hall/CRC. ISBN 978-1466561595.

Xie, Y. 2015. Dynamic documents with R and knitr. 2nd edition. Chapman and Hall/CRC. ISBN 978-1498716963.

Xie, Y. 2025. knitr: a general-purpose package for dynamic report generation in R. R package version 1.50. https://yihui.org/knitr/.

Appendix A: Sample Sizes

Table A1. Overall sample size of polar bears and sample sizes by age group and sex (males = n_M, females = n_F, and both sexes combined = n), with negative numbers indicating years before birth, 0 indicating the year of birth, and positive numbers indicating years since birth.

Age	n_M	n_F	n
-5	84	97	181
-4	85	102	187
-3	87	107	194
-2	89	109	198
-1	91	111	202
0	65	81	146
1	62	84	146
2	61	84	145
3	56	85	141
4	54	82	136
5	51	81	132
6	48	78	126
7	46	74	120
8	45	68	113
Total Sample Size	112	145	257

Appendix B: Simple Linear Regression Models

Table B1. Estimates, standard errors, confidence interval lower and upper bounds, and probabilities of direction for 14 simple linear regression models (age acceleration ~ ice-free season length) in polar bear males grouped by age from 5 years before birth until the age of 8. Year of birth (age 0) is highlighted with a dark background.

Age	Term	Estimate	Standard Error	Confidence Interval Lower Bound	Confidence Interval Upper Bound	Probability of Direction
	Intercept	1.83	3.71	-5.38E+00	9.11	0.69
-5	Ice-Free	-0.01	0.02	-5.17E-02	0.04	0.61
	R^2	0.02	0.03	9.67E-04	0.06	NA
	Intercept	0.16	4.00	-7.66E+00	8.11	0.51
-4	Ice-Free	0.00	0.02	-4.47E-02	0.05	0.57
	R^2	0.02	0.02	9.12E-04	0.05	NA
	Intercept	-1.22	3.88	-8.92E+00	6.37	0.63
-3	Ice-Free	0.01	0.02	-3.39E-02	0.06	0.71
	R^2	0.02	0.03	1.07E-03	0.06	NA
	Intercept	-7.13	3.47	-1.38E+01	-0.30	0.98
-2	Ice-Free	0.05	0.02	8.83E-03	0.09	0.99
	R^2	0.07	0.07	5.79E-03	0.17	NA
	Intercept	-7.47	3.68	-1.48E+01	-0.17	0.98
-1	Ice-Free	0.05	0.02	7.47E-03	0.10	0.99
	R^2	0.07	0.07	4.87E-03	0.16	NA
	Intercept	-0.13	5.02	-9.84E+00	9.59	0.50
0	Ice-Free	0.01	0.03	-4.46E-02	0.07	0.68
	R^2	0.03	0.04	1.33E-03	0.08	NA
	Intercept	4.77	4.95	-4.98E+00	14.61	0.84
1	Ice-Free	-0.02	0.03	-7.60E-02	0.04	0.71
	R^2	0.04	0.04	1.53E-03	0.09	NA
	Intercept	6.48	5.01	-3.41E+00	16.42	0.90
2	Ice-Free	-0.03	0.03	-8.69E-02	0.03	0.80
	R^2	0.04	0.05	1.99E-03	0.11	NA
	Intercept	0.28	5.15	-9.97E+00	10.11	0.53
3	Ice-Free	0.01	0.03	-4.84E-02	0.07	0.64
	R^2	0.03	0.04	1.48E-03	0.09	NA
	Intercept	-1.93	6.70	-1.53E+01	11.04	0.61
4	Ice-Free	0.03	0.04	-5.47E-02	0.11	0.73
	R^2	0.04	0.05	1.82E-03	0.10	NA
	Intercept	-5.66	6.36	-1.84E+01	6.53	0.81
5	Ice-Free	0.05	0.04	-2.50E-02	0.13	0.90
	R^2	0.07	0.07	3.65E-03	0.16	NA
6	Intercept	-3.22	7.62	-1.82E+01	12.11	0.67

	Ice-Free	0.03	0.05	-5.91E-02	0.13	0.77
	R^2	0.05	0.06	2.34E-03	0.12	NA
	Intercept	-6.95	7.68	-2.22E+01	8.37	0.82
7	Ice-Free	0.06	0.05	-3.70E-02	0.15	0.89
	R^2	0.07	0.08	3.95E-03	0.17	NA
	Intercept	-8.52	8.43	-2.51E+01	7.98	0.85
8	Ice-Free	0.06	0.05	-3.73E-02	0.16	0.90
	R^2	0.07	0.08	4.13E-03	0.18	NA

Table B2. Estimates, standard errors, confidence interval lower and upper bounds, and probabilities of direction for 14 simple linear regression models (age acceleration ~ ice-free season length) in polar bear females grouped by age from 5 years before birth until the age of 8. Year of birth (age 0) is highlighted with a dark background.

Age	Term	Estimate	Standard Error	Confidence Interval Lower Bound	Confidence Interval Upper Bound	Probability of Direction
	Intercept	3.94	3.32	-2.73E+00	10.28	0.88
-5	Ice-Free	-0.02	0.02	-6.40E-02	0.02	0.87
	R^2	0.03	0.04	1.75E-03	0.08	NA
	Intercept	1.73	2.97	-4.19E+00	7.49	0.72
-4	Ice-Free	-0.01	0.02	-4.48E-02	0.03	0.69
	R^2	0.02	0.02	8.77E-04	0.05	NA
	Intercept	2.36	2.59	-2.70E+00	7.54	0.82
-3	Ice-Free	-0.01	0.02	-4.51E-02	0.02	0.79
	R^2	0.03	0.03	1.17E-03	0.07	NA
	Intercept	-2.92	2.91	-8.59E+00	2.79	0.84
-2	Ice-Free	0.02	0.02	-1.59E-02	0.06	0.87
	R^2	0.03	0.03	1.49E-03	0.07	NA
	Intercept	-0.31	2.76	-5.78E+00	5.13	0.54
-1	Ice-Free	0.00	0.02	-3.13E-02	0.04	0.56
	R^2	0.02	0.02	6.75E-04	0.04	NA
	Intercept	3.27	3.51	-3.67E+00	9.96	0.83
0	Ice-Free	-0.02	0.02	-5.96E-02	0.03	0.78
	R^2	0.03	0.04	1.46E-03	0.08	NA
	Intercept	-0.38	3.78	-7.67E+00	7.06	0.54
1	Ice-Free	0.01	0.02	-4.10E-02	0.05	0.60
	R^2	0.02	0.03	9.20E-04	0.05	NA
	Intercept	-4.04	3.60	-1.11E+01	3.08	0.87
2	Ice-Free	0.03	0.02	-1.53E-02	0.07	0.90
	R^2	0.04	0.05	2.38E-03	0.11	NA
	Intercept	-2.92	3.88	-1.06E+01	4.64	0.78
3	Ice-Free	0.02	0.02	-2.60E-02	0.07	0.81
	R^2	0.03	0.04	1.50E-03	0.08	NA
	Intercept	-6.14	3.71	-1.34E+01	1.23	0.95
4	Ice-Free	0.04	0.02	-4.42E-03	0.09	0.96
	R^2	0.06	0.06	3.35E-03	0.14	NA
	Intercept	-3.72	4.65	-1.29E+01	5.41	0.79
5	Ice-Free	0.02	0.03	-3.35E-02	0.08	0.80
	R^2	0.03	0.04	1.55E-03	0.09	NA
	Intercept	-8.21	4.86	-1.77E+01	1.27	0.95
6	Ice-Free	0.05	0.03	-6.96E-03	0.11	0.96
	R^2	0.06	0.06	3.22E-03	0.14	NA

	Intercept	-5.49	5.77	-1.69E+01	5.75	0.83
7	Ice-Free	0.04	0.04	-3.63E-02	0.11	0.84
	R^2	0.04	0.04	1.86E-03	0.09	NA
	Intercept	-10.71	5.84	-2.22E+01	0.80	0.97
8	Ice-Free	0.07	0.04	-5.95E-03	0.14	0.96
	R^2	0.07	0.07	3.80E-03	0.16	NA

Appendix C: Linear Regression Models with Interaction Terms

Table C1. Estimates, standard errors, confidence interval lower and upper bounds, and probabilities of direction for 14 linear regression models with an interaction term (age acceleration ~ ice-free season length * 1995 before or from) in polar bear males grouped by age from 5 years before birth until the age of 8. Year of birth (age 0) is highlighted with a dark background.

Age	Term	Estimate	Standard Error	Confidence Interval Lower Bound	Confidence Interval Upper Bound	Probability of Direction
	Intercept	0.69	5.57	-10.16	11.67	0.55
	Ice-Free	0.00	0.04	-0.08	0.07	0.54
-5	1995	23.98	10.00	4.37	44.01	0.99
	Ice-Free : 1995	-0.13	0.06	-0.25	-0.01	0.98
	R^2	0.12	0.10	0.04	0.24	NA
	Intercept	2.56	5.88	-9.07	14.18	0.67
	Ice-Free	-0.02	0.04	-0.09	0.06	0.66
-4	1995	3.86	9.58	-14.86	22.55	0.66
	Ice-Free : 1995	-0.01	0.06	-0.13	0.10	0.59
	R^2	0.07	0.06	0.01	0.15	NA
	Intercept	3.61	5.85	-7.64	15.30	0.73
	Ice-Free	-0.02	0.04	-0.10	0.05	0.72
-3	1995	-0.71	11.26	-22.52	21.10	0.53
	Ice-Free : 1995	0.01	0.07	-0.12	0.15	0.59
	R^2	0.06	0.06	0.01	0.14	NA
	Intercept	-26.16	7.97	-41.86	-10.36	1.00
	Ice-Free	0.19	0.05	0.08	0.29	1.00
-2	1995	20.33	10.24	-0.37	40.04	0.97
	Ice-Free : 1995	-0.14	0.07	-0.27	-0.01	0.98
	R^2	0.13	0.11	0.05	0.27	NA
	Intercept	-12.68	5.91	-24.33	-1.13	0.98
	Ice-Free	0.09	0.04	0.01	0.16	0.99
-1	1995	8.31	9.64	-10.77	27.26	0.81
	Ice-Free : 1995	-0.05	0.06	-0.17	0.06	0.83
	R^2	0.09	0.08	0.02	0.19	NA
	Intercept	2.09	8.01	-13.83	17.72	0.61
	Ice-Free	0.00	0.05	-0.11	0.10	0.52
0	1995	4.22	13.38	-22.67	30.16	0.63
	Ice-Free : 1995	-0.02	0.08	-0.17	0.14	0.59
	R^2	0.06	0.06	0.01	0.15	NA
1	Intercept	23.23	8.12	7.48	39.42	1.00
	Ice-Free	-0.14	0.06	-0.25	-0.04	1.00

	1995	-31.31	13.14	-57.11	-5.26	0.99
	Ice-Free : 1995	0.21	0.08	0.04	0.37	0.99
	R^2	0.14	0.12	0.03	0.29	NA
	Intercept	18.09	9.87	-1.44	37.65	0.97
	Ice-Free	-0.11	0.07	-0.24	0.02	0.95
2	1995	-6.66	14.19	-34.77	21.51	0.68
	Ice-Free : 1995	0.06	0.09	-0.12	0.23	0.75
	R^2	0.10	0.09	0.02	0.22	NA
	Intercept	-1.90	8.00	-17.77	14.14	0.60
	Ice-Free	0.03	0.05	-0.08	0.13	0.70
3	1995	8.59	15.17	-21.68	38.33	0.72
	Ice-Free : 1995	-0.05	0.09	-0.23	0.13	0.71
	R^2	0.07	0.07	0.01	0.16	NA
	Intercept	-13.17	12.67	-38.07	11.61	0.86
	Ice-Free	0.10	0.09	-0.07	0.27	0.88
4	1995	34.59	19.90	-5.41	73.52	0.96
	Ice-Free : 1995	-0.21	0.12	-0.45	0.04	0.95
	R^2	0.11	0.10	0.02	0.23	NA
	Intercept	4.34	14.04	-22.95	32.16	0.63
	Ice-Free	-0.02	0.10	-0.21	0.17	0.59
5	1995	-11.02	19.74	-50.41	27.20	0.72
	Ice-Free : 1995	0.08	0.13	-0.17	0.33	0.74
	R^2	0.10	0.09	0.01	0.21	NA
	Intercept	2.00	13.14	-23.67	27.94	0.56
	Ice-Free	0.00	0.09	-0.18	0.17	0.51
6	1995	-3.37	21.61	-46.17	38.57	0.56
	Ice-Free : 1995	0.03	0.13	-0.23	0.29	0.59
	R^2	0.08	0.08	0.01	0.18	NA
	Intercept	6.14	13.12	-19.47	32.14	0.68
	Ice-Free	-0.03	0.09	-0.21	0.14	0.64
7	1995	-28.22	20.69	-69.33	12.70	0.92
	Ice-Free : 1995	0.18	0.13	-0.08	0.43	0.92
	R^2	0.12	0.11	0.02	0.26	NA
	Intercept	-7.55	15.22	-37.61	22.30	0.70
	Ice-Free	0.06	0.10	-0.14	0.26	0.73
8	1995	-12.14	24.43	-60.06	36.10	0.69
	Ice-Free : 1995	0.07	0.15	-0.23	0.36	0.68
	R^2	0.10	0.10	0.01	0.22	NA

Table C2. Estimates, standard errors, confidence interval lower and upper bounds, and probabilities of direction for 14 linear regression models with an interaction term (age acceleration ~ ice-free season length * 1995 before or from) in polar bear females grouped by age from 5 years before birth until the age of 8. Year of birth (age 0) is highlighted with a dark background.

Age	Term	Estimate	Standard Error	Confidence Interval Lower Bound	Confidence Interval Upper Bound	Probability of Direction
	Intercept	8.03	5.06	-1.92	17.94	0.94
	Ice-Free	-0.05	0.03	-0.12	0.01	0.94
-5	1995	0.00	10.76	-21.31	21.20	0.51
	Ice-Free : 1995	0.01	0.07	-0.12	0.14	0.55
	R^2	0.06	0.06	0.01	0.14	NA
	Intercept	2.29	4.49	-6.47	11.03	0.69
	Ice-Free	-0.01	0.03	-0.07	0.05	0.67
-4	1995	-1.73	9.01	-19.00	16.28	0.58
	Ice-Free : 1995	0.01	0.05	-0.10	0.11	0.58
	R^2	0.04	0.04	0.00	0.08	NA
	Intercept	3.47	4.07	-4.52	11.47	0.81
	Ice-Free	-0.02	0.03	-0.07	0.03	0.78
-3	1995	-2.29	6.93	-16.09	10.92	0.63
	Ice-Free : 1995	0.01	0.04	-0.06	0.10	0.64
	R^2	0.04	0.04	0.00	0.09	NA
	Intercept	-7.08	4.89	-16.64	2.64	0.92
	Ice-Free	0.05	0.03	-0.02	0.11	0.93
-2	1995	-2.77	8.94	-19.93	15.01	0.62
	Ice-Free : 1995	0.01	0.05	-0.10	0.11	0.55
	R^2	0.06	0.06	0.01	0.14	NA
	Intercept	-1.79	4.66	-10.82	7.05	0.65
	Ice-Free	0.01	0.03	-0.05	0.07	0.65
-1	1995	8.49	8.79	-8.76	25.89	0.84
	Ice-Free : 1995	-0.05	0.05	-0.16	0.06	0.83
	R^2	0.04	0.04	0.00	0.09	NA
	Intercept	2.30	5.98	-9.40	13.84	0.65
	Ice-Free	-0.01	0.04	-0.09	0.07	0.63
0	1995	14.59	9.98	-5.25	33.72	0.93
	Ice-Free : 1995	-0.08	0.06	-0.20	0.04	0.90
	R^2	0.09	0.08	0.01	0.19	NA
	Intercept	4.70	5.66	-6.39	15.85	0.80
	Ice-Free	-0.03	0.04	-0.10	0.04	0.79
1	1995	-11.83	12.29	-35.79	12.23	0.83
	Ice-Free : 1995	0.08	0.07	-0.07	0.22	0.85
	R^2	0.06	0.06	0.01	0.13	NA

	Intercept	-3.98	4.92	-13.62	5.79	0.79
	Ice-Free	0.03	0.03	-0.04	0.09	0.80
2	1995	4.11	10.04	-15.41	23.65	0.66
	Ice-Free : 1995	-0.02	0.06	-0.14	0.10	0.64
	R^2	0.06	0.06	0.01	0.14	NA
	Intercept	-1.13	6.86	-14.79	12.34	0.56
	Ice-Free	0.01	0.05	-0.08	0.10	0.56
3	1995	6.18	12.13	-17.64	30.27	0.70
	Ice-Free : 1995	-0.03	0.07	-0.17	0.11	0.66
	R^2	0.06	0.06	0.01	0.13	NA
	Intercept	-5.99	6.40	-18.22	6.76	0.83
	Ice-Free	0.04	0.04	-0.05	0.12	0.82
4	1995	3.46	12.22	-20.71	26.97	0.62
	Ice-Free : 1995	-0.02	0.07	-0.16	0.13	0.60
	R^2	0.07	0.07	0.01	0.16	NA
	Intercept	3.07	7.11	-10.86	17.08	0.67
	Ice-Free	-0.03	0.05	-0.12	0.07	0.71
5	1995	6.99	13.47	-19.40	33.34	0.70
	Ice-Free : 1995	-0.02	0.08	-0.18	0.13	0.61
	R^2	0.09	0.08	0.02	0.20	NA
	Intercept	-3.93	6.88	-17.24	9.84	0.72
	Ice-Free	0.02	0.05	-0.07	0.11	0.68
6	1995	4.18	16.52	-28.85	35.80	0.60
	Ice-Free : 1995	-0.01	0.10	-0.20	0.18	0.56
	R^2	0.09	0.08	0.01	0.19	NA
	Intercept	-1.34	7.06	-15.45	12.40	0.57
	Ice-Free	0.00	0.05	-0.09	0.10	0.53
7	1995	10.19	22.00	-33.69	53.34	0.69
	Ice-Free : 1995	-0.05	0.13	-0.31	0.22	0.65
	R^2	0.08	0.08	0.01	0.18	NA
	Intercept	-4.09	7.70	-19.29	11.26	0.71
	Ice-Free	0.02	0.05	-0.08	0.12	0.64
8	1995	-4.92	18.23	-40.16	31.45	0.61
	Ice-Free : 1995	0.04	0.11	-0.18	0.26	0.66
	R^2	0.10	0.09	0.02	0.22	NA

Table C3. Estimates, standard errors, confidence interval lower and upper bounds, and probabilities of direction for 14 linear regression models with an interaction term (age acceleration ~ ice-free season length * sex before or from) in polar bear males and females grouped by age from 5 years before birth until the age of 8. Year of birth (age 0) is highlighted with a dark background.

Age	Term	Estimate	Standard Error	Confidence Interval Lower Bound	Confidence Interval Upper Bound	Probability of Direction
	Intercept	3.80	3.57	-3.24	10.91	0.86
	Ice-Free	-0.02	0.02	-0.07	0.02	0.84
-5	Sex	-1.87	4.90	-11.48	7.67	0.64
	Ice-Free : Sex	0.02	0.03	-0.04	0.08	0.69
	R^2	0.03	0.03	0.00	0.07	NA
	Intercept	1.73	3.23	-4.63	8.10	0.71
	Ice-Free	-0.01	0.02	-0.05	0.03	0.68
-4	Sex	-1.54	4.96	-11.38	7.98	0.62
	Ice-Free : Sex	0.01	0.03	-0.05	0.07	0.66
	R^2	0.03	0.03	0.00	0.06	NA
	Intercept	2.42	2.71	-2.93	7.78	0.81
	Ice-Free	-0.01	0.02	-0.05	0.02	0.79
-3	Sex	-3.67	4.41	-12.43	4.87	0.80
	Ice-Free : Sex	0.03	0.03	-0.03	0.08	0.83
	R^2	0.03	0.03	0.00	0.07	NA
	Intercept	-2.99	3.02	-8.97	2.94	0.84
	Ice-Free	0.02	0.02	-0.02	0.06	0.86
-2	Sex	-4.15	4.25	-12.51	4.26	0.84
	Ice-Free : Sex	0.03	0.03	-0.02	0.08	0.88
	R^2	0.06	0.05	0.02	0.12	NA
	Intercept	-0.14	2.98	-5.90	5.76	0.52
	Ice-Free	0.00	0.02	-0.03	0.04	0.54
-1	Sex	-7.49	4.46	-16.15	1.29	0.95
	Ice-Free : Sex	0.05	0.03	0.00	0.10	0.97
	R^2	0.05	0.05	0.01	0.12	NA
	Intercept	-10.75	6.06	-22.55	1.30	0.96
	Ice-Free	0.07	0.04	-0.01	0.14	0.96
0	Sex	2.02	9.88	-17.58	21.12	0.59
	Ice-Free : Sex	0.00	0.06	-0.12	0.12	0.52
	R^2	0.09	0.07	0.02	0.18	NA
	Intercept	-5.58	6.21	-17.75	6.97	0.82
	Ice-Free	0.04	0.04	-0.04	0.11	0.82
1	Sex	-1.41	9.44	-20.48	16.66	0.56
	Ice-Free : Sex	0.02	0.06	-0.09	0.14	0.65

	R^2	0.08	0.07	0.02	0.17	NA
	Intercept	-8.15	5.20	-18.37	2.13	0.94
	Ice-Free	0.05	0.03	-0.01	0.12	0.95
2	Sex	5.12	8.69	-11.93	22.36	0.73
	Ice-Free : Sex	-0.02	0.05	-0.13	0.09	0.65
	R^2	0.08	0.07	0.02	0.16	NA
	Intercept	-3.67	5.03	-13.51	6.32	0.77
	Ice-Free	0.02	0.03	-0.04	0.09	0.78
3	Sex	-2.09	7.83	-17.55	13.35	0.61
	Ice-Free : Sex	0.03	0.05	-0.07	0.12	0.70
	R^2	0.07	0.07	0.02	0.16	NA
	Intercept	-6.08	4.19	-14.44	2.24	0.93
	Ice-Free	0.04	0.03	-0.01	0.09	0.94
4	Sex	4.21	7.15	-10.02	18.06	0.72
	Ice-Free : Sex	-0.02	0.04	-0.10	0.07	0.65
	R^2	0.06	0.06	0.01	0.14	NA
	Intercept	-2.84	3.93	-10.47	4.96	0.77
	Ice-Free	0.02	0.02	-0.03	0.07	0.80
5	Sex	3.11	6.29	-9.46	15.06	0.69
	Ice-Free : Sex	-0.01	0.04	-0.08	0.07	0.60
	R^2	0.06	0.06	0.01	0.13	NA
	Intercept	-3.96	3.84	-11.41	3.72	0.85
	Ice-Free	0.03	0.02	-0.02	0.08	0.88
6	Sex	10.35	5.84	-1.05	21.73	0.96
	Ice-Free : Sex	-0.05	0.04	-0.12	0.02	0.93
	R^2	0.07	0.06	0.02	0.15	NA
	Intercept	-0.27	4.01	-8.16	7.52	0.53
	Ice-Free	0.00	0.03	-0.04	0.05	0.58
7	Sex	5.10	6.11	-7.02	17.12	0.80
	Ice-Free : Sex	-0.02	0.04	-0.10	0.05	0.71
	R^2	0.06	0.06	0.01	0.13	NA
	Intercept	3.32	3.72	-3.85	10.64	0.82
	Ice-Free	-0.02	0.02	-0.06	0.03	0.77
8	Sex	-3.28	6.03	-15.34	8.30	0.71
	Ice-Free : Sex	0.03	0.04	-0.04	0.10	0.79
	R^2	0.06	0.05	0.01	0.13	NA