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THE POTENTIAL IMPACT OF CLIMATE CHANGE ON BLUE WHALE MIGRATION IN THE EASTERN PACIFIC

by

Amanda Shuman

A Thesis Submitted in Partial Fulfillment
of the Requirements for a Degree with Honors
(Marine Science)

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Abstract

Climate change is one of the most pressing problems the world is facing today. Due to human emissions, the amount of greenhouse gasses in the atmosphere is escalating at a concerning rate. This increase is causing ocean temperatures to rise, pH levels to lower, and altering the habitats of countless species. *Balaenoptera musculus*, or the blue whale, is a highly migratory species that relies on the stability of its' habitats for foraging and calving grounds. They rely on the upwelling of nutrients and consistent conditions that allow for substantial prey populations to accumulate. With the effects of climate change altering the temperature and pH of these areas, prey populations may shift their distribution, thus altering the blue whales migration patterns. I reviewed numerous papers with a focus on three main topics: current blue whale migration pattern, current conditions for their calving and foraging grounds, and the climate change projections for those key areas. The response to climate change of the blue whales main food source, krill, was additionally looked at. The cold, nutrient rich water of the Northeast Pacific provides a viable habitat for euphausiid crustaceans, such as krill, to flourish in numbers. The blue whales use these feeding grounds in the summer months, and winter in tropical waters. The Costa Rican Dome is an area of significant upwelling and warm waters, which provide suitable waters for birthing their calves. The unprecedented changes to these areas could significantly impact blue whale abundance and distribution.

Acknowledgements

First and foremost, I would like to thank my advisors and committee members for their patience while guiding me through this process. In addition, to all of my professors over the past three years that have provided me with the inspiration and knowledge needed to complete this work. Finally, a huge thank you for my family for their endless love and support.

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1. Background

Climate change, one of the biggest problems our world is facing today, is having countless impacts on habitats, ecosystems, and organisms. The increase of anthropogenic CO_2 emissions is causing irreversible damage to ecosystems around the globe. Impacts resulting from climate change include an increase in ocean surface temperatures, decrease in the pH (ocean acidification), and shifts in species distribution and abundance (IPCC, 2014). While politicians and world leaders discuss possible preventions and mitigation, the other species on Earth are feeling the immediate results.

To analyze the possible impacts of climate change on *Balaenoptera musculus*, or the blue whale, and their major migration in the Northeast Pacific, three main topics were researched: the blue whale migration pattern, current conditions of their calving and foraging grounds, and the projected impacts of climate change in those key areas of feeding and birthing. This review investigates the likely effects of increasing temperature and declining pH on blue whale distribution, as well as the current abundance and response to climate change of the primary prey species *Euphausia pacifica,* North Pacific krill. Krill have a chitinous exoskeleton and intricate compound eyes that allow them adapt to the different light levels of the daily vertical migration (Everson, 2001). They encounter a range of pH levels and temperatures throughout the water column, migrating from maximum depths of 200m to the surface waters to feed. Therefore, it is necessary to define the exact range that krill can withstand in order to understand how climate change projections will impact their abundance.

The blue whale is the largest animal on Earth, weighing an average of 300,000lbs and has one of the longest annual migrations, approximately 2,000 km. This species of whale is found in every ocean except the Arctic and remain on the Endangered species list. The blue whale, along with other species of whale, had their population seriously depleted due to whaling. People have been whaling for thousands of years and increased in popularity during the Middle Ages, or during the fifth to fifteenth century. By the 1700s, it had become increasingly to find whales within most oceans. After such depletion, scientists and policymakers worked to enforce regulations that protect populations of whale, with the intention to increase their numbers. The blue whale species is generally showing an upward trend, however it is very slight and gradual. The population in the Northeast Pacific, focused on in this paper, is seemingly the only population truly recovering in numbers.

1.1 Current Migration Pattern

Migration is broadly defined as directional movement to take advantage of spatially distributed resources. It is a dramatic behavior and is instrumental to life histories and the transfer of nutrients in varying ecosystems (Dingle, 2014). The blue whale is a highly migratory species and relies on the habitat and nutrient stability of its destinations, both at the foraging grounds and the calving grounds. This species has the longest migrations of all organisms, which is supported by their large body size (Stone et al. 1990). Such a body size allow for blue whales to travel great distances with little food, by utilizing their fat stores.

Overall, blue whales prefer open-ocean rather than coastal waters. This preference however, limits the areas where they can adequately find nutrients and prey. Coastal waters provide more biodiversity, run off nutrients, and blooms, while in the open-ocean, there are less overall nutrients and prey organisms. This is especially true for tropical waters. However, the open ocean provides the space and depth for the blue whales to successfully navigate and dive. As a result, blue whale populations around the world have developed consistent and established migration patterns from cold nutrient-rich foraging grounds to tropical calving grounds.

One populations of blue whale in the Pacific Ocean migrates from just north of the equatorial region, to the waters off the coast of northern California and Oregon (Figure 1; Bailey, 2009). Their feeding grounds correspond with a major upwelling zone in the Northeast Pacific, which provides a sufficient habitat for their main prey (Munger, 2009). Zooplanktons, such as krill, create a giant link in the global food chain by being the main source of food for some of the Earth's largest creatures (Yoon, 2000). The North Pacific water, off the coast of northern California provides ample nutrients for phytoplankton growth and, as a result, large plankton and euphausiid abundance.

The blue whales large body size and high metabolic rate result in having the highest average daily total energy requirements of all species (Croll, 2005). Therefore, unlike other baleen whales that fast during winter months, blue whales continue to feed in their calving grounds, making it essential to find a nutrient-rich tropical area. This population of blue whale in the Northeast Pacific utilizes the Costa Rican Dome as their calving and breeding grounds. The Costa Rican Dome is an area of significant upwelling off the west coast of Costa Rica and Nicaragua and provides a habitat with warm waters and substantial prey populations (Fiedler, 2002). The availability of prey is what attracts and allows the blue whale population feed in their calving grounds. In addition, the tropical waters allow the blue whales to maintain internal heat balance with a lower energy cost than in colder waters. The thermal environment provides a suitable place for blue whale calving, because the cetacean newborns have thin blubber layers, providing little insulation. The favorable conditions for energy conservation are also beneficial to nursing mothers, who use much of their energy in lactation (Dingle, 2014).

In order to track the blue whale migration, studies such as Bailey et al. (2009) use satellite tags. For that particular study, 92 satellite tags were deployed and used to track the individual whale movements (Figure 1). The variability throughout the migration pattern is thought to be from area-restricted movements of the blue whale. When a predator locates a prey patch, in this case of krill, it is expected that they would decrease their speed and increase their turning angle (Bailey, 2009). After feeding, the blue whales would return to a relatively straight movement to the next prey patch (Zollner & Lima, 1999). Irvine et al. (2014), also analyzed satellite tag data to confirm that blue whales congregate at the major upwelling zones (Figure 2).

Though the overall migrations of the blue whale are relatively constant, they do vary slightly with gender and season. For example, pregnant females will spend the longest time in the northern feeding grounds, in order to store enough energy for her and her upcoming nursing newborn (Dingle, 2014). In contrast, suckling females and their calves are the last to leave the warm waters. Also, while the majority of the whales will stay off the coast of northern California, some individuals will migrate up to the Gulf of Alaska.

1.2 Current Conditions

There is strong upwelling in the North Pacific of old nutrient rich water that has travelled from the North Atlantic, where the largest amount of down welling of surface water occurs, down to the Southern Ocean, where the densest water is added to the deep-water circulation. Some of this deep water enters the Indian Ocean and upwells, while most moves into the Pacific and travels north, before upwelling in the North Pacific (Gordon, 2001). This high nutrient cold water then travels along the west coast of North America. The high nutrient levels of the area result in a dominance of larger phytoplankton, such as diatoms, as opposed to the smaller phytoplankton usually found in the open ocean. Phytoplankton populations form the base of the food web of the North Pacific, feeding the zooplankton and krill populations, and attracting the population of blue whales.

The Costa Rican Dome is located on about 2,000km from the blue whales foraging grounds and provides the essential calving habitat. Due to the strong Northeast Trade Winds blowing off of Central America, the water off the west coast will have a lower surface height than surrounding waters and experience significant upwelling of the nutrient rich deep water (Fiedler, 2001). This upwelling will cause the thermocline, or temperature gradient of the water column, of this area to be steeper than the average water column of the open-ocean (Figure 3, 4). The pycnocline, or area of greatest density gradient, would also be in shallower depths than the average open water system (Fiedler, 2001). A steeper thermocline and pycnocline allows for more mixing of the surface and deep waters, providing more nutrients for surface water organisms (Chang, 2012). The area is dominated by picophytoplankton, which support a substantial zooplankton and krill population as well (Landry, 2016). From the results of research done on the biological pump of the Costa Rican Dome, the system seems to rely on mesozooplankton, such as krill, for major energy transferring to higher trophic levels (Landry, 2016). This refers to predator-prey relationships such as krill and blue whales. The Costa Rican Dome provides wintering habitat for numerous migrating species. Researchers have found a large overlap at the Dome of cetaceans migrating from the Southern Hemisphere and cetaceans migrating in the Northern Hemisphere (Reilly and Thayer, 1990).

2. Projected Changes

The increased volumes of CO_2 and other greenhouse gases released by the burning of fossil fuels, land clearing, agriculture, and other anthropogenic activities, are believed to be the primary sources of the global warming that has been changing over the past 50 years. The greenhouse effect is the term used to describe the trapping of infrared radiation from the Sun, by the gases making up the Earth's atmosphere, in order to warm the surface of the Earth. The main gases include, water vapor, carbon dioxide (CO_2), methane, and ozone (O_3). The increase of these gases released from the use of fossil fuels, causes more solar radiation to be kept closer to the Earth's surface and continues to heat it up. The majority of scientists around the world agree that global temperatures will continue to rise and ocean pH will decrease.

2.1 Increased Temperatures

One of the most prevalent consequences of increased fossil fuel emissions is the increase in global temperatures. The Intergovernmental Panel on Climate Change (2014) estimated that the average temperature of the Earth has risen between 0.4 and 0.8 °C over the past 100 years and continues to rise at an alarming rate. Projection models of global warming have recently predicted that average global temperatures could increase between 1.4 and 5.8 °C by the year 2100 (IPCC, 2014).

The areas that will feel the initial impacts of the excess CO_2 are cold nutrient rich waters. Areas of great biodiversity near the tropics are important to study, but those habitats will have a delayed reaction relative to the colder waters. Human caused global warming is negatively effecting both of these marine environments. Models based on current climate change scenarios from IPCC reports (Hazen et al., 2012), show the projected temperature and chlorophyll level changes by the 2100 (Figure 6). The projections indicate a significant rise in temperature for the Pacific waters along the west coast of North America (a&b), in addition to lowered chlorophyll levels (c&d). The increase of surface temperatures range from 1-6°C and the chlorophyll decline is up to 0.2mg/L. While these do not sound like significant numbers, a fraction of that change could seriously damage the ecosystem dynamics of the area (Hazen, 2012). This includes the distribution and abundance of keystone species, or ecosystem engineers. The increase in temperature causes a more stratified water column, which decreases the nutrient upwelling of the area. The decrease in upwelling would limit phytoplankton populations and cascade through the trophic levels to impact krill and blue whale abundance.

2.2 Ocean Acidification

From the 18th century and the start of the Industrial Revolution, the world's oceans have absorbed about 28%, or 550 billion tons of the total anthropogenic CO_2 emissions (Canadell et al. 2007). This increase in CO_2 levels disrupts the oceans' chemical ratios and increases the overall acidity. Ocean acidification due to anthropogenic emissions has caused the open water surface pH to decrease approximately 0.11 units (Feely, 2016). A change of one pH unit changes the hydrogen ion concentrations by a factor of ten. Therefore, this increase in hydrogen ion concentration over the past 250 years is significant, especially for the organisms living in the altering habitat (Feely, 2016). The addition of CO_2 to what is already naturally in the system are continuously increasing and changing the environment of marine organisms. Feely et al. (2016) highlights this increase of the dissolution of CO_2 along the coast of California in 2013 (Figure 5).

When atmospheric CO_2 molecules react with surface water molecules, they form carbonic acid. Shown below are the basic formulas for the formation of carbonic acid and the resulting reactions that lower the pH of the water.

$H_2O\ (aq) + CO_2\ (aq) \leftarrow\rightarrow H_2CO_3\ (aq)$

$H_2CO_3(aq) \leftarrow\rightarrow H^+ + HCO_3$

$HCO_3 \leftarrow\rightarrow H^+ + CO_3$

The formation of excess carbonic acid directly leads to with the dissolution of calcium carbonate shells of phytoplankton. As a result, carbonate concentrations of the ocean have declined about 16% since preindustrial values. Based off of IPCC (2013) projections, even if CO_2 emissions held constant, instead of continuously increasing, the ocean's surface pH is expected to decline another 0.3-0.4 units by 2100. In addition, the carbonate concentration is expected to drop by 50% in the same time period (IPCC, 2013).

The average pH levels in the waters off the coast of California have already dropped to values that were not projected to be reached for several decades (Hauri, 2009). While this decline is concerning, there is still considerable spatial and temporal variability. This variation allows organisms to have a certain range of habitability in the area. However, if the current upturned trend of CO_2 emissions continues, the pH levels will reach constant lows that organisms have not encountered and will not be adapted to survive in (Hauri, 2009).

3. Impacts

The current migrations of the blue whales in the Northeast Pacific are subject to change with the continuous impacts of climate change. As described above, their foraging and calving grounds are unique areas of upwelling and plankton abundance. If climatic changes to those key areas cause changes to their prey in abundance or distribution, the blue whale population will be directly affected.

3.1 Prey Response

Phytoplankton and zooplankton are able to bloom in open-ocean areas because of the upwelling of the nutrient rich waters. North Pacific krill mainly feed on phytoplankton and algae that drifts near the ocean's surface. The krill found in the North Pacific usually have increased population numbers in the summer when more light is available for phytoplankton growth (Yoon, 2000). Accordingly, the blue whales in the Northeast Pacific spend summer months off the coast of Oregon and Washington, where there are substantial populations of krill.

The high solubility of CO_2 in the cold water sustains the productivity of the phytoplankton. The increased CO_2 dissolving from the atmosphere will allow for more primary production up to the population's carrying capacity. However, there will be excess that will not be used and either it will sink to enter the deep ocean, or enter the California current and impact coastal ecosystems. The increased levels of CO_2 in the ocean have already impacted the pH levels and will continue to lower them as the CO_2 continues to react with the water molecules. The impact of this in CO_2 is an area of ongoing study. Krill vertically migrate daily through the water column and, therefore, are exposed to a range of temperature and pH. However, this exposure to varying levels is only for short periods of times and there has been little research on the long-term effects of high CO_2 exposure on krill.

Cooper et al. (2016), for example, researched the effect of increased CO_2 levels on krill metabolism (Figure 7). They sought to observe the effect of prolonged exposure to higher levels of CO_2 that would correspond with levels projected for the year 2100. The results of the experiment (Figure 7) showed a 31% decline in oxygen consumption in the first 24 hours when krill were exposed to the high levels of CO_2. The consumption remained low the entire length of the experiment (21 days). In addition, the ingestion and ammonium excretion rates were both significantly lower in the high exposure, meaning the krill had a hard time feeding and digesting prey. Overall the krill had lower metabolic rates in the projected levels of CO_2. In addition, McLaskey et al. (2016), researched the response of krill at different critical life stages to high levels of CO_2 and reduced pH (Figure 8). The results of the exposure revealed that the larvae can hatch at a variety of pH levels, but development and survival was limited to the pH levels naturally found in the krill's habitat. The results of both experiments are concerning with the decline in pH throughout the ocean, which may impact the abundance of krill populations.

The rise in water temperatures is also likely to have a negative impact on the populations of North Pacific krill, which prefer water temperatures to be below 10°C (Yoon, 2000). If climatologist predictions are accurate, the Northeast Pacific waters are projected to increase 4°C from current temperatures in the coming decades. This would likely cause krill to shift their distribution further to the poles for the cooler waters and result in moving out of the upwelling zone. Overall, with the increasing temperature and acidity levels resulting from climate change, phytoplankton and krill distribution is subject to change in the coming years, in order to compensate for their changing habitat. The baleen whales that migrate to the populations of krill would then have to alter their course and risk more energy loss for extra swimming.

3.2 Migration Changes

Due to recent advances in tagging and tracking of large marine mammals, researchers are able to analyze satellite data of the blue whale movements to observe their key areas of migration. Key areas for blue whales include North Pacific waters, where they forage and build up their fat stores in the summer, and the Costa Rican Dome, where the breed and calve in the winter. Concerning changes to these habitats brought on by anthropogenic pollution include changes in pH, temperature, and nutrient levels.

The North Pacific is an area of large amounts of dissolved gases, because of upwelling of cold, nutrient rich waters, and would be greatly impacted by the increased levels of CO_2. The effects would cascade to impact the plankton, krill and blue whale populations. If the upwelling area is altered from increased temperatures to the point that phytoplankton can no longer thrive, krill numbers will drop, forcing blue whales to find other sustainable and reliable feeding ground. The increased CO_2 concentrations are likely to further the alteration of the foraging grounds by increasing the acidity, which directly leads to breaking down plankton exoskeletons. Krill populations are likely to shift northward to the waters off the coast of Alaska and sub-polar regions in order to remain in their preferred pH and temperatures. Hazen et al. (2012) projected habitat response to current climate change models and estimated that by the year 2100 current blue whale foraging habitats will decrease by 17% (Figure 9).

The Costa Rican Dome is also subjected to change with the increasing temperatures and decreasing pH levels. This area is recurrently impacted by global events, such as El Nino, but it always returns to its’ natural state afterwards. With climate change, however, impacts could permanently alter the divergent zone. The temperature increase would negatively affect the abundance of nutrients for plankton to use and cause stressed populations on all trophic levels. Although, when compared to the foraging grounds of the blue whale, the Costa Rican Dome would not be subject to as dramatic of changes. This means that when the foraging grounds shift further north to the sub-polar waters, the breeding and calving grounds would not shift as much. This would result in longer migrations for the blue whales, causing them to become more stressed and their fat stores to be depleted to an unprecedented amount.

The Gulf of Alaska would provide a similar habitat to the current coast of California in the coming decades and would likely be an area that blue whales shift to for feeding grounds (Figure 6). The species of krill in Alaska would remain the *Euphausia pacifica,* meaning that the metabolic requirements would be met and the prey population found there would attract the blue whales. With little shift in the calving grounds and the possible shift to the Gulf of Alaska or sub polar regions, the blue whales are facing a significant increase in migration distance (Figure 11).

4. Conclusion

From my research, I project that the blue whale will become more stressed in the coming years due to the likely change in abundance of their prey species. Krill have shown to have negative response to lowered pH levels (Cooper, 2016: McLaskey 2016).

With the increasing levels of CO_2, the ocean's surface waters are becoming more acidic, which would stress the krill populations. The blue whale's calving grounds are not subject to as significant changes in temperature and pH in the coming years and would therefore not alter as much as the foraging grounds. The foraging grounds in the north Pacific will see a noticeable change in pH and temperature, likely causing phytoplankton and zooplankton to shift northwards, where the conditions of their current habitats will have shifted. As a result, the blue whales of the Northeast Pacific will have a longer migration between their calving and foraging grounds. The overall loss of habitats for mammals in the North Pacific is projected to be about 7% (Hazen et al., 2012; Figure 10).

It is important to understand how blue whale migrations are going to change in the coming years, because they are essential for open ocean ecosystems. There are also important policy implications for understanding their movements. For example, Irvine et al. (2014) looked at the current shipping lanes in regards to the calving grounds of the blue whale, in order to argue for better policy to avoid ship strikes. However, if the congregating areas of the blue whales shift, the shipping lanes will have to be reestablished accordingly. In order to fully understand how blue whale migrations will likely change, more research needs to be done on the metabolic response blue whales have to the change in temperature and continued research on the changing conditions of the ocean. Further research is also needed to fully understand the impact of ocean acidification on keystone species, such as krill, as well as where other possible foraging grounds could be to sustain blue whale populations. Overall, blue whale distribution and abundance is subject to change in the coming decades with the continued impacts of climate change.

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Figure 1. Shows the overall migration pattern of blue whales in the northeast Pacific. Yellow circle highlights the summer foraging grounds, while the red circle highlights the summer calving grounds. (Bailey, 2009)

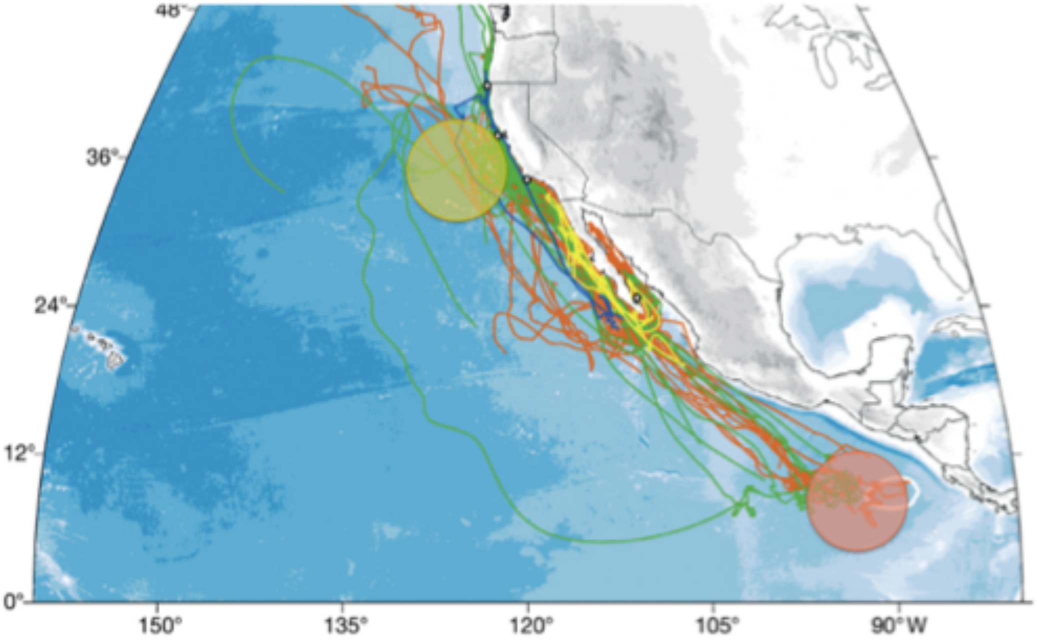

Figure 2. Shows the latitudinal distribution of blue whales over the months of the year. (Irvine et al., 2014)

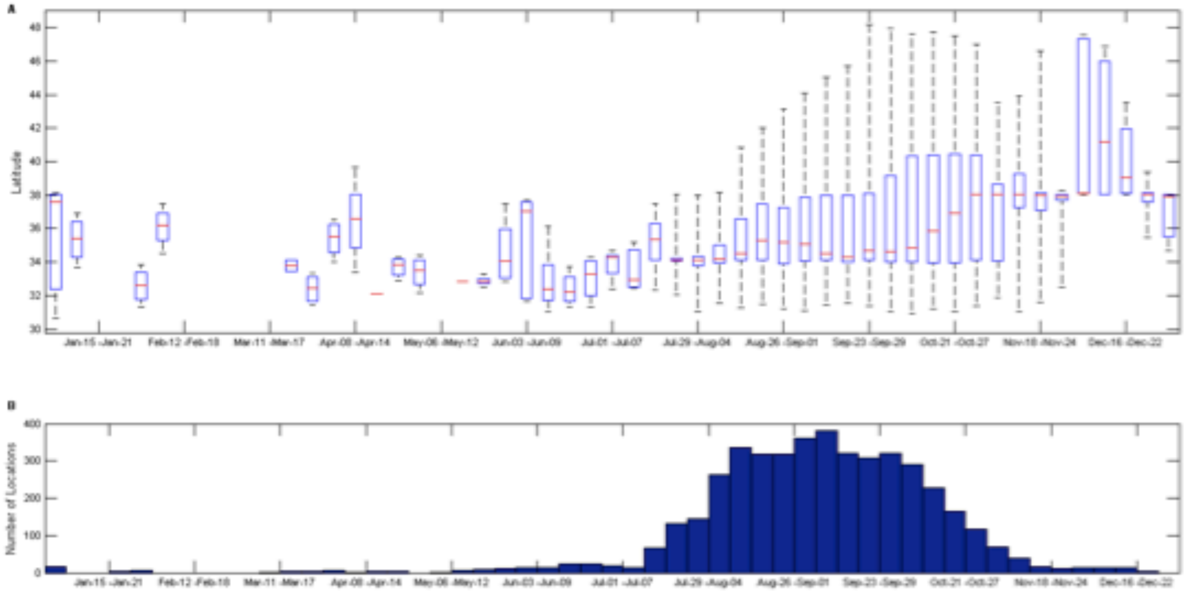

Figure 3. Magnifies the Costa Rican Dome and shows the change in thermocline depth. (Fiedler, 2001)

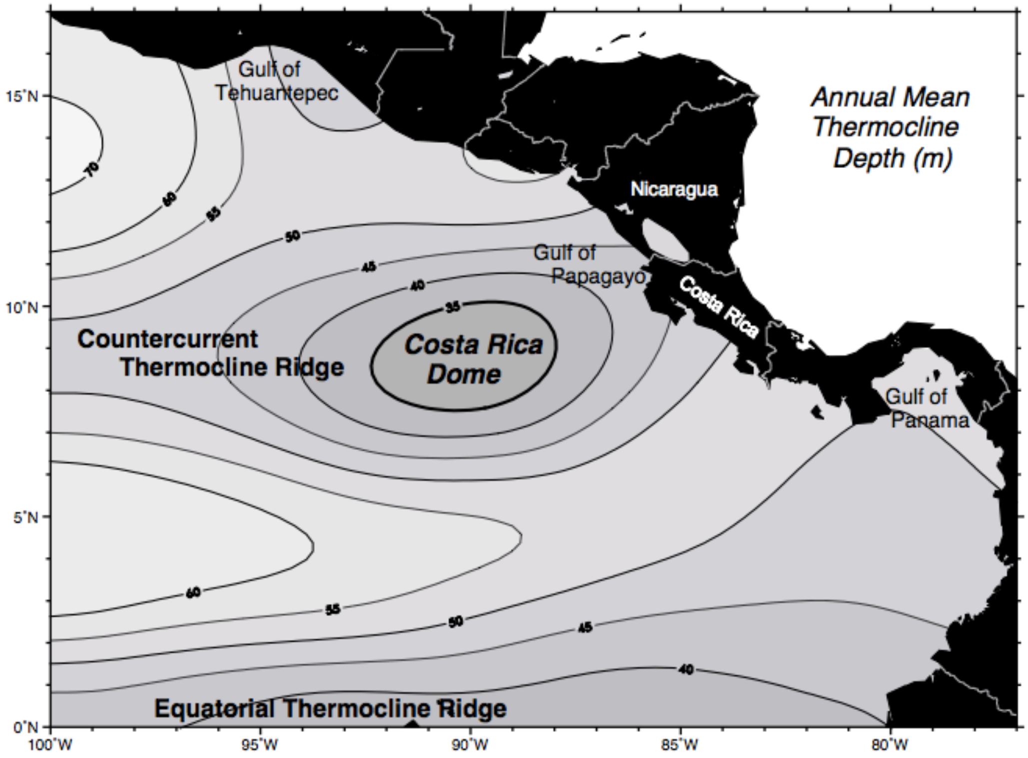

Figure 4. Another view of the shallower thermocline at the Costa Rican Dome. (Fiedler, 2001)

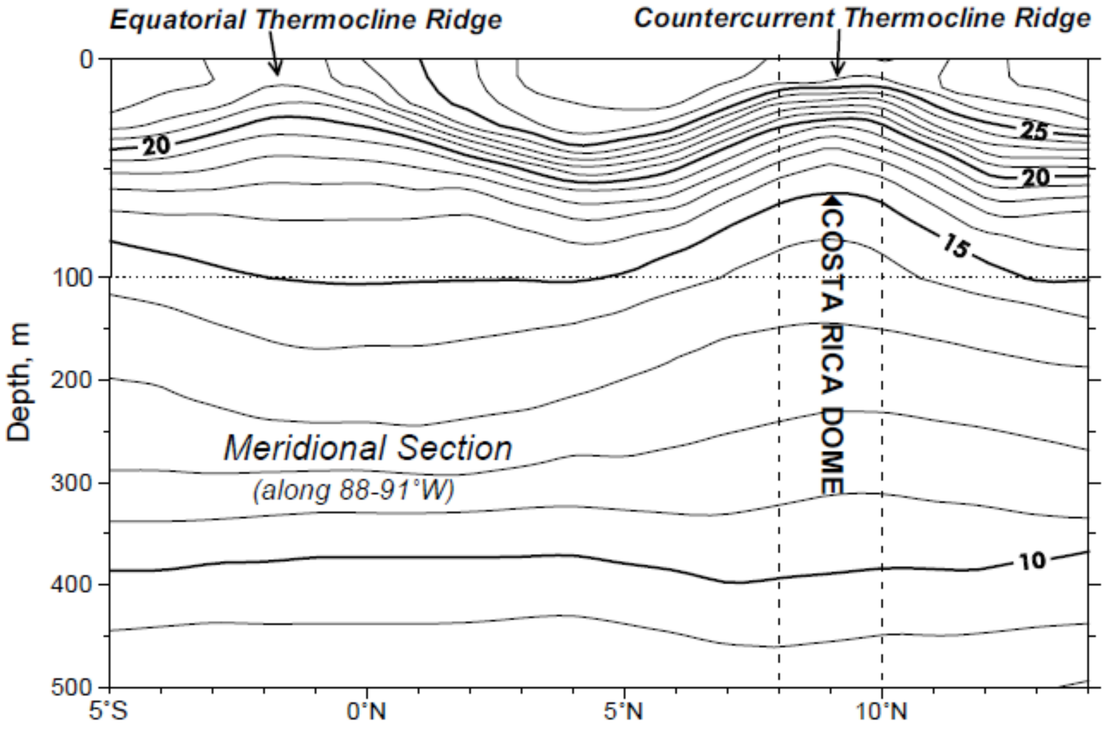

Figure 5. Shows the amount of anthropogenic dissolved CO_2 in the California Current System at various depths in 2013. (Hazen et al., 2012).

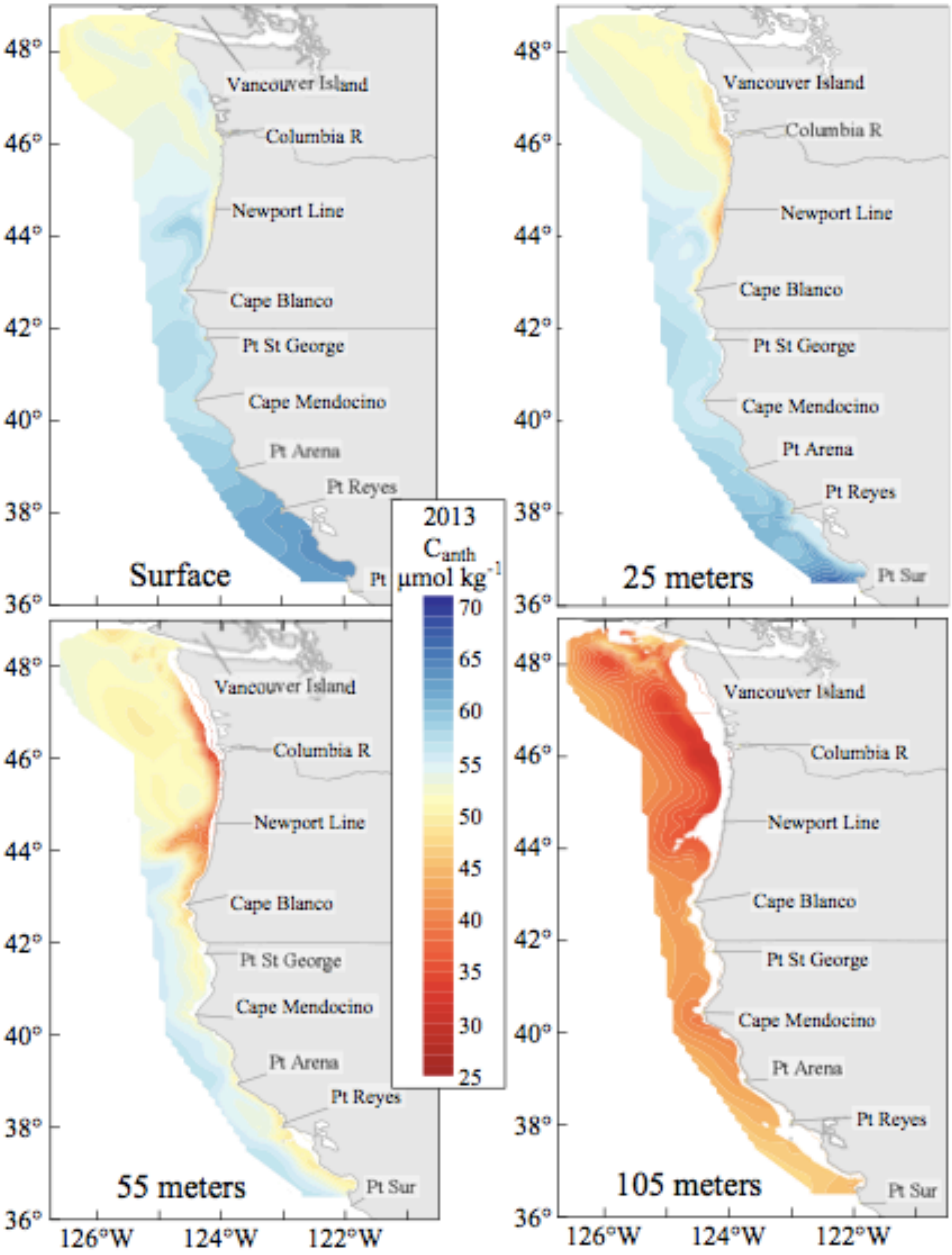

Figure 6. Current temperature (a) and chlorophyll a (c) conditions of the northeast Pacific, compared to the projected changes by 2100 (b&d). Lowered levels of chlorophyll a, projected to be as much as 0.2 mg/L by 2100. (Hazen et al., 2012)

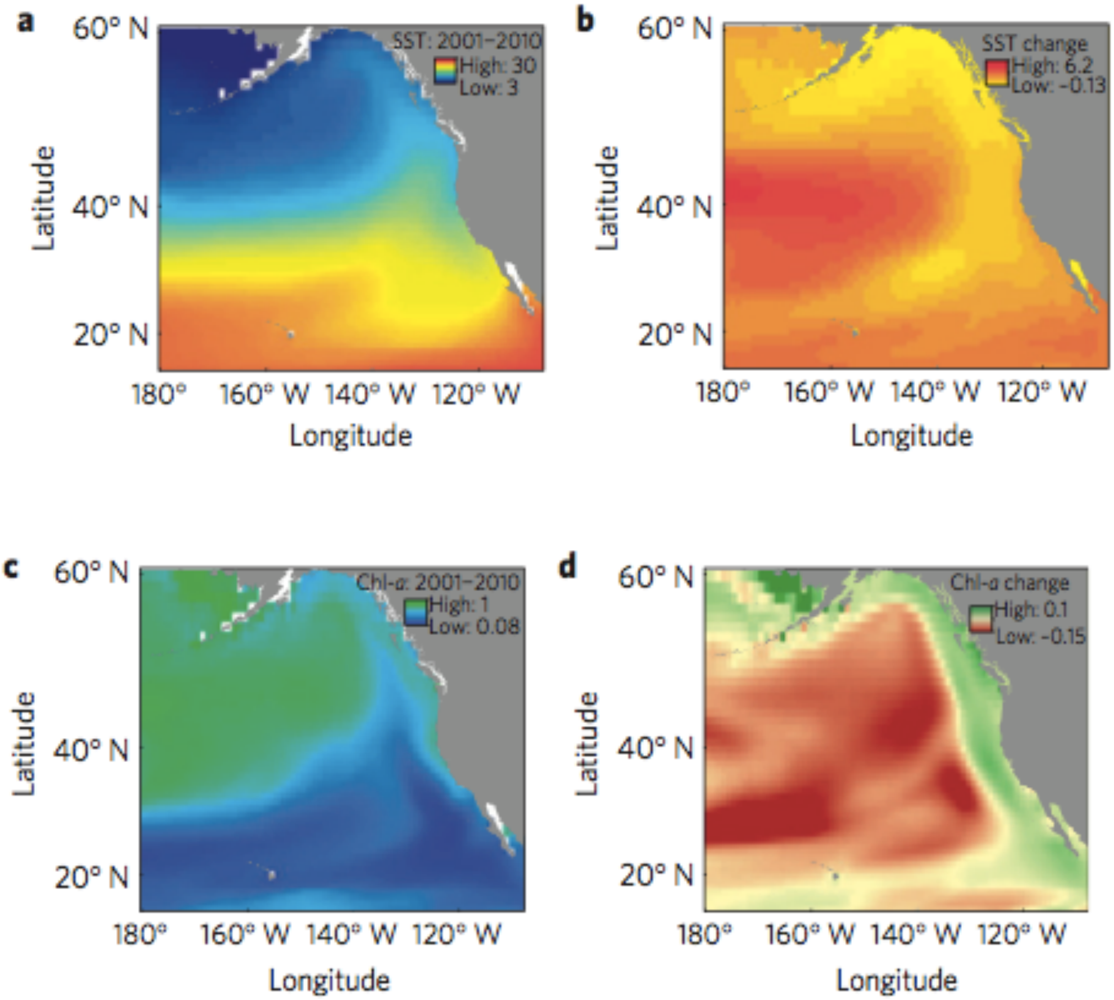

Figure 7. Shows the initial and longer term oxygen consumption rates of krill when exposed to the high projected pCO_2 for the year 2100. The low pCO_2 represent ambient levels. Krill exposed to projected 2100 levels of CO_2 (dotted line) at 1200 ppm had a 42% decline in oxygen consumption in the first 24 hours. (Cooper et al., 2016)

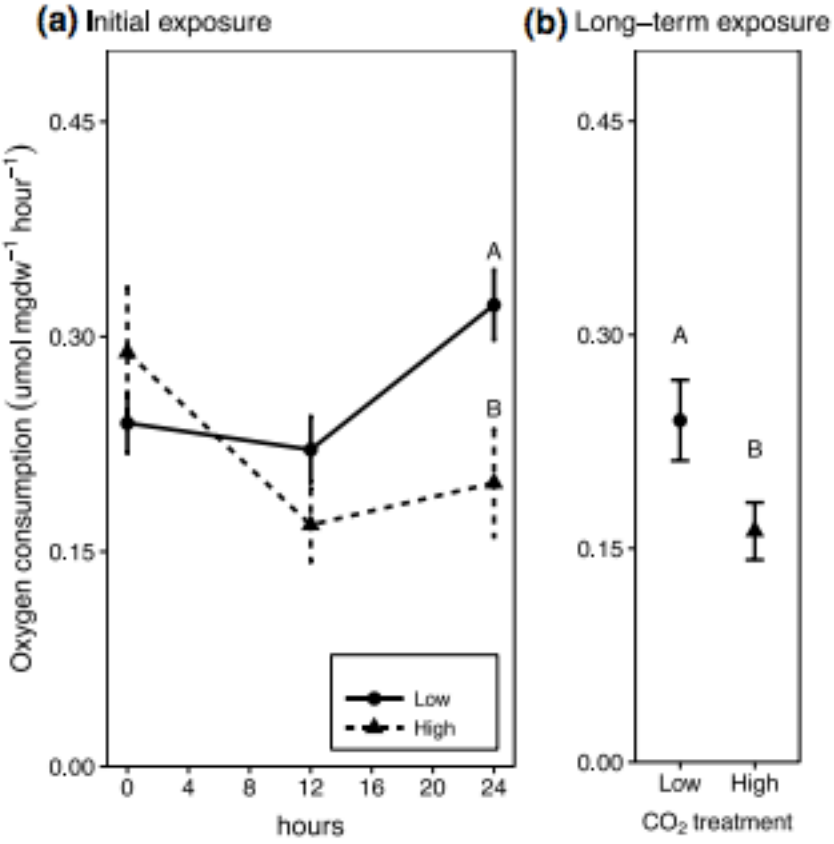

Figure 8. *Euphausia pacifica* hatching, survival, and development as a function of pH. Each point represents the final proportion of a single female's offspring that (a) hatched, (b) survived, and (c) developed to a critical stage. Offspring that were tested during the same trial share the same color. Horizontal error bars show the standard deviation from 4 pH measurements taken. Solid lines show the best-fit model, and dashed lines show the 95% CI for the effect of [H^+]. Shaded area shows the range of pH values observed in their natural habitat. (McLaskey et al., 2016)

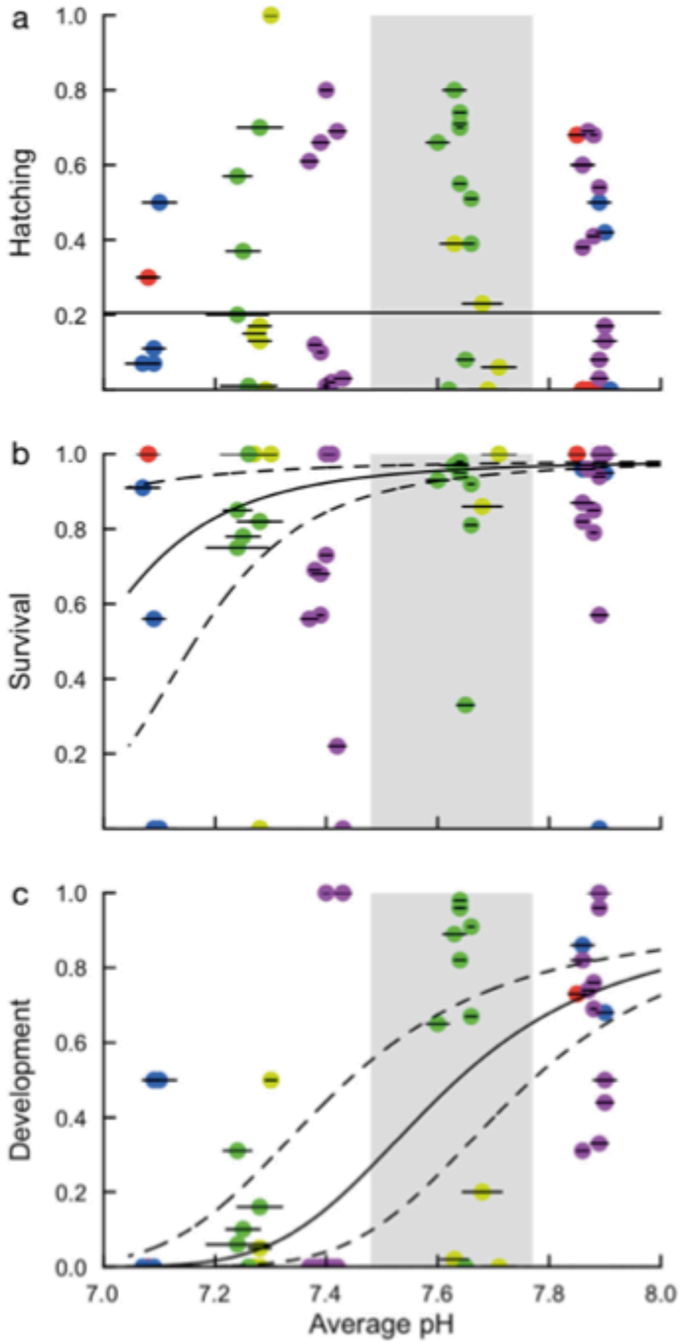

Figure 9. Based on current climate change projections for changes in temperature and primary production. Shows the overall effect on current core habitats for top predator species in the north Pacific. Blue whale loss is highlighted with about 17% loss in current habitats by 2100. (Hazen et al., 2012)

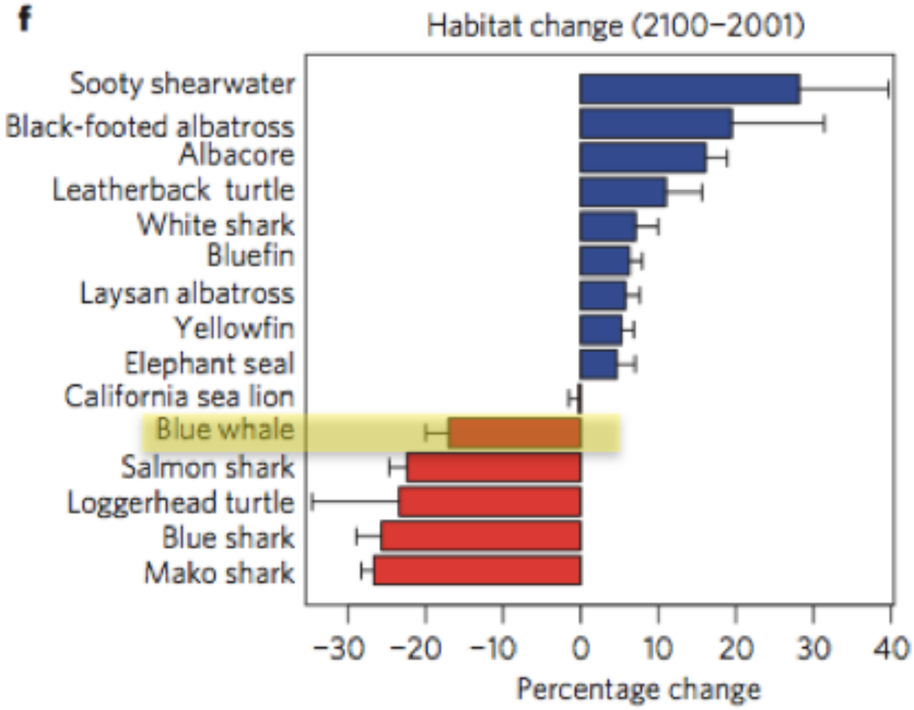

Figure 10. Projected loss of foraging habitat for blue whales off the coast of California. From 2000 to 2100 shown as monthly (grey), yearly (red) and 5-year filtered (blue) time series with 1 standard deviation marked by dashed lines. (Hazen et al., 2012)

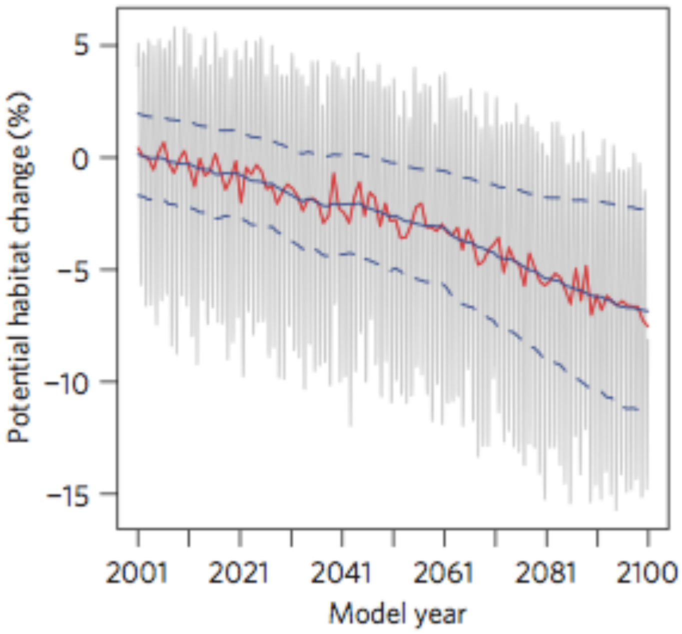

Figure 11. Showing the possible increase in blue whale migration in the Northeast Pacific, with current foraging grounds highlighted in purple, calving grounds highlighted in yellow, and theorized foraging grounds by the year 2100 highlighted in green.

Biography

Amanda L. Shuman was born to Donald and Kathy Shuman on October 9, 1996. She was raised in Cicero, NY, where she graduated from Cicero-North Syracuse High School in 2014. Majoring in marine sciences, with a marine biology concentration, Amanda fast tracked her education by completing her degree in three years. She is an active member of Phi Beta Kappa and Phi Kappa Phi. In addition to being a three-season student-athlete; competing in cross country, indoor, and outdoor track for the black bears.

After graduating in May 2017, Amanda has accepted enrollment at the University of New Haven to pursue a Master's Degree in Environmental Science. There, she will be working with Professor Whelan of the Department of Biology and Environmental Sciences and using her last seasons of NCAA eligibility.