EVALUATING POTENTIAL EFFECTS OF ANTARCTIC ICE-SHELF RETREAT ON BLUE WHALE (*BALAENOPTERA MUSCULUS)* POPULATIONS: A SIMULATION MODEL OF INTERACTIONS AMONG SEA ICE, ANTARCTIC KRILL (*EUPHAUSIA SUPERBA)*, AND BLUE WHALES

An Undergraduate Research Scholars Thesis

by

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TABLE OF CONTENTS

ABSTRACT

Evaluating potential effects of Antarctic ice-shelf retreat on blue whale (*Balaenoptera musculus*) populations: A simulation model of interactions among sea ice, Antarctic krill (*Euphausia superba*), and blue whales

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In the Antarctic, blue whales (Balaenoptera musculus) feed primarily on Antarctic krill (Euphausia superba), which feed primarily on under-ice algae. The retreat of the Antarctic ice shelf may pose potentially serious problems for blue whale populations by causing shifts in the abundance and distribution of sea ice and, hence, under-ice algae and Antarctic krill. I will develop a stochastic simulation model representing the interactions among sea ice, Antarctic krill (Euphausia superba), under-ice algae, and blue whales, and use the model to explore the potential effects of Antarctic ice-shelf retreat on blue whale populations under various assumptions regarding the rate of retreat of the Antarctic ice shelf.

CHAPTER I

INTRODUCTION

The blue whale (*Balaenoptera musculus)* is the largest animal ever known to have lived on Earth, with adults in the Antarctic having reached a maximum body length of about 33 m and weighing more than 150,000 kg (Reeves et al. 1998). Intraspecific inconsistency studies have led to the distinction of three subspecies, *B. m. musculus* in the Northern Hemisphere, the *B. m. intermedia* from the Antarctic, and *B. m. brevicauda*, the "pygmy" blue whale from in the sub-Antarctic zone of the southern Indian Ocean and southwestern Pacific Ocean (Reeves et al. 1998). For the purposes of this study, I will focus primarily on the *B.m. intermedia* from the Antarctic. The status of blue whale populations has been a topic of much concern for decades, as blue whales once extensively inhabited the Southern Hemisphere, but their population was decimated due to widespread whaling exploitation starting in 1904 (Branch et al. 2004). This fact was especially disastrous on the Antarctic population. The Antarctic blue whales were wiped out at numbers greater than both the northern blue whales and pygmy blue whales combined (Branch et al. 2004). The operation of modern whaling vessels capable of catching these fast swimming animals began operating in the Antarctic in 1905 (Branch et al. 2004). Prior to introduction of steam power in the second half of the 19^{th} century there were no ships fast enough to keep up with larger whales (Reeves et al. 1998). Whaling reached the pinnacle at 29,409 Antarctic blue whale catches in the 1930/1931 austral summer (Tomilin 1967; Branch et al. 2004). At this time, blue whales supplied 75% of the world's whale oil production (Tomilin 1967; Branch et al. 2004). The exploitation of marine mammals for oil, meat, and baleen in the Antarctic has been regarded as the biggest human-caused disturbance of the marine environment ever to occur

(Mori & Butterworth 2004). Blue whales were hunted to near extinction through direct human overexploitation, as their population size in 1905 at an estimated 239,000 whales was depleted to an estimate of 1,700 by 1996 (Branch et al. 2004; Thomas et al. 2015). Blue whales were hunted legally for 60 years before any legislation was put in place to protect the species (Mori & Butterworth 2004).

As their numbers diminished drastically, protection laws were enacted first by the International Whaling Commission (IWC) in 1964 (Branch et al. 2004). Whaling continued illegally as countries operating without regard to IWC regulation further depleted or at least stalled the recovery of some populations (Branch et al. 2007; Thomas et al. 2015). It was only when observers were employed on all whaling vessels in 1973 that illegal whaling was significantly deterred (Branch et al. 2004). Under U.S. laws such as the Endangered Species Conservation Act (ESCA) in 1969, the Marine Mammal Protection Act (MMPA) in 1972, and the Endangered Species Act (ESA) in 1973 the blue whale, along with seven other species of large whales were added to the List of Endangered and Threatened Wildlife (Perry et al. 1999).

Certain studies indicate that the number of Antarctic blue whales is increasing, however, abundance numbers indicate the blue whale population has still not recovered from this history of anthropogenic devastation. A population size estimate of the Antarctic blue whale was 2,280 (between 1,160 and 4,500) in 1998 (Branch et al. 2007). This estimate is still less than 1% of the pre-disturbance abundance (Thomas et al. 2015). Blue whales are currently considered endangered by the IUCN red list. As the species attempts to recover to a stable population abundance, it is important to be aware of the vulnerability of the blue whale and study the consequences of any interference in recovery in order to make predictions to prevent any further devastation for the population in the future.

Blue whales are essentially stenophagous, relying on euphausiids as their primary food source (Clapham et al. 1999). In the Antarctic, blue whales feed most prominently on one species of euphausiid, the Antarctic krill*, Euphausia superba* (Branch et al. 2007). The stability and recovery of many krill predators, including Blue whales, are contingent upon the biomass of krill present in the Southern Ocean (Wiedenmann 2010). This characteristic dependence on krill in the Antarctic can be illustrated by the population dynamics during the extensive whaling of the 20th century. Blue, fin and humpback whales are major krill predators (Kawamura 1980). Their abrupt removal from the food chain is hypothesized to have resulted in a surplus of krill (Laws 1977). This may have consequently stemmed a population proliferation in other krill predators (Laws 1977; Wiedenmann 2010).

Krill are essential to marine life in the Antarctic, and their survival is dependent on sea ice. Krill depend on algae that grow on the underside of sea ice for food (Wiedenmann 2010). Sea ice sustains both larval and juvenile krill by providing a substrate for algae to grow, and additionally sea ice serves as habitat for larvae to develop, and a shelter away from predation for young krill (Brierley & Thomas 2002; Siegel & Loeb 1995; Wiedenmann 2010). Therefore, a loss of sea ice, an effect of global climate change, would likely result in substantial reductions in krill abundance. There is significant regional and annual variation in the sea ice extent in the Antarctic (Wiedenmann 2010). In the Southern Ocean, the annual sea growth is from a minimum of 3.5 million km to a maximum of about 19 million km, based seasonally (Wiedenmann 2010). In recent years, fluctuations in climate, which can alter entire ecosystems (Dorschel et al. 2016), have emerged as a new threat to blue whale populations. As described in Wiedenmann (2010), warming of the Southern Ocean and subsequently a loss of sea ice extent would indicate drastic changes in the arrangement of the food chain. Because krill are a fundamental component to the diets of most apex predators in this region, monitoring their population and predicting potential responses to global warming is crucial for an entire ecosystem (Wiedenmann 2010). Bracegirdle et al. (2008) predicted a continued diminishing of sea ice off the Antarctic Peninsula, which would likely produce drastic fluctuations in this trophic intermingling most dependent upon krill (Wiedenmann 2010). Usually after ensuing years of reduced ice coverage, the krill population can become scarce in many areas, and as a result salps, *Salpa thompsoni,* a species zooplankton, replace the niches of krill (Loeb et al. 1997; Atkinson et al. 2004). However, these salps are not a primary dietary constituent for predators in the Southern Ocean. When there is an insufficient source of krill there is a lack of available and suitable prey and the population of krill predators is affected (Wiedenmann 2010; Loeb et al. 1997). For species like the blue whale, which rely on krill to sustain their population, the potential repercussions of diminishing sea ice are unknown. It can, however, be hypothesized that their population will be reduced or hindered. The retreat of the Antarctic ice shelf may pose potentially serious problems for blue whale populations by causing shifts in the abundance and distribution of sea ice and, hence, under-ice algae and Antarctic krill. The expansion and deterioration of the Antarctic ice sheet is one of the most significant and indicative physical mechanisms on Earth (Brierley & Thomas 2002). By recognizing the relation of the population density of blue whales and their primary prey of Antarctic krill, the effect of sea ice extent on the Blue whale can be modeled and a prediction can be made in order to put in place the proper procedure for protecting and conserving this charismatic species.

Climate change is an evident and looming concern for krill and in turn, blue whales. There is a shattering irony in the possibility of another devastation for blue whales as a result of anthropogenic disturbance. It is particularly important to research population dynamics in relation to anthropogenic events to make known the unintended consequences of human activity and the role it plays in climate change. The reason it is important to study each vehicle of a mechanism is to become aware of both direct and indirect relationships of magnitude. Environmental conditions in the biosphere are the foundation of biological processes, impacting the food web from primary producers to apex predators, and therefore fluctuations in climate often alter entire ecosystems and their biodiversity (Dorschel et.al 2016). Studying the interdependence of trophic levels helps to recognize all the components of a system and how each component is of substantial importance to the entire system. The relationships and interdependence of this ecological system in the Antarctic are important indications of the fragile balance of nature. Antarctic krill can act as an indicator of climate change, as a diminutive component of a system can lead to predictions of a fluctuating environment on a global scale. With specific modeling as a predictive tool, the effects of sea ice variation on the population dynamics of the blue whale can indicate potential anthropogenic consequences on ecological systems.

CHAPTER II

METHODS

The basic framework of interrelated population dynamics of keystone species in the Antarctic is conceptualized in two models created based on blue whale mortality and krill biomass in relation to sea ice effect. The specific relationships represented are between the Antarctic krill and Antarctic blue whale populations in the Southern Ocean and takes into account the effect of sea ice on krill. Antarctic krill are dominant in this marine ecosystem as they depend upon sea ice for specialized feeding and reproductive mechanisms. This keystone species is therefore subject to biomass fluctuation based on variation in sea ice extent. The diet of the Antarctic blue whale population consists primarily of this species of krill and so a significant decrease in krill biomass can be correlated with an increase in blue whale mortality. Antarctic krill are subject to both natural mortality and predation mortality. Mortality rates are influenced by environmental factors, this includes predator population dynamics and sea ice conditions. Blue whales are subject to natural mortality that can be affected by prey biomass and availability. This concept of interrelatedness has been used to construct three stochastic simulation models, (1) mortality of blue whales in the Antarctic, (2) mortality of Antarctic krill in relation to sea ice, and (3) a combination model that correlates krill biomass with blue whale mortality. These models were created using STELLA®7.0.1. Input data required by each model is shown in Tables 1, 2, and 3. The blue whale mortality model is stage structured, separating calves (<1year), adults (1-5 years), sexually reproductive adults (5-10 years), and non-reproductive adults (>10 years). Total number of calves (Calf (t)) was determined by the formula Calf(t) = Calf(t-dt) + (Recruitment - S1 - M1) * dt. Recruitment is equal to the number of sexually mature adults multiplied by a recruitment rate of .40 (determined by a study suggesting an annual pregnancy rate of .40) divided by 2 (Branch et al. 2004). Surviving number of calves (S1) was determined by multiplying the total number of calves and a calf survival rate of .819 (Taylor et al. 2007). Mortality (M1) is found by subtracting S1 from total number of calves. The total number of adults (Adult(t)) was determined by the formula Adult(t) = Adult(t-dt) + (S1 - S2 - M2) * dt. The number of surviving adults (S2) was calculated using the inflow from surviving calves multiplied by the adult survival rate of .975 (Ramp et al. 2006). The mortality of adults (M2) was found by subtracting the adult survival rate from 1. The adult survival rate from Ramp et al. (2006) was also used to determine the mortality and survival of sexually mature adults (M3, S3) and mortality of non-reproductive adults (M4). The total population of blue whales is determined by adding the total number of calves, adults, sexually mature adults, and non-reproductive adults. The model relating Antarctic krill population dynamics to sea ice variation was adapted from a figure from Atkinson et al. (2004), exhibiting the krill/ice relationship in the Southern Ocean. Ice effect refers to the negative exponential impact on krill biomass. For the first year (1976) trended by Atkinson et al. (2004), the effect recruitment is 1, indicating no effect on krill biomass. As years pass, the effect recruitment becomes smaller and krill recruitment values and biomass values decrease. The final model combines the two previous models to conceptualize a relationship between sea ice and blue whale population dynamics based on the effect of sea ice on Antarctic krill biomass. The input values remain constant from the basis models (1) and (2) and the krill biomass is incorporated to affect whale mortality.

Table 1. Input values for simulation of mortality of blue whales in the Antarctic.
1. Recruitment rate.
2. Recruitment of blue whales.
3. Number of calves.
4. Mortality of calves (M1).
5. Survival of calves (S1).
6. Number of adults.
7. Mortality of adults (M2).
8. Survival of adults (S2).
9. Number of sexually mature adults.
10. Mortality of sexually mature adults (M3).
11. Survival of sexually mature adults (S3).
12. Number of non-reproductive adults.
13. Mortality of non-reproductive adults (M4).
14. Total population of blue whales.

Table 2. Input values for simulation of mortality of Antarctic krill in relation to sea ice.
1. Ice effect.
2. Recruitment of krill.
3. Krill biomass.
4. Krill loss.

Table 3. Input values for simulation of krill biomass and blue whale mortality correlation.
1. Recruitment rate.
2. Recruitment of blue whales.
3. Number of calves.
4. Mortality of calves (M1).
5. Survival of calves (S1).
6. Number of adults.
7. Mortality of adults (M2).
8. Survival of adults (S2).
9. Number of sexually mature adults.
10. Mortality of sexually mature adults (M3).
11. Survival of sexually mature adults (S3).
12. Number of non-reproductive adults.
13. Mortality of non-reproductive adults (M4).
14. Total population of blue whales.
15. Ice effect on krill.
16. Recruitment of krill.
17. Krill biomass.
18. Krill loss.

CHAPTER III

RESULTS

Exponential Ice Shrinkage Model

Results of a simulation demonstrating the relationship between ice shrinking exponentially and krill biomass are shown in Figure 1. The model indicates that when sea ice decreases exponentially krill recruitment would be equal to $1.19 \times \exp(-0.204 \times T)$. With krill population biomass set at 500 to begin at year 1, biomass peaks between the 3^{rd} and 4^{th} year and decreases until the simulation ends after 24 years with a krill population biomass of 1.05. The results of a simulation showing the association between ice shrinking exponentially and whale population size are displayed in Figure 2. Because of the krill recruitment equation derived from Figure 1, the whale population decreases accordingly. The starting whale population size at year 1 was set at 2,000, instantly reduced to 1,484.50 by year 2, then increased and peaked at about the 7^{th} year. From year 7 on it decreased until the population size reached 0 individuals in the 19^{th} year. The model predicts a decrease in krill recruitment based on exponential ice shrinkage by the equation 1.19xexp(-.0204xT), and consequently a decrease in the whale population to extinction.

Figure 1.- Simulated effects on krill biomass based on an exponential ice shrinkage.

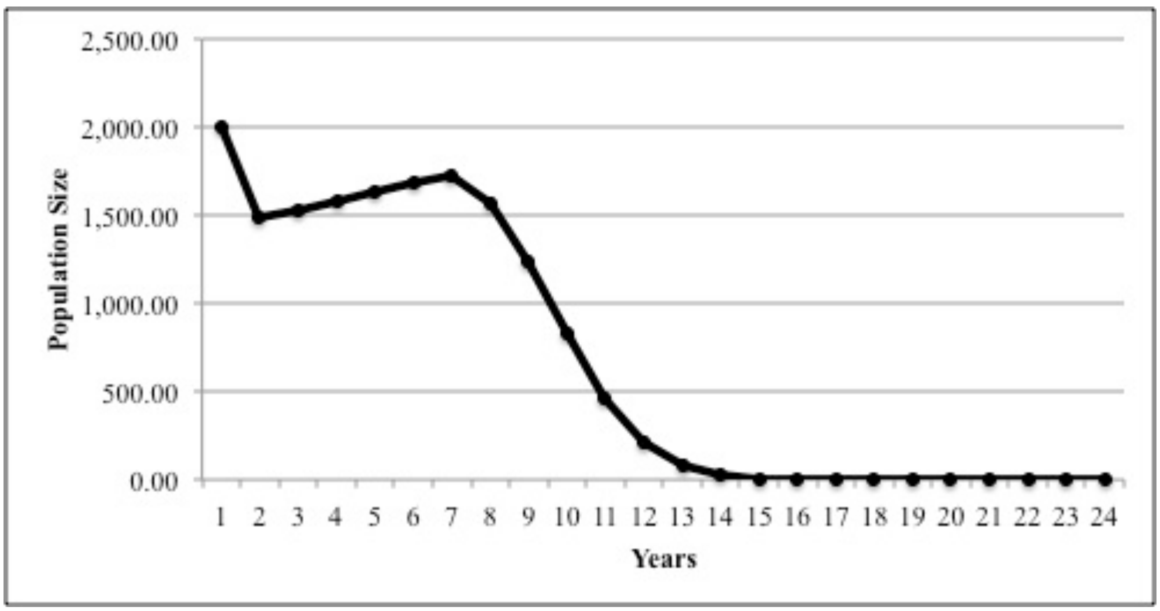

Figure 2.- Simulated effects on blue whale population size based on an exponential ice shrinkage.

Linear Ice Shrinkage Model

Figure 3 shows the simulation of linear ice shrinkage and effects on krill biomass. When ice shrinks linearly, the model predicts krill recruitment to be -0.0391xT+1.0391. With a starting population biomass of krill at 500 once again, the biomass numbers increase until between year 6 and 7, where the biomass peaks, and then decreases steadily until the 24th year where the biomass is predicted to be at 7.85. Results of the model displaying the relationship of linear ice shrinkage with blue whale population size are shown in Figure 4. We begin the population size set at 2,000 at year 1, and the population decreases quickly to 1,484 individuals at year 2. From year 2 to year 11 the population size increases. The peak at year 11 is 1,976.08 individuals, and from year 11 the population decreases until it reaches 0 individuals in the 24th year. The simulation predicts a decrease in whale population size based on a decrease in krill recruitment to -0.0391xT+1.0391 from the linear decline in ice.

Figure 3.- Simulated effects on krill biomass based on an linear ice shrinkage.

Figure 3.- Simulated effects on blue whale population size based on an linear ice shrinkage.

Without Ice Shrinkage Model

The final simulation shows the population effects if there was no decrease in ice. Figure 5 shows the krill population biomass in response to stable ice conditions. We, once again, begin with 500 krill population biomass, and there is a steady increase through to the 24th year, where model predicts the biomass would be 5,180.42. The blue whale response to steady ice conditions is shown in Figure 6. Starting at 2,000 individuals, the population size sharply declines at year 2, but increases relatively steadily through with a population of 3,637.76 at the 24th year.

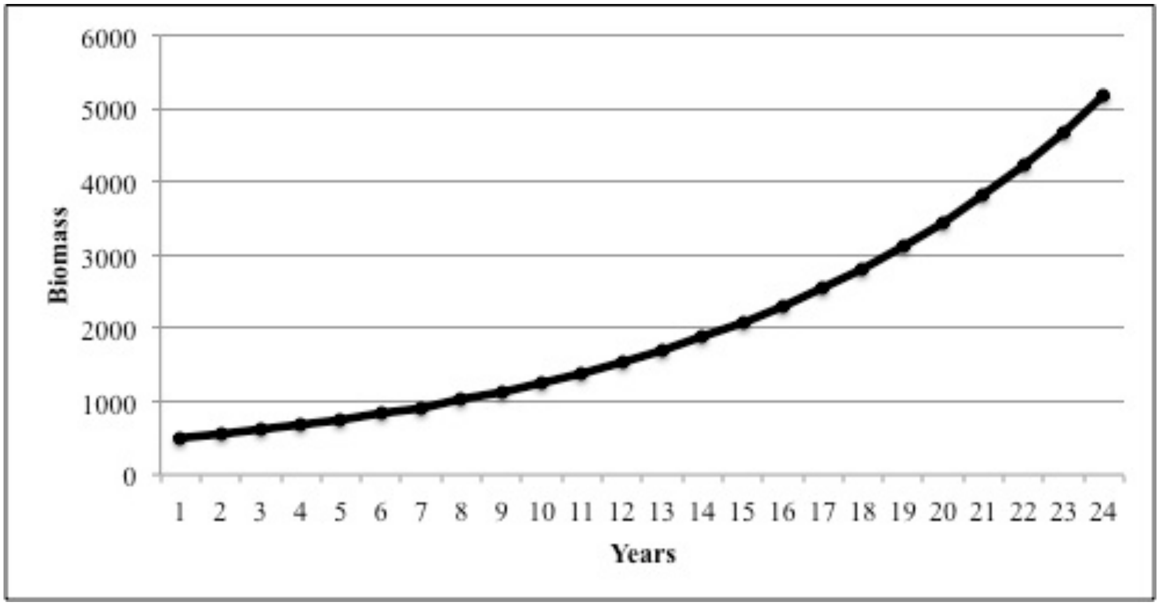

Figure 5.- Simulated effects on krill biomass based on stable ice conditions.

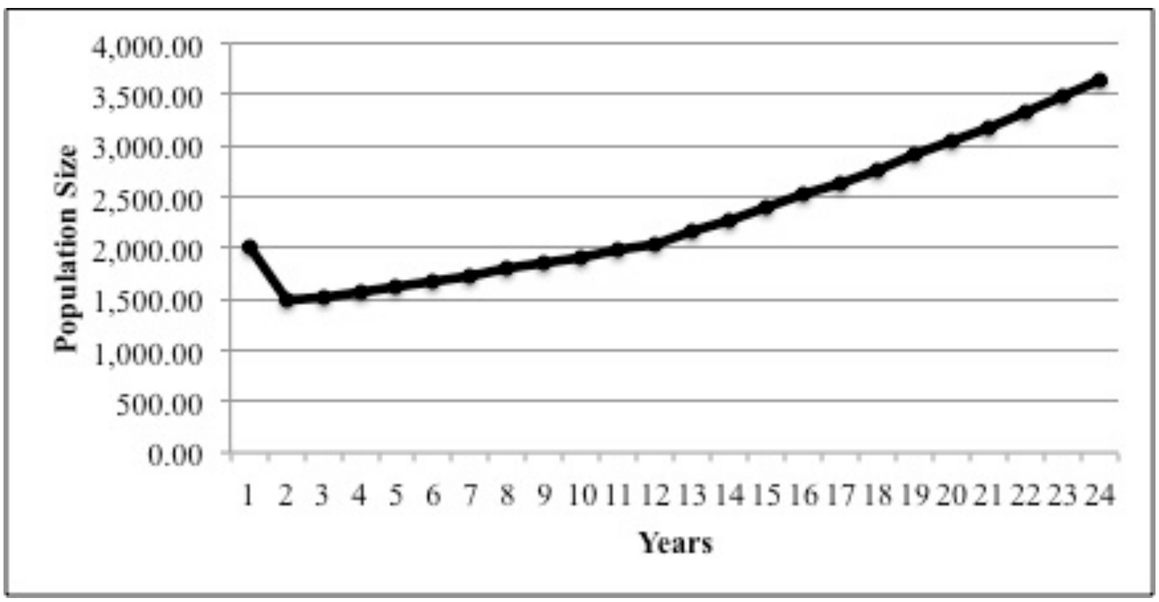

Figure 6.- Simulated effects on blue whale population size based on stable ice conditions.

CHAPTER IV

DISCUSSION

The main objective in developing this model was to create a predictive tool to evaluate the impact of sea ice expansion variation on endangered blue whales. Connecting blue whale population dynamics to those of their primary prey, the Antarctic krill, reveals an indirect relationship of sea ice effects on blue whales. The simulation models predict a loss in krill biomass and consequently, blue whale population size, with both linear and exponential depletion of sea ice. With no sea ice decline, blue whale population size could almost double in 24 years. It is important to note that this simulation has been run based on speculative representations of the sea ice/krill biomass relationship. Therefore, this model can be altered to include simulations of different ice variation schemes as more exact data on the relationship between ice extent and krill biomass becomes available. It is also important to note that because the Antarctic ecosystem is highly variable, the input values within this deterministic model can be altered to evaluate the changes within the mechanism represented. Lastly, to address the currents trends of sea ice extent in the Antarctic, research from the past couple of decades has shown an increase in Antarctic sea ice extent in contrast to a decline in Artic sea ice extent, but this notion is based on circumpolar averages. Antarctic sea ice is not increasing in all areas, and there are even regions that show similar trends to the observed Arctic sea ice rates of change (Stammerjohn & Maksym 2017).

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