Effects of Arctic warming and killer whale infiltration on the polar bear population of Hudson Bay

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1 Introduction

Polar bears are one of the most beloved species on the planet, improbably carving a habitat for themselves on the Arctic ice despite their large appetite and warm blood. So beloved in fact that the rallying cry "Save the polar bears" has become synonymous with Arctic conservation efforts. But can they be saved? In this paper, I try to answer the question of whether the polar bear population around Hudson Bay, Canada, can withstand a changing climate and the unexpected competition for food that has come with it.

As the global temperature has steadily increased, ice coverage in the lower Arctic has changed dramatically; specifically, the mouth of Hudson Bay no longer stays frozen for the whole year. This allows passage into the Bay from the North Atlantic ocean for killer whales and other alien species during the summer months. Killer whales are apex predators and eat the same seals that the polar bears depend on. The question I will answer is: can the seal population sustain two apex predators, or will one die out while the other flourishes? And a secondary question: will ice depletion hurt the polar bears more than competition for food? In this paper I explain the methodology behind the formulation of my system of differential equations, analysis of this system, results of simulation, and the conclusions wrested from the simulation.

2 Methodology

To attack this problem, the first step is determining initial conditions. According to my research, there are approximately 450,000 seals and between 800-900 polar bears currently inhabiting Hudson Bay. Additionally, there are killer whale communities in the Northwest Atlantic numbering about 150 [1]. I also calculated the number of seals eaten by a single polar bear and a single killer whale in a year to be approximately 50 and 240 respectively [2,3]. Next, I had to determine the birth and death rates for each of these animals. Polar bears reproduce and die fairly steadily, with a birth rate of 0.1 and death rate of 0.05 [4]. The specifics of killer whale reproduction are not known with great accuracy, but using data on a well studied pod off the coast of southern California, I have estimated the birth rate to be $\frac{1}{37}$ and the death rate to be $\frac{1}{60}$ [5]. Seals reproduce rapidly, but not many of the newborns make it to adulthood. Thus I have the seal birthrate at 0.56 and their death rate at 0.06 [6].

One of the key aspects of my model is the change of ice coverage on Hudson Bay from year to year and how that affects the populations in question. The polar bear and seal birth rates are dependent to some extent on ice coverage (as this is their habitat). Additionally, the freeze-up and melting dates change each year, with the Bay freezing later and melting earlier as time goes on. The length of seasons is significant because polar bears can only feed in the winter, and killer whales can only feed in the summer. To model these changing conditions, I have used results from a paper showing the relationship between increasing average surface temperatures and ice coverage on the Bay, as well as the freeze-up and melting dates [7]. I have used this in conjunction with the average rate of global temperature increase [8] to create equations modeling these phenomena, which I applied to my system of differential equations.

From the paper, an increase in fall seasonal temperature of $+2.5^o$C correlates to a change in ice coverage of $-1.4\times10^5\text{km}^2$. And an increase in spring seasonal temperature of $+2^o$C correlates to a change in ice coverage of $-2.97\times10^5\text{km}^2$. I averaged these to find that the total impact of an increase of $+2.25^o$C is a reduction in ice coverage of $-2.19\times10^5\text{km}^2$. Assuming a change of $+0.01^o$C per year, we get a change in ice coverage of $-0.01\times10^5\text{km}^2$ per year. With an initial condition of full ice coverage of $12.3\times10^5\text{km}^2$, the ice coverage of a specific year is $I_p(t) = -0.01t + 12.3$.

Also from the paper came information regarding the change in ice break-up and freeze dates with respect to increasing temperature. The break-up (or melt) date occurs 1.9 weeks earlier for a change in temperature of $+2^o$C and the freeze date occurs 0.71 weeks later for a change of $+1^o$C. Thus the length of summer $L_s(t)$ (beginning at the break-up date and ending at the freeze date) increases 1.66 weeks per change of $+1^o$C. Assuming annual change of $+0.01^o$C and an initial length of summer of 24 weeks, we get $L_s(t) = (24 + 0.0166t)/52$ as a proportion of one year. And since winter is occurring the rest of the year, we can deduce that the length of winter is $L_w(t) = 1 - L_s(t)$. These functions of course exist between values of 0 and 1; after the 1687^{th} year the freeze and melt dates will be the same (we actually do not witness this in the model because the ice coverage reaches zero first, at the 1230^{th} year).

3 Model and Analysis

I began with a classic predator-prey model between the polar bears and the seals, presumably a system in equilibrium prior to the opening of the passage to the ocean.

$$P' = (\frac{S}{x+S}\alpha_P - \beta_P)P$$

$$S' = (\alpha_S - \beta_S)(1 - \frac{S}{N_{max}})S - (\gamma_P \frac{S}{x+S})P$$

I performed nullcline and trajectory plane analysis on this system, finding P' nullclines:

$$P = 0$$

and

$$\frac{S}{x+S}\alpha_P = \beta_P$$

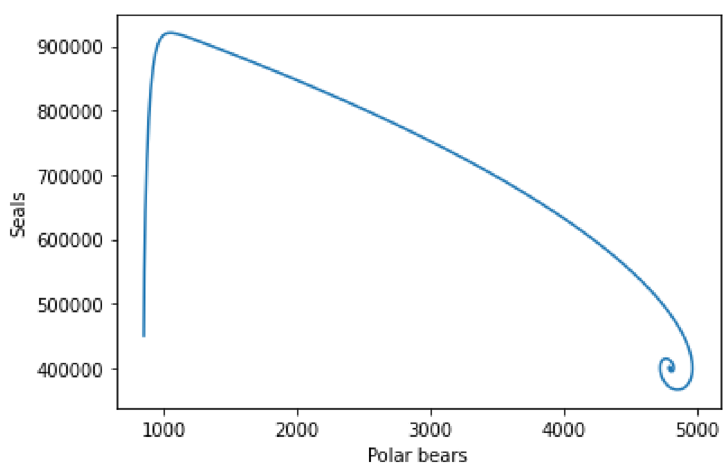
and S' nullclines:

$$S = 0$$

and

$$P = \frac{(\alpha_S - \beta_S)(1 - \frac{S}{N_{max}})S}{\gamma_P \frac{S}{x+S}}$$

Here we can find a constant value for S on the P' nullcline and plug into the S' nullcline and find P for an equilibrium solution. For values $x = 400,000$ and $N_{max} = 1,000,000$, we find an equilibrium solution of 4800 polar bears and 400,000 seals. In the following figure, polar bear and seal populations are plotted against each other, in this case moving left to right on the curve over time beginning at the initial conditions stipulated above. The relation eventually comes to a single point, signifying an equilibrium exactly where the nullcline analysis predicted. Using this analysis is important in obtaining the x and N_{max} coefficients for use in the larger model by beginning in a stable equilibrium.



Next, I added the killer whale population to the model (giving them a slight bump in reproduction due to a new food source) and adjusted the seal population equation accordingly:

$$S' = (\alpha_S - \beta_S)(1 - \frac{S}{N_{max}})S - (\gamma_P \frac{S}{x+S})P - (\gamma_K \frac{S}{x+S})K$$

$$K' = ((1.1\frac{S}{x+S})\alpha_K - \beta_K)K$$

The final step was to add the changing conditions of ice formation and seasonal behavior. I made functions for these variables described above:

$$I_p(t) = -0.01t + 12.3$$

$$Ls(t) = (24 + 0.0166t)/52$$

$$Lw(t) = 1 - (24 + 0.0166t)/52$$

Then I applied these terms to my system as proportionally affecting the populations:

$$P' = (\frac{I_p}{I_{max}} \frac{Lw}{Lw_0} \frac{S}{x+S}\alpha_P - \beta_P)P$$

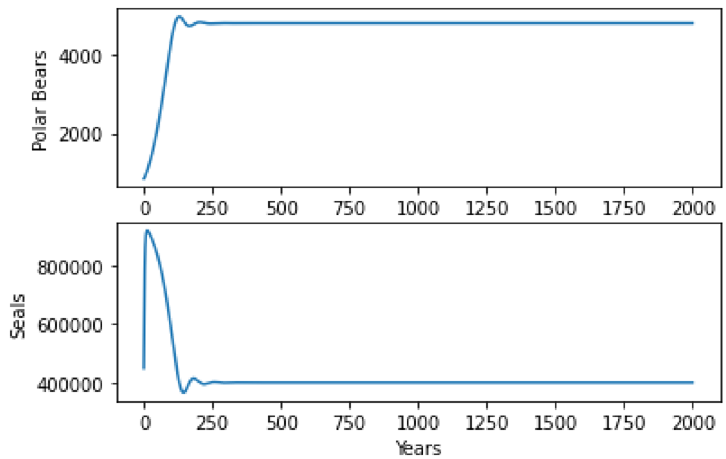
$$S' = ((\frac{I_p}{I_{max}})\alpha_S - \beta_S)(1 - \frac{S}{N_{max}})S - (\gamma_P \frac{S}{x+S})P - (\gamma_K \frac{S}{x+S})K$$

$$K' = (\frac{Ls}{Ls_0}(1.1\frac{S}{x+S})\alpha_K - \beta_K)K$$

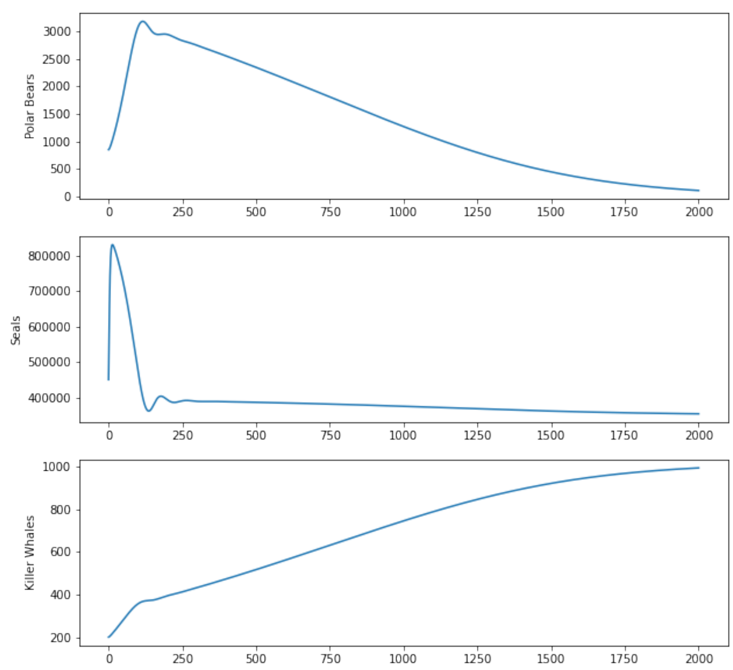
Now, the proportion of ice formation versus the maximum amount of ice is affecting the reproduction of polar bears and seals; the length of winter (i.e. the polar bear hunting season) is affecting polar bear reproduction; and the length of summer (i.e. the killer whale hunting season) is affecting the reproduction of killer whales. This is the system of equations I used for the simulation model.

4 Simulation

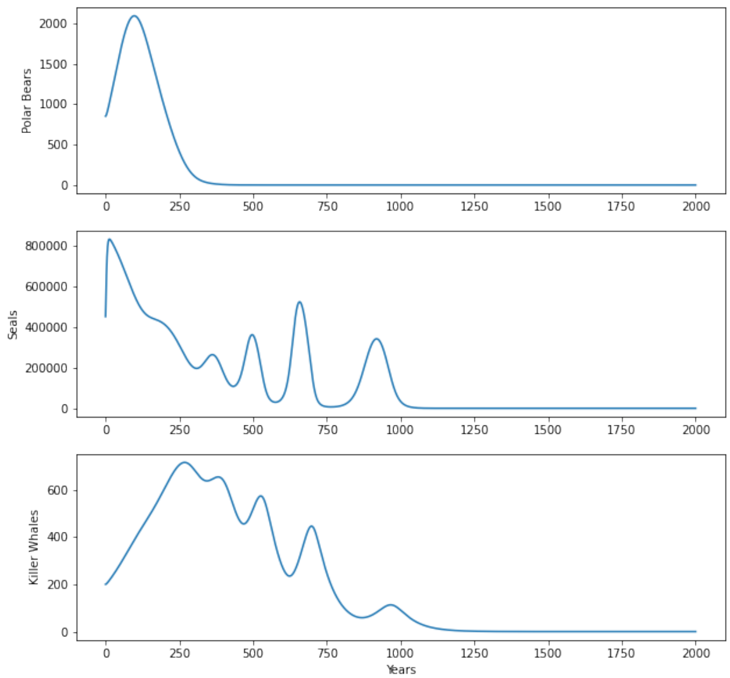
With the model formulated above, I simulated how the populations of polar bears, seals and killer whales would behave over the next 2000 years.



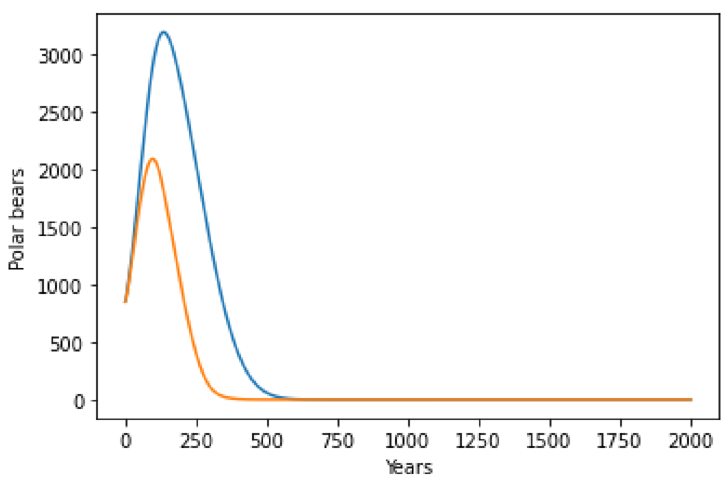
This first figure shows the populations of polar bears and seals in equilibrium. They reach the equilibrium point stipulated above after about 250 years and remain there indefinitely.



The second figure shows the populations once the killer whales are introduced. We see that the seal population stabilizes a little lower than before, while the polar bear population eventually goes to zero. Interestingly, if we extrapolate a bit further down the timeline, we find that there is an equilibrium system between seals and killer whales at about 350,000 seals and 1000 killer whales.



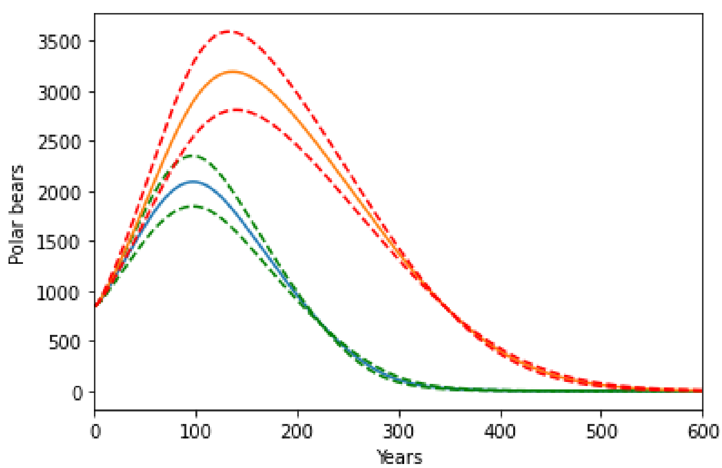
This next figure shows our three populations after the seasonal and ice variances have been included. The polar bear population goes to zero much more rapidly, and the seal and killer whale populations both go to zero as well. It should be noted that the killer whale pod existed prior to having access to Hudson Bay, thus their population should be maintained above zero at whatever the carrying capacity of their other environment is. What this graph represents at the least then is that there will be no more killer whales in Hudson Bay.



The final figure shows the population of polar bears in two scenarios: with the effects of melting ice (blue) and with the effects of both melting ice and competition with killer whales (orange). According to my model, the presence of killer whales accelerates the extinction of polar bears in the region by about 200 years.

5 Error

The primary sources of potential error in this model come from the derivation of the melt equations, as well as inaccuracies with estimating the growth rate parameters of the three species being studied. The paper from which the information was taken to formulate the melt equations boasted a $p-$value of less than or equal to 0.0001 for their assertions, meaning their work has statistical significance of greater than four sigma and almost certainly can be trusted. Unfortunately, less can be said about the growth rates. While they can be estimated with fair accuracy based on research, the growth rates are not exact scientific numbers. Thus I ran the final simulation (all three species and the melt coefficients) assuming I was off by $\pm 10\%$.



In the above figure, I plotted this confidence interval (green) against the actual model (blue) and there is not significant difference in behavior, nor is there significant difference in timing of the ultimate demise of the polar bears. The only difference is the peak polar bear population (which occurs at the same time for all three cases). This gives my estimates some numerical stability and confidence that the model is accurate even if the growth rates are off by a little. Additionally, these error-driven calculations did not affect how much the inclusion of killer whales accelerates polar bear extinction. The model without killer whales (orange) and its confidence interval (red) are plotted alongside, and the difference is always about 200 years.

6 Findings and Conclusion

From the simulations, we see that the situation for the polar bears of Hudson Bay is a dire one. If they do not die from competition for food, then they die from lack of ice on which to live and hunt. The speed at which this extinction occurs, though, is highly variable depending on the circumstances. The sudden presence of killer whales in an otherwise stable ecosystem does eventually put enough pressure on the food source to bring the bear population to zero. But this system is more complex than that, and the changing climate and its adverse effects on the habitat of the polar bear are massively impactful. Much more so, even, than the infiltration of killer whales into the polar bear hunting grounds when each is taken alone and is clearly the dominant driver of extinction. However, when taken together, there is an obvious and significant acceleration of the extinction timeline. Rather than taking about 650 years for the polar bears to die out due to lack of habitat and access to food, the additional competition for this food will cause them to go extinct in about 450 years according to my model. If we adjust the model to predict extinction in about 100 years (as is widely predicted), then competition with killer whales could see the absence of polar bears in Hudson Bay before the turn of the century.

7 Bibliography

1. Lawson, J. and Stevens, T., 2013. Historic and current distribution patterns, and minimum abundance of killer whales (Orcinus orca) in the north-west Atlantic. Journal of the Marine Biological Association of the United Kingdom, 94(6), pp.1253-1265.

2. Kautz, E., 2020. What Do Polar Bears Eat?. [online] Good Nature Travel. Available at: www.nathab.com/blog/what-do-polar-bears-eat

3. The Whale Museum, 2020. Frequently asked questions about the southern resident endangered orcas. Available at: www.whalemuseum.org/pages/frequently-asked-questions

4. Wiig, Øystein. "Survival and Reproductive Rates for Polar Bears at Svalbard." Ursus, vol. 10, 1998, pp. 25–32. JSTOR, www.jstor.org/stable/3873105.

5. Orca Network, 2020. Southern Resident Orca Community Births and Deaths since 1998. Available at: www.orcanetwork.org

6. Bjørn A. Krafft, Kit M. Kovacs, Anne Kirstine Frie, Tore Haug, Christian Lydersen, Growth and population parameters of ringed seals (Pusa hispida) from Svalbard, Norway, 2002–2004, ICES Journal of Marine Science, Volume 63, Issue 6, 2006, Pages 1136–1144, https://doi.org/10.1016/j.icesjms.2006.04.001

7. Klaus P. Hochheim & David G. Barber (2014) An Update on the Ice Climatology of the Hudson Bay System, Arctic, Antarctic, and Alpine Research, 46:1, 66-83, DOI: 10.1657/1938-4246-46.1.66

8. Nsidc.org. 2020. Climate Change In The Arctic — National Snow And Ice Data Center. [online] Available at: https://nsidc.org/cryosphere/arctic-meteorology/climate_change.html.

8 Appendix

α_P	Polar bear birth rate
β_P	Polar bear death rate
α_S	Seal birth rate
β_S	Seal death rate
α_K	Killer whale birth rate
β_K	Killer whale death rate
γ_P	Polar bear predation rate
γ_K	Killer whale predation rate
x	Threshold between linear and constant availability
N_{max}	Carrying capacity
I_p	Ice coverage for the period
I_{max}	Maximum ice coverage
Lw	Length of winter for the period
Lw_0	Initial length of winter
Ls	Length of summer for the period
Ls_0	Initial length of summer