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Life In The Cold: An Investigation Of Polar Regions

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Life in the Cold:

An Investigation of Polar Regions

Written by the MAR 464 course
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Preface

Polar areas provide unique environments that, though they may seem extreme and uninhabitable, are flourishing with life. These areas around the North and South poles include deep oceans, shallow shelf regions, tundra, mountain ranges and vast glaciers. With the increasing effects of global climate change, a basic knowledge of polar regions is crucial to understand future impacts and implications. The purpose of this book is to give a broad background of polar biology, and also provide details on specific examples through case studies. Topics included throughout this book are: Ice, Life in Polar Regions, Species Interactions, and Anthropogenic Impacts.

The students in the Polar Biology course (MAR 464) at the University of New England have researched and reviewed scientific literature to educate readers about these regions. The class, comprised of fourteen junior and senior Marine Science, Ocean Studies and Marine Affairs, and Environmental Sciences students, selected the different topics, presented the material, wrote the chapters, and assembled the final versions into this book. This book cannot be all-inclusive, but we think it will provide an excellent broad overview of the most important aspects of Polar Biology and will stimulate the reader to dive into the material further.

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Biddeford, Maine, May 2016

The photo on the cover page illustrates top predators in the Arctic and Antarctic. Both species are highly dependent on ice and face multiple threats due to global climate change.

Photo credit:

Polar bear: Coleman J. Global Warming Comments. US Centrist. p. 17 http://uscentrist.org/platform/positions/environment/context-environment/john coleman

Seal and penguin: McDermott K. 2013. Swimming into jaws of death: Incredible photos capture penguin's final moments as it is engulfed by leopard seal's gaping mouth. Daily Mail. http://www.dailymail.co.uk/news/article-2268265/Swimming-jaws-death-Final-moments-penguin-inches-leopard-seals-gaping-mouth.html

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Introduction

By: Sharlene Maynard
Edited by Erin Mohr and Alex Makucewicz

The Poles are a unique and interesting place. Although the Antarctic and Artic may seem very similar at first glance, they vary greatly. They each have similarities and differences, but their geography and basic facts about the surrounding environments, are essential to understanding both poles respectively.

Arctic

The Arctic is located in the Northern Hemisphere. To give a broad overview: geography, currents, plate tectonics, salinity, temperature, and dissolved oxygen are looked at to give you a general understanding of the factors that affect most research and life in the poles.

Geography

The Arctic is unique because there are different ways to classify the boundary. The first and the most common definition is by the Arctic Circle. The Arctic Circle is at 66^{o}. The Arctic Circle is a solid, imaginary line goes through land and ocean. Everything that is within this boundary is considered the Arctic, according to this definition. Another boundary that is sometimes used as a defining geographic boundary is the average July water temperature of 10^{o} C. This boundary is not cut and dry. The line is a little more skewed and seems to cover a larger area. This is a good definition when looking at marine life. Marine life is dependent on water temperature since that is where they inhibit. Another area that is defined is the tree line. The tree line is only defined on land, this meaning trees only grow on land, and areas that have water and no land, are left as gaps. The tree line starts on the edge of Russia and along to the Bering Sea. From there it skips over a small gap and continues on the coast of Alaska. Then it finishes by following along Canada's coast. This leaves the bottom of the Arctic Circle without a defining tree line boundary. The areas covered by water don't have a defined area. Another definition can be by the presence of seasonal or perennial sea ice. There are many definitions that are used to describe the Arctic and this is because there are many people that inhabit the area and there is no

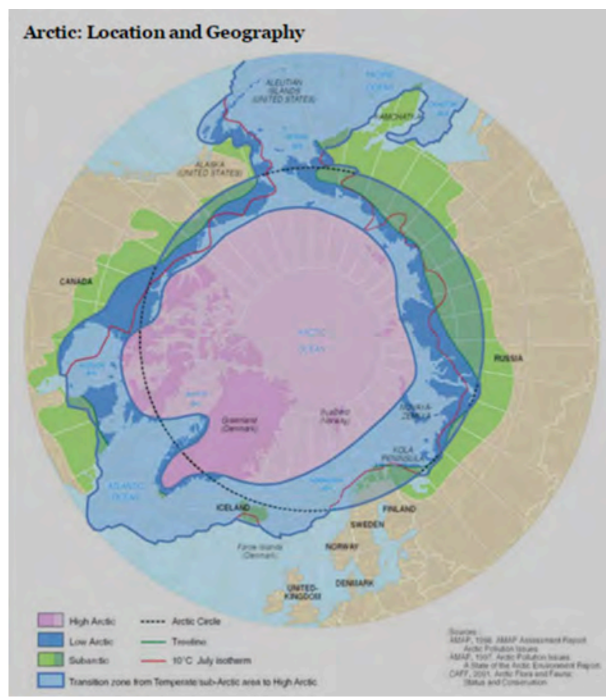

Figure 1
Picture representation of the Artic boundaries using different parameters *(http://polardiscovery.whoi.edu/arctic/geography-en.html)*

defined continent like the Antarctic. People have inhabited the Arctic for around 20,000 years. People have inhabited Russia, Greenland, Alaska, Canada, and Norway (Woods Hole Oceanographic Institution 2006). Many different governments and people have been using the Arctic, and that can cause many different issues to arise.

Currents

There are many strong and prominent currents located in the Arctic region. The largest in the area is the Transpolar Drift. The Transpolar Drift starts up near Siberia, then flows towards Greenland, and then heads to combine with the West Greenland Current. Heading left of this current is the Beaufort Gyre. A gyre is a current that makes a complete circle. This specific gyre makes a complete rotation in about four years. This is a slow moving current, but it is the largest gyre in the Arctic. There is another smaller gyre that is to the right of transpolar drift, and that is the Barents Current. The Barents current is smaller than the Beaufort current and the Barents current moves clockwise, is very weak, and the speed of current is variable. The last major current that is found in the Arctic is the Labrador Current. The Labrador Current is on the left side of Greenland and runs opposite of the West Greenland Current.

Figure 2
Picture representation of the Artic boundaries using different parameters *(http://polardiscovery.whoi.edu/arctic/geography-en.html)*

Plate Tectonics

Underneath the currents lie different crustal plates. Plate tectonics are responsible for the separation of Pangea, when all of the land was intact. In the Arctic, the plates are all relatively stable. This meaning that the plates move slowly and rarely. The plates that are there are of low seismic activity. There are low amounts earthquakes. The earthquakes that are in the Arctic and do occur, occur on the fault lines. They are usually clustered and all around in the same areas. The earthquakes are low and closely compacted.

Salinity

Going back up just above the different plate tectonics in the ocean column is a topic that is crucial for different marine species survival. The salinity of the water, how much salt is in the water, is important for understanding what organisms live in certain areas and depths. In the Arctic the average salinity is found to be anywhere from 28 ppt (parts per thousand) to 34ppt. See figure 3 for a map of average surface salinity. The surface layer is the most varying due to fresh water input from rivers,

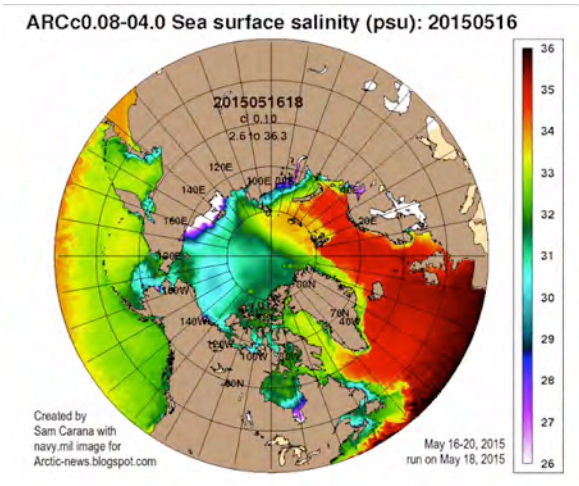

Figure 3
Picture representation of the Artic boundaries using different parameters
(http://polardiscovery.whoi.edu/arctic/geography-en.html)

ice, and rainfall. The salinity of the Arctic is the highest where the transpolar current head and then empties out.

Temperature

Along with salinity, temperature is also important. Although temperature has been changing rapidly in the last few years, an average temperature still can be gathered.

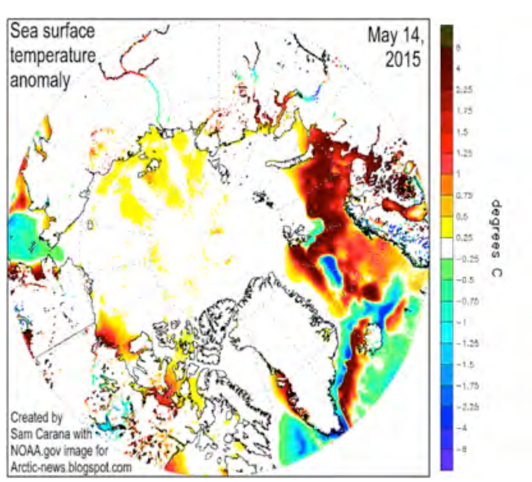

Figure 4:http://arctic-news.blogspot.com/2015/05/mackenzie-river-warming.html
Average Temperature in the Arctic

Figure 4 shows the average temperature in the Arctic in Celsius. There are alarming warm areas of the artic that would cause the melting the ice. Further, into reading this topic will be discussed in its entirety including the topics of global warming, ice coverage, law policies, and the effects on different organisms and habitats.

Dissolved Oxygen

Oxygen is needed for organisms to survive, aquatic or otherwise. Oxygen can be dissolved into the water, occur from photosynthesis, or wind cycling, and is most commonly expressed as mols of O_2. Typically, you see more dissolved oxygen in bodies of water that are colder. This is because solubility decreases as water becomes warmer (Kemker 2013). This means that as water becomes warmer, the less oxygen that it holds. This is why we see the higher amounts of DO, dissolved oxygen, concentrations at both poles, the Arctic and Antarctica.

Antarctica

Moving south, we find ourselves in Antarctica. Either though Antarctica is similar in many ways, or geographically they are both placed at the poles, Antarctica has some outstanding differences.

Geography

Antarctica is in the Southern Hemisphere and the first thing that we notice is Antarctica is a continent. This makes for an easier definition for scholars and scientists. Antarctica is most commonly defined by the Antarctic Circle (Woods Hole Oceanographic Institution 2006). The Antarctic Circle is a 66^{o} south of the equator. Antarctica is a large continent that occupies around 20 percent of the Southern Hemisphere and has a few larger islands that are located off its peninsula. These islands are South Orkney, South Shetland, South Georgia, and the South Sandwich islands. No native people are from Antarctica unlike the Arctic and because of this, countries have claimed certain parts of Antarctica, but no one governs them, which will later go into more detail.

Currents

Antarctica, like the Arctic has major surrounding currents. The largest and well-known would be the ACC, Antarctic Circumpolar Current (Woods Hole Oceanographic Institute 2006). The ACC is the only current that goes completely around the globe. It flows around the globe at a slow easterly rate of 15-24 knots. The other current that is also located there is the Subantarctic Current. The Subantarctic Current is defined as the ACC northern boundary, but unlike the ACC, it does not travel solely around Antarctica. There are also two small gyres that are located on the east and west of Antarctica, along with another small current known as the Polar Front Current. (See Figure 5.)

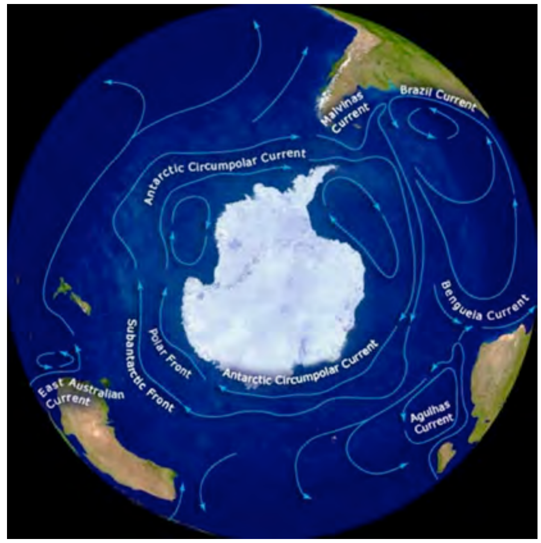

Figure 5http://www.teara.govt.nz/en/map/5915/circumpolar-currents Antarctica's major currents and directional flow

Plate Tectonics

To understand why Antarctica is where it is, the solution can be found on the plate that Antarctica sits on. Antarctica is on the Antarctic plate. As years went on, Antarctica separated from Pangea, and then slowly moved southward, and is now found at the South Pole. The Antarctic plate is large and covers 60,900,000 km^2 of space (Ovyind 2003). There are not as many plates that are affecting the area as the Arctic, and due to this, Antarctica is seismically stable with not much activity occurring. However, there is an active volcano that is under Antarctica called, Mount Erebus, and it is the most active volcano in Antarctica (Pappas et al 2014).

Salinity

Salinity looks very different when it is compared to the Arctic. There is not as much run off from fresh water in Antarctica as there is in the Arctic, and this affects the salinity concentrations. The Salinity of

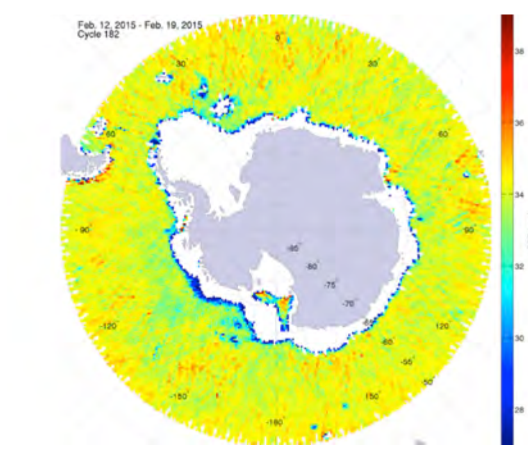

Figure 6: Salinity Concentrations for Antarctica. http://aquarius.umaine.edu/cgi/gal_latitudes_sss.htm

Antarctica hovers right around 34 ppt, which is around average for most of the world's oceans.

From the Satellite footage, we see that the map looks much different from the Arctic. Here there is greater variability around the shores, showing more on the lower end, most likely caused by ice melting, and not as much areas for high salinity. This just shows that there will be different organisms living in each area.

Temperature

Temperature of the Antarctic is similar to the Arctic in regards that temperature is increasing overtime. Temperature is important to organisms that live in both places, but are both different. We know that Antarctica is colder than the arctic. The answer to why is due to a few different factors. The first is that Antarctica is at a higher elevation (Woods Hole Oceanographic Institution 2006). The higher up you are from sea level, the drier the air and the colder it gets. There is less moisture in the air and that leads to the temperature feeling extremely cold. Antarctica also has thinner ice than in the Arctic. The thinner ice allows the cold from the water to seep up through the ice. This causes a colder temperature above the water.

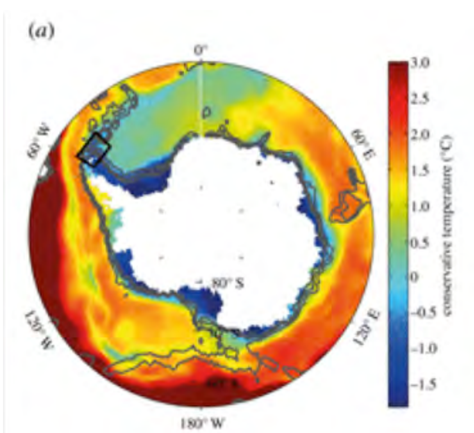

Figure 7: (Heywood, 2014) Average ocean temperatures in the Antarctic

Figure 7: shows that the average temperature right off the cost of Antarctica stays relatively within the -1^{o}C range. This is different from the Arctic being around 0.5^{o}C.

Both Poles Respectively

Seasons

Looking at both of the poles, they both function similarly when it comes to changing seasons. Seasons are different at both of the poles due to the earth's rotation. (Woods Hole Oceanographic Institution 2006) The sun never completely sets in the poles, but rather the poles tilt. This tilt causes the two seasons that is experienced. The poles both experience summer and winter weather. There are six months of summer and then six months of winter respectively.

While the earth is rotating around the sun, the earth has a slight tilt. This tilt, looking at it from either pole, is either towards the sun or away from the sun. The summer months, you have the earth's tilt towards the sun, and for the winter months, it is tilted away from the sun. In the summer when the poles are facing the earth you get more direct sunlight and heat and that is considered the warmer months, summer, and when the poles are not near the sun it is darker and colder, putting it in the category of winter.

Conclusions

Compiling and having background knowledge is important for other research. The paper here touches just on the surface of some of the major topics needed to understand the Antarctic and Arctic. In future chapters, we will zoom in on both poles and look at organisms, policy change, climate change, ice, and more that are important to understanding both unique and diverse systems.

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Ice

This section discusses the physical, geological, and biological aspects of sea, shelf, and glacial ice in polar regions. Differences between the Arctic and Antarctic are clarified, highlighting the impacts of ice on biotic and abiotic components of ecosystems.

Arctic and Antarctic Ice

Author: Erin Mohr
Edited by: Kaitlyn Kennedy and Ashley Breault

Glaciers, Ice Shelves, and Sea Ice

A glacier is a year-round mass of ice that originates on land and forms from compacted layers of snow. After a fresh layer of snow falls, the previously fallen layers of snow compress into ice. The compression forces of the newly fallen snow forces the previous layers of snow to re-crystalize, forming very small grains. Over time, these grains grow larger and the air pockets that are between the grains get smaller, which results in the snow compacting and becoming more dense. After a certain number of years (usually around two years) the snow turns into firn, which is an intermediate state between snow and glacier ice. As time passes, the large grains become more and more compressed and the air pockets become very small resulting in glacier ice. These large masses are constantly moving despite the fact that they are solid ice. Glacial movement is the result of the weight of a thick layer of ice as well as the force of gravity on the ice mass (https://nsidc.org).

The majority of the world's glacial ice is found in Antarctica and Greenland, however, glaciers are in fact found on every continent. Glaciers can be divided into two main types: alpine glaciers and ice sheets. Alpine glaciers, also called mountain glaciers, are found in only mountainous areas. As an alpine glacier increases in size and begins to flow downward into a valley, it is considered a valley glacier. Unlike Alpine glaciers, ice sheets are not limited to mountainous areas and they extend more than 50,000 square kilometers. These ice masses form broad domes that spread out in all directions from their centers. Today the largest ice sheets are called continental ice sheets, which are only found in Antarctica and on the island of Greenland (http://extremeicesurvey.org). During the past ice ages, ice sheets were also found in Canada as well as Scandinavia, however, these have since disappeared leaving behind only ice caps and alpine glaciers (https://nsidc.org).

Figure 1: Antarctic ice sheet. (theclimatescepticsparty.blogspot.com)

The Antarctic ice sheet, which is the largest single mass of ice on earth, extends nearly 14 million square kilometers and is around 2 meters thick. It contains 30 million cubic kilometers of ice and holds approximately 90% of the freshwater on the planet. If the entire ice sheet were to melt, it would raise sea level by roughly 60 meters (http://education.nationalgeographic.org). T he Antarctic ice sheet is divided by the Transantarctic Mountains into the East Antarctic Ice Sheet and the West Antarctic Ice Sheet (http://ete.cet.edu). Most of the Western Antarctic ice sheet lies below sea level making it a marine ice sheet. Of today's ice sheets, the West Antarctic ice sheet is in the most danger of collapsing due to warm water melting the ice below, and many scientists believe that its downfall in inevitable. The Thwaites Glacier, along with the Pine Island Glacier which are described as the "weak underbelly" of the West Antarctic ice sheet, have been retreating for the past 20 years. The reason for this retreat is that warm seawater has been melting the floating ice shelves at the base of the glacier. Currently, an underwater ledge is keeping the glacier in place, however, once the glacier retreats past this ledge, it will collapse into the ocean (Gramling 2015).

Sea ice as a whole is decreasing as expected with global warming and climate change, however not every area that does have sea ice is seeing a downward trend in ice extent. For example, Antarctica has gained an average of 7,300 square miles of ice per year. In 2014, sea ice surrounding Antarctica reached a new record high extent. At this time, it covered more of the southern ocean than it has since scientists began a long term satellite record to map sea ice extent in 1979. Possible explanations for why Antarctic sea ice reached a new record high in 2014 include the fact that there is no northern barrier around the whole perimeter of the ice. This makes it easy for ice to expand during favorable conditions. Scientists are also considering the changes occurring in wind patterns that are currently circulating warm air over the Antarctic Peninsula, while sweeping colder air from the Antarctic continent over the Ross Sea. Also, ice is melting around the edges of the Antarctic continent, which might be resulting in more freshwater that is just above freezing temperatures, moving out to sea. This makes it easier to refreeze into sea ice. Changes in water circulation patterns that are bringing colder water up to the surface around the continent might also lead to sea ice growth (http://www.nasa.gov). Antarctic sea ice covers a minimum of $3x10^6$ km^2 in February to a maximum of $18x10^6$ km^2 in September. Sea ice in Antarctica is mostly thin (~0.6 meters thick) and is single year ice meaning it does not build up from year to year, but instead melts each summer (Davies 2015).

Figure 2: Greenland ice sheet. (www.ete.cet.edu)

The Greenland ice sheet extends about 1.7 million square kilometers and is the second largest body of ice on the planet. It covers 82% of Greenland's surface and it's estimated that 239 cubic kilometers of ice are melting per year. If the entire ice sheet melted, sea levels would rise by roughly 7.2 meters (http://ete.cet.edu). The annual snow accumulation rate on the Greenland Ice Sheet is more than double that of the Antarctic ice sheet and melting of glaciers happens across almost half of the entire ice sheet (http://education.nationalgeographic.org). Along the southeastern and southwestern margins of the ice sheet, the number of melting days was close to or below the long-term average. However, along the northeastern and northwestern regions of the ice sheet, the number of melt days was up to

30-40 days above the 1981-2010 average. This set new records for melt water production and runoff in the northwestern region (Jeffries et al. 2015). On the Greenland ice sheet, meltwater lakes are the result of warm summer temperatures. The water that pools on the surface of either the ice sheet or the glacier is heavier than the ice. This water eventually flows into stream channels that drill through the ice. As a result, water flows out the base of the glacier and into the ocean. The melted water speeds up the flow of ice into the ocean by lubricating the glacier bed (http://extremeicesurvey.org). For the first time since the exceptional melting of 2012, melting occurred over more than 50% of the Greenland ice sheet. The minimum sea ice extent that was observed in September of 2015, was 29% less than the average between the years of 1981 to 2010 and the fourth lowest value in satellite record, which began in 1979. On February 25th, the lowest ever maximum ice extent in satellite record was observed. It was 7% less than the average for the time period between 1981-2010 and was also the second earliest in the record occurring 15 days earlier than average. (Jeffries et al. 2015).

Since the late 1970's, the Arctic has lost an average of 20,800 square miles of ice a year. The magnitude of the loss of sea ice in the Arctic Ocean is occurring three times more rapidly than the gain of ice that is occurring in the Antarctic. Arctic sea ice grows during the fall and winter months and reaches an annual maximum between February and April. The ice then shrinks in the spring and summer and reaches its minimum extent in September. Arctic sea ice is generally thick, multi-year ice that survives several seasons. Overall, scientists have seen a downward trend in Arctic sea ice extent during both the growing and the melting seasons.

Melting ice sheets can affect the climate of ecosystems around the world. When they do experience periods of melting, they not only directly affect sea level rise, but they also can change the salinity of the oceans as massive amounts of freshwater are added (http://education.nationalgeographic.org). T hermohaline circulation is also altered by melting ice sheets. Overall, glaciers, both alpine and ice sheet are extremely valuable in climate studies. Ice cores are drilled and extracted from glaciers and ice sheets and provide scientists with year by year information about past climates. Scientists observe trapped air bubbles within the ice, which give information on the past atmospheric composition, temperature variations, and types of vegetation that were present during a certain time period. Beginning in the early twentieth century, glaciers have been retreating at unprecedented rates, which scientists are attributing to climate change. Glaciers are also able to provide information on how the atmosphere naturally warms up between ice ages. (https://nsidc.org).

As ice sheets extend to the coast and over the ocean, they become ice shelves. Ice shelves are permanent floating sheets of ice that connect to a landmass. These structures are found only in Antarctica, Canada, and Greenland and form wherever ice flows from land into cold ocean water. Ice shelf formation occurs when ice from glaciers and ice streams spreads into the ocean and floats and grows as the glacial ice behind it continues to flow. The world's largest ice shelves are the Ross Ice Shelf and the Filchner - Ronne Ice Shelf, both in Antarctica. During the last 30 years, scientists have observed a series of unusual ice shelf collapses throughout the Antarctic Peninsula. Due to the fact that they are already floating in the ocean, they do not directly contribute to sea level rise when they break up. Ice shelf collapses do, however indirectly affect sea level rise. These ice shelves are constantly pushed by glaciers and ice streams. Eventually the shelves reach coastal features like islands or peninsulas which slows their movement into the sea. Once an ice shelf collapses, the backpressure from the glaciers and ice streams is gone, which causes the speed of the water from the glacier into the ocean to increase, contributing to sea level rise. Studies have shown that following a quick ice shelf retreat, glaciers behind ice shelves may accelerate up to five times (https://nsidc.org).

Life in, on, and under the ice

Sea ice serves as a unique habitat in polar areas. A diverse group of plants and animals live in the two main habitat locations: the interior of the ice and at the ice-water interface. The distribution of these plants and animals is largely dependent on abiotic parameters such as light, salinity, food availability, and space. In both the Arctic and the Antarctic, the highest metazoan concentrations occur mostly in the bottom centimeters of the ice. These dominant metazoans include nematodes, turbellarians, rotifers, and crustaceans and they feed mainly on the algae that grow under the ice. In order to survive in sea ice habitats, ice biota needs to adapt to extreme variation in salinity (from below 5 PSU to above 60 PSU). The ice interior has a two-phase system that involves ice crystals that are interlaced with networks and that are filled with brine pockets and channels. Brine channels range anywhere between 0.1 to 1,000 micro- meters in diameter and experience extremely variable conditions depending on air temperature and snow cover. Unlike the interior of the ice which experiences extreme variability in salinity and temperature, these factors are relatively constant at the ice-water interface (Thomas et al. 2002).

The major in- ice fauna taxa within Arctic ice include flagellates, ciliates, turbellarians, crustaceans, nematodes, and rotifers. The major under-ice fauna include amphipods, copepods and *Boregadus saida.* The Arctic sea ice provides a multi-year habitat that allows organisms to complete their life cycles without being released into the water column. In the autumn months, when moving up through the water column, many planktonic organisms including viruses, bacteria, algae, protists, flatworms, and small crustaceans, stick to and/or get caught between ice crystals. Ice grows and traps these organisms within the brine channels (Gradinger 2001). The major in- ice fauna taxa in Antarctic ice include flagellates, ciliates, forminifera, turbellarians, crustaceans, and some nudibranchs. The major under-ice fauna include amphipods, *Euphausia superba, E. crystallorophias,* and *Pagothenia borchgrevinki.* Unlike the Arctic ice, in the single year Antarctic pack ice, biota must be capable of surviving a pelagic lifestyle for a certain period of time.

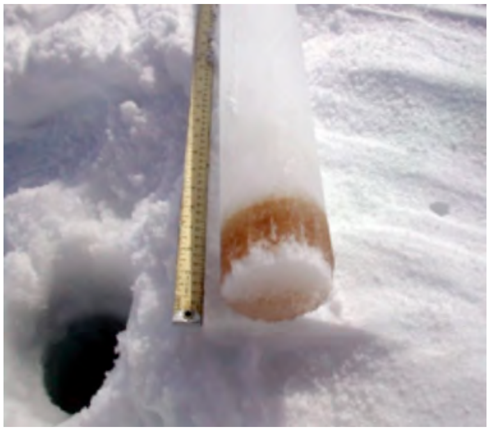

Figure 3: Ice core showing the highest metazoan concentrations within the bottom centimeters (www.ed694.community.uaf.edu)

Acting as an integral part of the food chain, krill are the primary food source of many marine mammals and fish. Krill feed on phytoplankton and in turn serve as a food source to hundreds of different organisms from fish to birds to whales (http://animals.nationalgeographic.com). Th e distribution and feeding activity of krill is strongly related to pack ice cover, and recent studies have shown that Antarctic krill stocks have dropped by 80% since the 1970s. Scientists believe that the decline in krill populations is a result of a loss of ice cover caused by global warming. Loss of sea ice results in a loss of ice algae, which is the main food source of krill (http://animals.nationalgeographic.com).

With the polar regions becoming warmer, many species are now struggling to survive. In the Arctic, walruses rely on sea ice that floats close to land, in order to haul out. With disappearing sea ice, walrus pups face drowning as well as being trampled to death as they attempt to climb out onto crowded beaches. In the Antarctic, certain emperor penguin colonies are predicted to decline by 95% before the end of the century with sea ice decreasing at the current rate (http://wwf.panda.org).

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Life in the Ice

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Edit: Peter Swan and Erin Mohr

Introduction

When thinking about polar areas, many believe it to be cold, desolate places, without much life. However, according to research, this previous thought is now void of validity. Life within the ice is productive and a home for a vast amount of organisms. Ice covers thirteen percent of the Earth's surface (Thomas, Dieckmann 2002). This is a substantial amount considering that the Earth is approximately 70% water. Many organisms located within the ice are highly unique, while photosynthetic organisms within polar areas are critical to primary production as well. A total of 5 percent of annual primary productivity occurs within the poles (Thomas, Dieckmann 2002). A significant percentage, considering the size of polar regions in comparison to the rest of the world. Diving further into this topic, it can be seen that there is a lot going on within large pieces of ice.

Ice Environment

Ice is not just important as a source of fresh water, but it is also home to many organisms. There are multiple channels, providing both temporary and permanent homes for many arctic creatures. These organisms are vast in variety. Organisms living within the ice include, but are not limited to viruses, bacteria, and algae (Gradinger 2001). A vast majority of organisms exist in the ice, many of which remain undiscovered., live together in the ice creates a small ecosystem,

Organisms use the brine channels within the ice. Most of these organisms are photosynthetic. Some organisms, such as zooplankton, use the brine channels to graze for their food, as well as protection from their predators (Krembs, Deming 2011). In addition, ice can serve as a nursery ground for different juveniles. Fish and algae usually take advantage of the ice, when temperatures are not ideal for growth or survival (Krembs, Deming 2011). The importance of ice does not stop there, when ice is melting, ice is still critical. When the ice melts, it creates a shallow mixed layer (Krembs, Deming 2011). This mixed layer fosters ice edge blooms. These ice edged blooms further contribute to the overall productivity in polar regions.

Understanding the conditions that are within the ice are imperative to how animals are able to live in these harsh conditions. Several factors that should be considered important for the ice in polar regions are temperature, salinity and UV radiation. Temperature and salinity play key roles in determining the presence of organisms, and often temperature helps to regulate salinity. Temperature and salinity within brine channels are said to be comparable with intertidal zones (Gradinger 2001). These factors are important when determining what will live in the ice, including, where and how they are able to accomplish living in these variable environments.

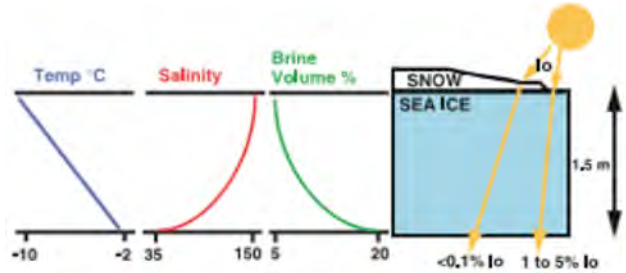

Figure 1. Gradients of temperature, salinity and light established across ice flow. The surface of the ice is largely dependent on snow cover, while the underside is always at the point of freezing seawater. Taken from Thomas et al. 2002.

Through exploring *Figure 1* it can be seen that there are dramatic changes in salinity and temperature. The surface temperatures are colder than temperatures that are found deeper. However, temperature at the surface of the ice can be extremely variable. This is determined by factors such as wind, sunlight availability, and surface snow cover. Deeper under the ice, as far down as 2 meters, the water is warmer. In summary, the sea ice surface can be around -35^{o}C and the base of the ice can be around -2^{o}C (Krembs, Deming 2011). These are extremes that can vary based on location and global climate change, over time.

Figure 1 also shows that there are great changes in salinity. Salinity is already variable within the water column however, in the ice, there is a steeper and greater change when looking inside the ice. At the base of the ice under the water salinity is around what is considered to be livable for a majority of organisms, 35 ppt, (parts per thousand). However, at the surface of the ice, the salinity greatly increases. The salinity can reach around 250 ppt. Most organisms are not adjusted to this kind of extreme.

Another extreme that organisms need to be able to adjust to is the light availability. Light availability decreases with depth. However, it can be noted that at these lower depths, organisms are more apt to be found. The difficulty that these organism encounter, while living at these extremely low depths, are the amount of light that they are receiving. Light can be nearly zero if there is substantial snow cover on top of the ice. (Thomas, Dieckmann 2002). This leaves the organisms that live within the ice, mostly photosynthetic algae, to deal with very low light conditions. However, with the lack of light, these organisms are less exposed to the negative effects of UV radiation, which may inadvertently provide an advantage, see UV Radiation, Chapter 18.

Brine Channels

Taking a closer look to what life in the ice is like, we can explore the brine channels. Brine channels form when salty liquid droplets, or brine, get trapped within pockets of ice. Thus, the interior of the ice creates a two phase system, where ice crystals are interlaced with fluid filled brine channels. Typically, brine channels range in size from .1µm to a few centimeters (Gradinger 2001). Summer brine volume can exceed 30% of sea ice, while in the winter it can become as little as 5% (Gradinger 2001). There are many organisms that take advantage of this space. These brine channels are extremely variable when looking at salinity. They can range anywhere from 0 to 200 practical salinity units (PSU) (Gradinger 2001). In comparison, dead sea reaches levels of approximately 300 parts per thousand (ppt), where PSU and ppt values are relatively equivalent. Therefore, parts of the polar regions have some of the highest salinity values on Earth. That being said, some researchers believe that organisms can expand these brine channels. However, this is a new and understudied field, and there is still a great deal to be studied.

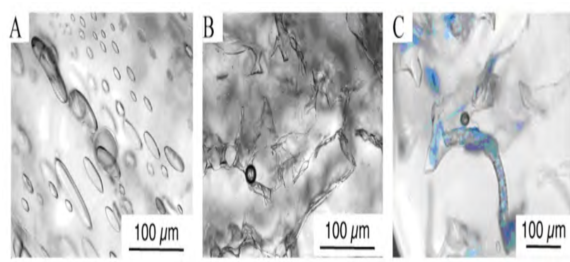

Figure 2: Image a) is lab growth brine channels. Image b) are algal sculpted channels with the absence of organisms. Image c) are natural brine channels with organisms present, observed in blue coloration. Taken from Krembs et al. 2011.

Looking further into the brine channels, *Figure 2* shows a lab experiment looking at natural brine channels, and lab made brine channels. In this figure you can see that the left picture is of lab made brine channels. These channels are short, not connected, and they are smooth. These look very unnatural. However, it can be observed that in the middle and right picture these are what natural brine channels look like, and are not lab-made. These channels are longer, connected, and they are occupying much more space. The right picture it is a close up of one natural brine channel that has organisms living within the channel. The right picture's brine channels are the most developed, demonstrating the key role organisms have in influencing the construction of brine channels. Overall, these brine channels help support photosynthetic life, and habitat protection for various organisms. Dwelling deeper into the ice, it can be seen that organisms are uniquely adapted to living in the ice.

Living in the Ice

Since much of the life within the ice is found within brine channels, it is sufficed to say that the greater the number of pores found will yield a greater number of organisms for that region. The ice offers numerous survival limitations. Organisms must be able to adapt to extreme temperatures, salinity and pressure gradients. Organisms within the ice must be able to withstand temperatures of -20°C (Thomas et al. 2002). Others much devise a way to manage the extreme salinity.

In order to tolerate these harsh conditions some organisms have been able to develop means of managing their internal systems to combat their environment. It is crucial that organism living within the ice prevent the growth of water crystals into their body. As most organisms do not

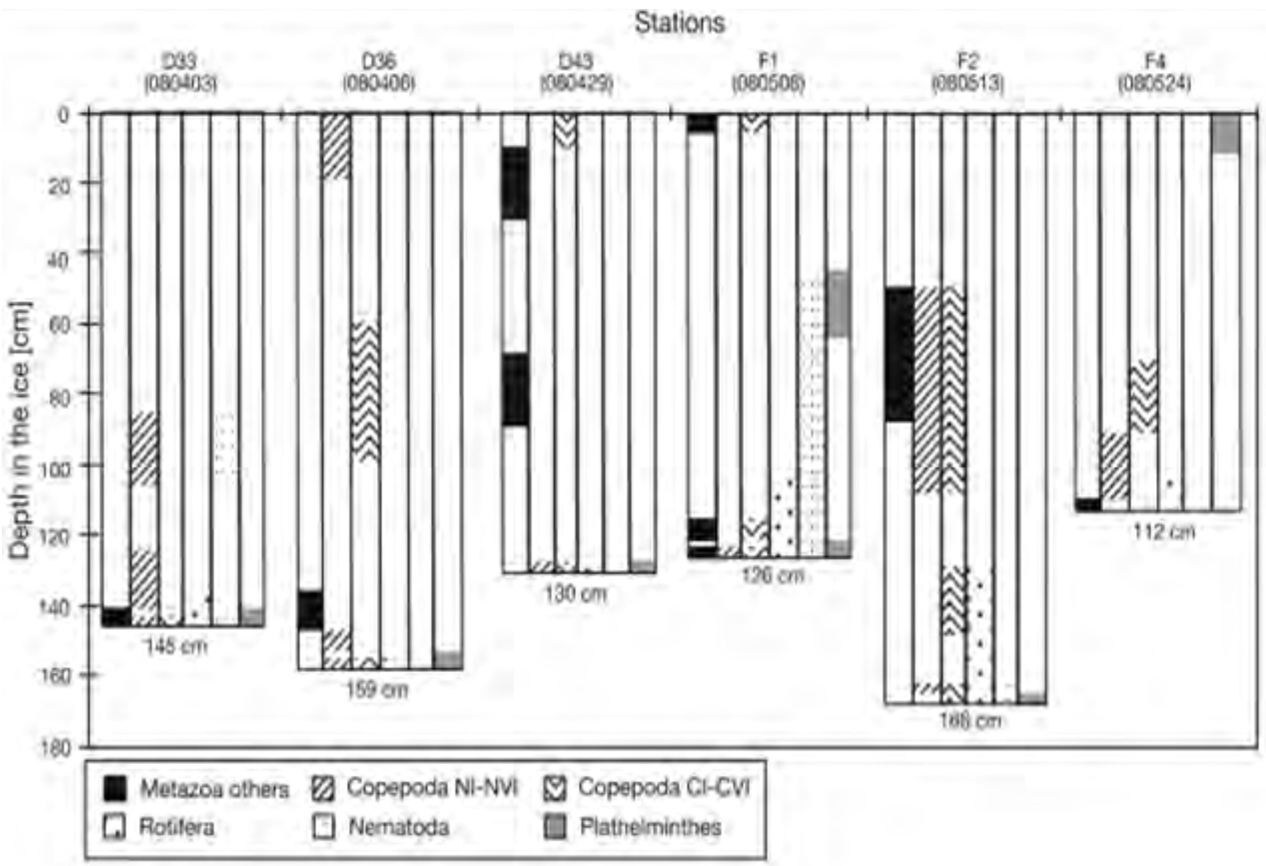

Figure 3. Qualitative profiles of vertical distribution of metazoan meio-species composition within 6 different sea ice stations located in the Arctic. Taken from Marquardt et al. 2001.

regulate their internal body temperature, meaning that often they have the same temperature as the ice which surrounds them, some have organic molecules and fat-like materials to combat the cold (Thomas et al 2001). These organisms known as ectothermic. There are two known methods for managing these high salinities. The first: extracellularly and anisoosmotically, which uses inorganic compounds and the second: intracellularly, which uses organic compounds. Organisms, such as algae, protozoans, and meiofauna are able to withstand salinities around 80 (PSU) (Gradinger 2001). Because there is such a large variation of temperature (and therefore salinity) within sea ice, species composition varies over vertical distribution (Marquardt et al. 2011).

Current research on these creatures has found that the majority of organisms have the greatest abundance in the lowermost centimeters of the ice. Protozoans and metazoans are the best at tolerating high salinities and not restricted to lower layers of the ice (Marquardt et al. 2001). They are to the surface of the ice. Refer to *Figure 3*. It is important to note that while it seems counterproductive for photosynthetic organisms to be so far from the surface as to receive limited light there may be some advantage. In addition to the salinity and temperature pressures at the surface, the UV radiation in polar regions poses a threat to these organisms, so much so that it might be more beneficial to live deeper in the ice. Temperature and salinity largely determine where different organisms are located within the depths of the ices; however, other factors such as ice type (pack vs. fast), season, pressure, and food availability also contribute (Marquardt et al. 2011).

The Arctic offers a multi-year habitat for organisms. These means that organisms are able to stay within the ice year-round. In contrast, Antarctic biota survive in both pack ice and a pelagic life-style, which provides additional challenges to these organisms (Marquardt et al. 2011). Because of this additional strain meiofauna is less diverse in non-permanent ice coverage regions than year-round areas of ice coverage. Endemic sea ice species are therefore more characteristic of the Arctic than the Antarctic for this reason (Gradinger 2001).

Antarctica and Arctic Organisms

Scientists estimate that there are approximately 0 to $3.2x10^5$ organisms per m² (Gradinger 2001). Many of the organisms which appear within the ice become stuck between ice crystals as the water freezes (Thomas et al. 2002). Others, though less commonly, enter through the base of the ice into the existing brine channels (Gradinger et al. 2001). Some of the organisms which inhabit the ice and brine channels are viruses, bacteria, diatoms, flatworms, algae, small crustaceans, and nematodes (Thomas et al. 2002 and Schnack-Schiel et al. 2001). Of the protozoans and metazoans present are: heterotrophic flagellates, ciliates, foraminifera, turbellarians, and copepods. Scientist have discovered that there is an absence of rotifers and recently discovered a under-described nudibranch(Gradinger 2001). It is predicted an abundance of new organisms will arise with increased research in the polar regions. These organisms are not only of interest for their ability to withstand extreme environmental conditions, but many of these organisms, specifically algae become the primary food source in the winter months for krill (Thomas et al. 2002).

Compared to the Antarctic, the Arctic has a less abundant, but a wider distribution of organisms. Scientists approximate 1.3 to $2.233x10^5$ organisms per m² (Gradinger 2001). The Arctic has a large number of

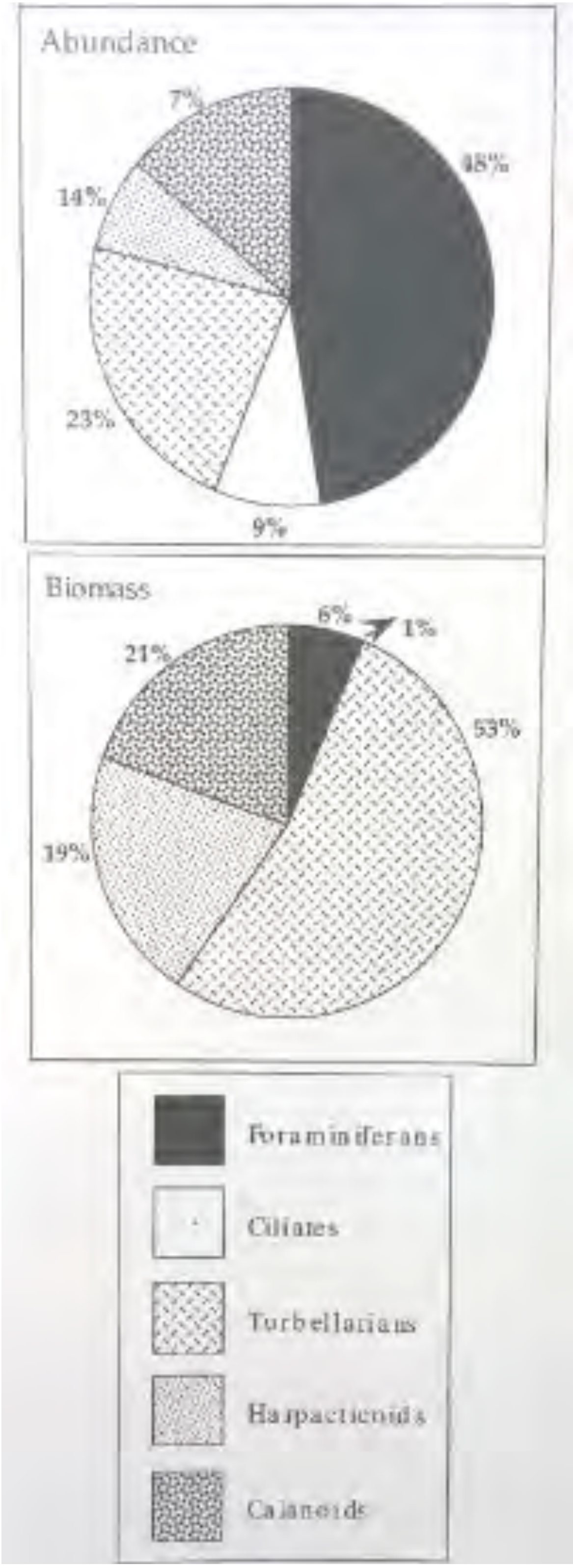

Figure 4. Antarctic ice meiofauna taxa to mean abundance and biomass. Schnack-Schiel et al. 2001.

sympagic meio-organisms. Organisms within the Arctic ice include: proto- and metazoans (ciliates), juvenile polychaetes, cirripeds, mollusks, nematodes, copepods, platyhelminthes, rotifers, cnidarians (Gradinger 2001 and Marquardt et al. 2011).

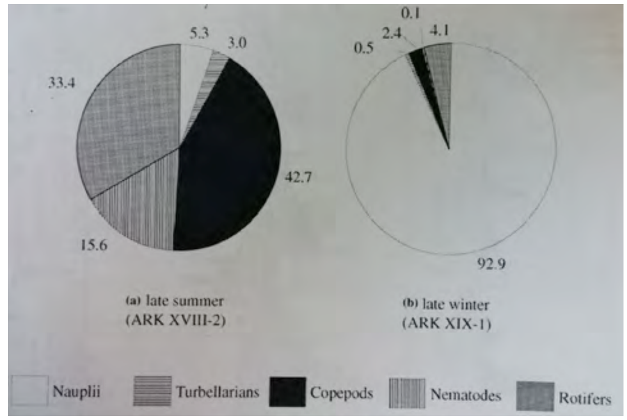

Figure 5. Relative contribution of sympagic meiofauna taxa to abundances found in the Arctic pack ice in winter and summer months. Schunemann et at. 2005.

In addition, there are some rare taxa which extends to zooflagellates and nemerteans. Also present are some macrofauna species, such as amphipods and large copepods (Marquardt et al. 2011). Chlorophyll a, produced by a majority of photosynthetic organisms is mainly concentrated in the lowermost 10cm, which further supports research that organisms mainly inhabit in the lower regions of the ice. With the decreasing amount of sea ice in the Arctic from global warming, the meiofauna diversity is becoming threatened (Marquardt et al. 2011). This poses a danger to the balance of the Arctic environment, as much of the life within the ice can be a main primary food source to higher level organisms.

Conclusion:

A great deal of research is needed in polar regions. There is still much to be discovered regarding life within the ice. Progress needs to be made on fully understanding the interworking of brine channels, before scientist delve into the mechanisms which allow organisms to withstand such extreme conditions. Currently there is some debate about species distribution, composition, and diversity of the organisms in both the Arctic and Antarctic. Scientist also question the influence of pack ice vs. fast ice on these organisms. While it is established that the ice textures are both similar pack ice is believed to contain more benthic origin species. In addition, the life cycles of species are still poorly understood (Marquardt et al. 2011) and many of the mechanisms to tolerate the salinity and temperature extremes is still largely unknown. Some scientists believe that polar organisms share some of the mechanisms of intertidal regions; however, further research needs to be conducted (Thomas et al. 2001).

What scientist have learned about some of the extremophile species have implications for human use. The production of PUFA (polyunsaturated fatty acids) in some organisms can be used in aquaculture, human food, livestock and cold adaptive agents, which can be used in cleaning agents to food processing. Some of the most interesting research being conducted is in the field of astrobiology, where some scientists believe that polar organisms living within the ice can give insight into the possibility of finding life on other planets (Thomas et al. 2002). Brine channels and its inhabitants have become a interesting topic of study, full of new discoveries; however, it is not the only area of the polar regions still being explored.

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Subglacial Lakes

By, Briar Bragdon and Rebecca Hudak
Edited by, Emily Johnston and Hailey Pruitt

Introduction

In the previous chapter, we introduced the idea of living organisms in and under the ice. These organisms are extremophiles and can live in extremely harsh conditions. Life in the ice doesn't just stop there, recent discoveries have found life in subglacial lakes. What are subglacial lakes? Subglacial lakes are areas of freshwater that are found underneath ice sheets.

These glaciers have become a 'hot topic' because research could show what organisms might have lived on Earth millions of years ago and what life might look like in outer space. Some researchers hypothesize that this lake water may have been isolated for 15-25 million years (Studinger et al. 2004).

Glacial lakes were first hypothesized by Andrey Kapitsa in 1959 and 1964 during the Soviet Antarctic Expeditions and identified in 1970 by Robin and his crew through airborne radio echo sounding (RES) investigations of the ice-sheet interior (Siegert 2000). These lakes were then confirmed in the 1990s through radar and seismic mapping. Currently there are 400 known subglacial lakes with a total volume of water estimated between 4,000 - 12,000 km^3 in Antarctica with more being discovered (Siegert 2000). The three most studied lakes (Figure 1) are Lake Ellsworth, Lake Whillan, and Lake Vostok founded by Britain, American, and Russian researchers respectively.

These lakes are fed by water that melts from the base of the ice sheet at rates of a few millimeters per year caused by geothermal heat from deep within the Earth (Siegert 2000). Recent evidence points to the

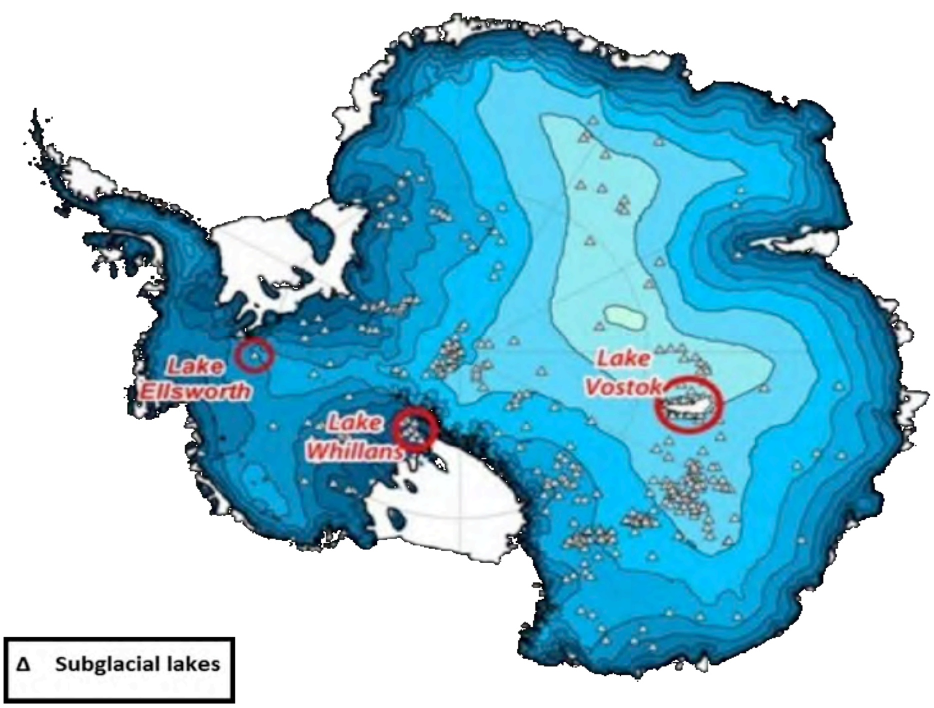

Figure 1. Map of discovered subglacial lakes in Antarctica. The three most studied: Lake Ellsworth, Lake Whillans, and Lake Vostok are highlighted. (Kaplan 2013)

development of channels in deformable sediment in W. Antarctica with significant water exchanges between till and ice. Most active lakes drain over a short time scale and respond rapidly to upstream variations (Figure 2). As you look at the model it is clear that there are confined small oceans underneath an embedded ice shelf (Pattyn et al 2015).

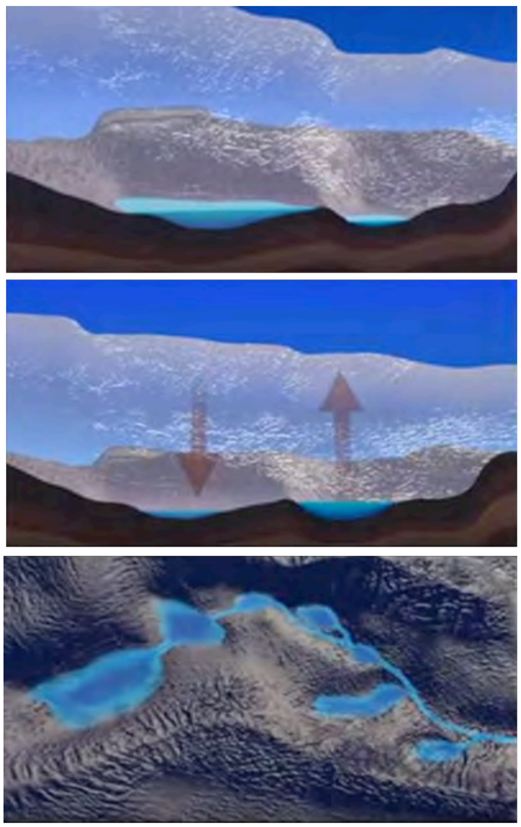

Figure 2. Subglacial lakes form underneath glaciers through the melting of glaciers above (A). As pressure from the ice is exerted on one lake, the water flows into the adjacent lake (B) resulting in an elevation change at the surface of both of the lakes that can be detected by NASA satellites. Evidence shows that these lakes and streams are interconnected (C). (Rwardry et al. 2009)

Since the discovery of these sub-glacial lakes, researchers have been trying to determine the safest and least intrusive way to drill into the lakes and take samples. In doing this they want to determine if any living organisms reside in these areas as well as how these lakes formed. The first to start drilling in the Antarctic were Russian researchers who initially started drilling to produce the world's deepest ice core, which was approximately 4,000 meters. This core contains the chemical record of more than 400,000 years of Earth's changing climate and atmosphere. In 1998, the drill reached within a hundred yards of the surface of the lake but was deliberately stopped because they did not want to contaminate the water. To prevent the hole from freezing, researchers added antifreeze liquid such as aviation fuel and freon into the boring hole, resulting in approximately 60 tons of toxic chemicals within reach of the 'pristine' Lake Vostok with no capability to remove these chemicals (Hotz 2001). As a result, the Russian team started drilling a new borehole to reach the Lake Vostok. They were able to breach Lake Vostok in February 2012, however, once the lake was breached water from the lake flooded into the contaminated borehole and compromised the samples. Since then, Russia has claimed that they have obtained 'pristine' water in January 2015 (Russia Today 2015). At about the same time, the British had started drilling into Lake Ellsworth with a hot water drill, free from any contaminates, but were unable to complete drilling due to insufficient water available to continue drilling towards the lake (Lake Ellsworth 2013). The first successful breach of a subglacial lake was conducted by an American research team on January 28th, 2013. They breached Lake Whillan using the same hot water drill that the British research team used in 2012 for their attempt.

The hot water drill was created through Whillan Ice Stream Subglacial Access Research Drilling (WISSARD). The project's aim is to study ice sheet stability and subglacial geobiology in West Antarctica, but also to gain access to subglacial environments and to deploy

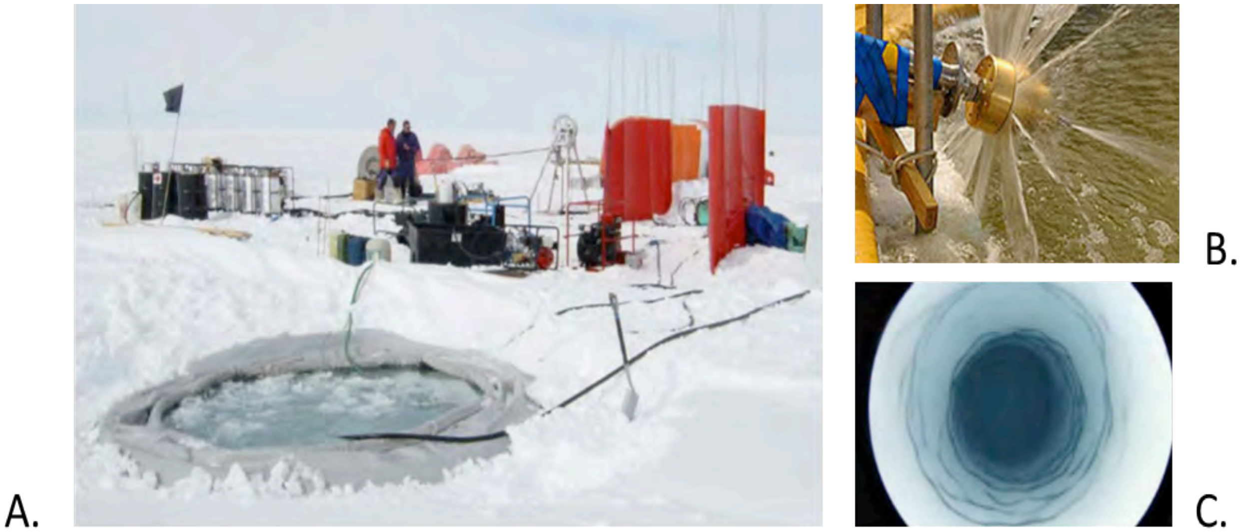

Figure 3. (A) The American research team set up camp over Lake Whillan with all of their equipment. (B) They use a hot water drill to bore into the ice without fear of contaminating their samples. (C) This drill creates a borehole that has curves and crevices due to the turbulence of the hot water drill. (Watts 2010, Oskin 2013, Planet Earth Online 2012)

scientific instruments through the borehole (WISSARD 2013). WISSARD is a conglomeration of 13 principal investigators, 8 different US Institutions, and additional US and International collaborators. The hot water drill melts the surrounding ice and recirculates the water simultaneously decontaminating the water (WISSARD 2013). The hot water drill was used in both Lake Ellsworth and Lake Whillan projects and could drill through ice up to 1000m thick (Rack 2015). Figure 3 shows the operations of Lake Whillan drilling and a borehole created by the hot water drill.

Lake Vostok

In 1996, Lake Vostok was the first subglacial lake to be discovered (Bell et al. 2007). This lake is not only the largest subglacial lake ever discovered but is also one of the largest lakes on Earth. It is 230km (143 miles) long, 50km (31 miles) wide, and 800m (2625 feet) deep. It is comparable to the size of Lake Ontario in Canada. This lake is found approximately 3.7km (2.2 miles) below the Antarctic ice sheet. Despite the average temperature in this lake being approximately -3°C (27°F), it is able to remain in its liquid form as a result of the heavy weight of the ice above exerting strong pressure on the water making it difficult for water molecules to form ice crystals. Lake Vostok has a very unique structure. There are two basins, one larger basin that is the biggest portion of the lake, and next to it, a significantly smaller basin. These two basins are separated by a ridge within the lake; this ridge is most likely a hydrothermal vent within the lake (Figure 4). It is hypothesized that the ecosystem around this hydrothermal vent could be similar to that of black smokers in the deep sea (Oskin 2015).

Russia has been trying to reach the lake for many years in order to determine if there is any life forms within the lake. As mentioned before, Russia has drilled alarmingly close and has finally breached the subglacial lake. Unfortunately, there is much debate on whether samples taken were contaminated or not by the antifreezing

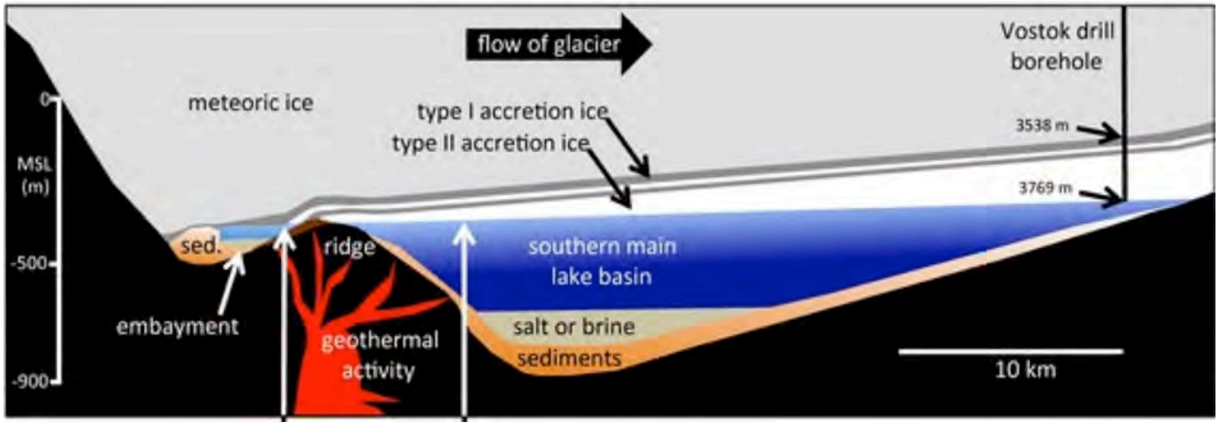

Figure 4. A diagram of what Lake Vostok might look like: two basins split by a ridge, different stratification of the water (Oskin 2015).

chemicals. Another study looked at Type II accretion ice, water from the subglacial lake that has been most recently frozen, and ran tests on it to determine if there were any forms of life being trapped in the ice as it was freezing off of the lake. They found that there were 3,507 unique gene sequences found in about 500ml of filtered accretion ice meltwater from the lake. Of the genes sequenced, 94% were classified as bacteria and 6% were determined to be from Eukarya kingdom. Of the bacterium discovered, some are only found within the gut of fish, mollusks, and other larger aquatic animals. For this reason, some scientists hypothesize that there might be fish swimming in Lake Vostok, but others believe that the discovered bacteria must have come from a contaminated source. (Shtarkman et al 2013).

Lake Whillan

Another well-known subglacial lake found in Antarctica is Lake Whillan. Lake Whillan lies beneath approximately 800m of ice in western Antarctica in contrast to 3.7km (Lake Vostok) and 3.4km (Lake Ellsworth). This lake is quite shallow and is believed to be less than a few decades old (Oskin 2013). As the water level fluctuates, the lake water height shifts up and down the overlying ice. There is documentation that water has filled and drained the basin twice since 2006, but there is no evidence of lake level fluctuation before 2004, supporting the hypothesis that the subglacial lake is relatively new (Oskin 2013). Water samples were successfully taken when American researchers breached the lake in 2013. Data from these samples show a water temperature of -0.5°C and some evidence of bacteria. Researchers have found nearly 4,000 species of bacteria and archaea found in Lake Whillans, with 130,000 cells in each milliliter of lake water - a density of microbial life similar to that in much of the world's deep oceans (Oskin 2013). Methane bubbles were seen at a density of 7.7 lbs/day. Samples were taken and are being analyzed to see if the methane is newly produced, such as by bacteria, or if it is a relic gas from ancient sediments. As researchers drilled further down they discovered that the sediment samples grow increasingly more salty (Oskin 2013). The project stopped abruptly due to the closure of the American government in 2013, forcing the National Science Foundation (NSF) to stop funding the research. Until more funding can be secured, there will be no more drilling into Lake Whillans, but plenty of research is being conducted with samples that have already been taken.

Samples collected show evidence of fluoride, which is proof of hydrothermal vents in the lake and the possibility of other organisms that specifically live around these vents. These organisms seem to be providing iron to subglacial waters that eventually reach the ocean (Death et al. 2014). Iron is a limiting factor in polar regions and this evidence could be the explanation as to how Antarctic organisms receive enough iron to perform essential functions.

One of the key questions being asked right now is: Are these organisms survivors or arrivers? Are these organisms descendants of microbes over the past 20 million years? Or are they microbes deposited on ice that have worked their way down to the water as the ice melted, froze, and remelted? Another source for these microbes could be sea water seeping under the ice sheet. Current research is in the process of answering these very questions. More data needs to be collected from other subglacial lakes, particularly Lake Vostok a much older lake than Lake Whillan.

Greenland

Antarctica gets most of the fame when it comes to subglacial lakes, such as lake Whillan and lake Vostok mentioned above, but there are other places where subglacial lakes are found. Recently subglacial lakes have been discovered underneath the Greenland ice sheet. These subglacial lakes are very intriguing because scientists are not sure where the water in these subglacial lakes originated. We know that subglacial lakes form in Antarctica due to a combination of the pressure from the ice sheet and a slight warming from geothermal activity which allows the water to remain in liquid form even at below freezing temperatures. After doing some calculations, the combined pressure of the ice and warming from the Earth, the water would not be able to stay in it's liquid state. This supports the hypothesis that these lakes are new and have not been around for many years. During the summer, when the Greenland ice sheet melts, it was determined that water would pool at the edge of the ice sheet and flow under the ice, filling the empty lake basins underneath. This revelation is concerning when it comes to climate change because the ice is not only being melted at the surface due to the heat, but it is also melting below from the water flowing underneath the ice sheet. Another concern is that the water underneath the ice sheet creates a more lubricated surface for the ice sheet to move more quickly than previously hypothesized (Palmer et al 2015).

This environment is unique because these lakes have not seen light for thousands to millions of years and it is integral to understanding a wide variety of concepts. For example, these organisms may give us insight of what life on early earth looked like, and what type of adaptations they may have had. Also, these areas are very similar to that of areas under giant ice sheets on other planets. For this reason, there is a possibility that these planets and moons may have this type of life on them, thus an understanding of what life looks like in these lakes will give us further information of life on other planets. In reference to climate change, it is important to understand how these subglacial lake interact with the ice sheet above. For example, most climate change models have not taken into consideration the melting that occurs due to subglacial lakes underneath the ice sheet, thus they are inaccurate. There is currently more research of these subglacial lakes that should give us more insight on these extreme places on Earth.

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Life in Polar Areas

This section discusses the various biological and ecological components that are unique to polar regions. Specific examples are drawn for both arctic and Antarctic regions, comparing ecosystem diversity, as well as evolutionary and physiological differences.

Polar Habitats and Ecosystems

Author: Katie Kennedy
Edited by Halie Pruitt and Peter Swan

Between the two poles, there are numerous different ecosystems and habitats and even greater variation in the organisms that utilize them. Like any other marine ecosystem, organisms have adapted to living in all areas in the region including on shores and sea ice, pelagic and benthic ecosystems, on the continental shelves and even in the ice itself.

Arctic Land

When using the definition of the arctic boundary as the area north of the arctic tree line, there is solid land in the Arctic. This land is known as tundra, which comes from the Finnish word *tunturi*, meaning treeless plain. This relatively flat landscape is known for its layer of permanently frozen subsoil called permafrost, extremely low temperatures and dessert- like conditions (UCMP 2004). The average winter temperature is -34 degrees Celsius but the average summer temperature ranges from 3-12 degrees Celsius which provides enough energy and nutrients for the biome to sustain life. The growing season is short, generally 50-60 days. Although polar areas are extreme environments to live in, many species of plants and animals have adapted to thriving in the region's harsh conditions.

Approximately 1,700 different kinds of plants grow in the tundra areas (UCMP 2004). The plants that are found north of the Arctic tree line are grasses, mosses, lichens

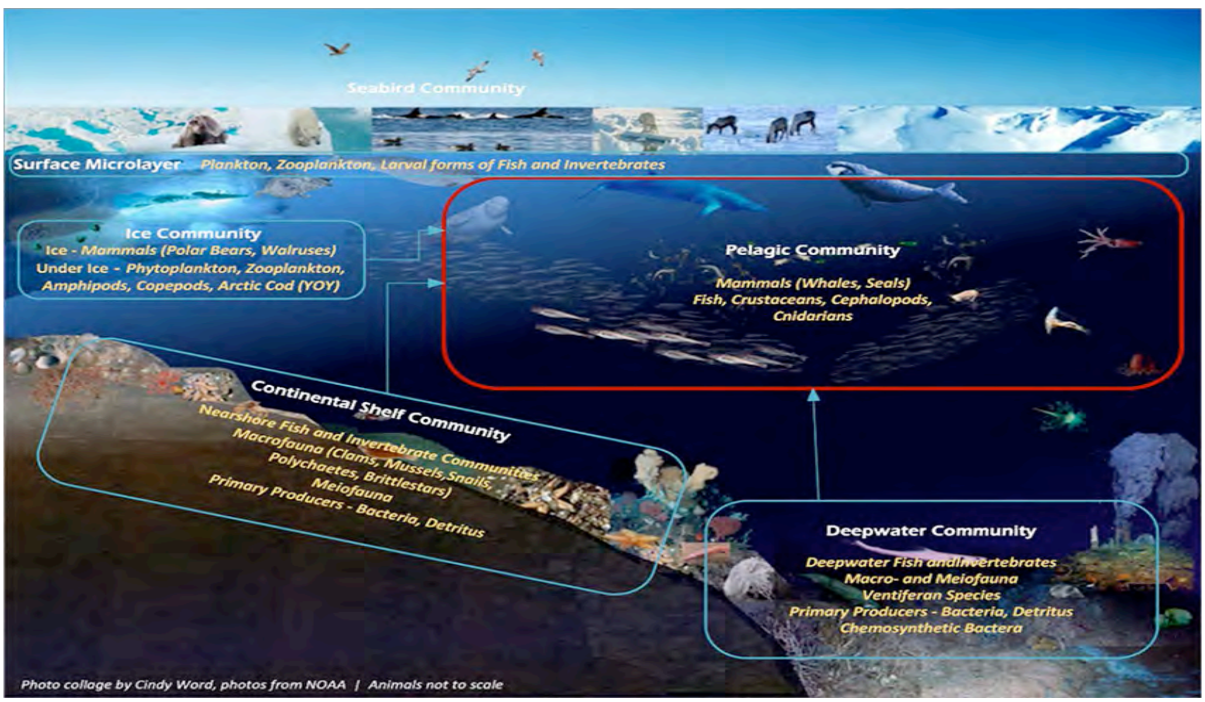

Figure 1: Like in other regions, organisms living at the poles take advantage of all types of habitats ranging from land to the very bottom of the ocean floor (Taken from: http://www.arctic.noaa.gov/gallery_arc2015.html).

(flowerless plants that grow on rocks and trees) and dwarf shrubs (low-growing woody plants) (Giannetta 2000). Arctic plants usually reproduce by budding and division rather than sexual reproduction, which is the more common method of their temperate region counterparts. Studies suggest, however, that sexual reproduction has been and will continue to be enhanced as warming in the Arctic increases (Klady 2010). Arctic species grow close together and are low to the ground to protect themselves from cold temperatures and strong winds. Other adaptations include darker coloration to absorb more of the sun's heat and wooly seed and stem coverings to insulate the plant. The majority of the ground is frozen throughout the year, allowing only plants with shallow roots to thrive in this environment.

Fig 2. A variety of low-lying plant species that inhabit the Arctic.(Norwegian Polar Institute 2008).

The Arctic is also the home to a diverse variety of terrestrial mega fauna. Herbivorous mammals such as lemmings, caribou, arctic hares and squirrels along with carnivorous mammals, migratory birds and insects can be found it the Arctic (UCMP 2004).

Polar bears and arctic wolves are two species that make unique habitats called maternity dens to protect their young from the harsh, polar conditions. The majority of wolf dens have been found near the tree line in the Northwest Canadian Territory. Scientists suggest that mothers choose this area because caribou are normally abundant around the tree-line for the majority of the denning season and will provide convenient prey. Habitat structure also appeared to be a determining factor of choosing a den; mothers prefer to den where roots of trees and shrubs provide structural support for their tunnels (Heard 1992).

Polar bears make their dens out of deep snowdrifts. Although the majority of the bear's life is spent on ice, mothers return to land to give birth to her cubs sever kilometers in from the coast. Polar bears are known for site fidelity, meaning that females return to the same area to den each year (Liston 2014). This may be interrupted by increased climate change if the sea ice melts before the mother returns to her previous denning site.

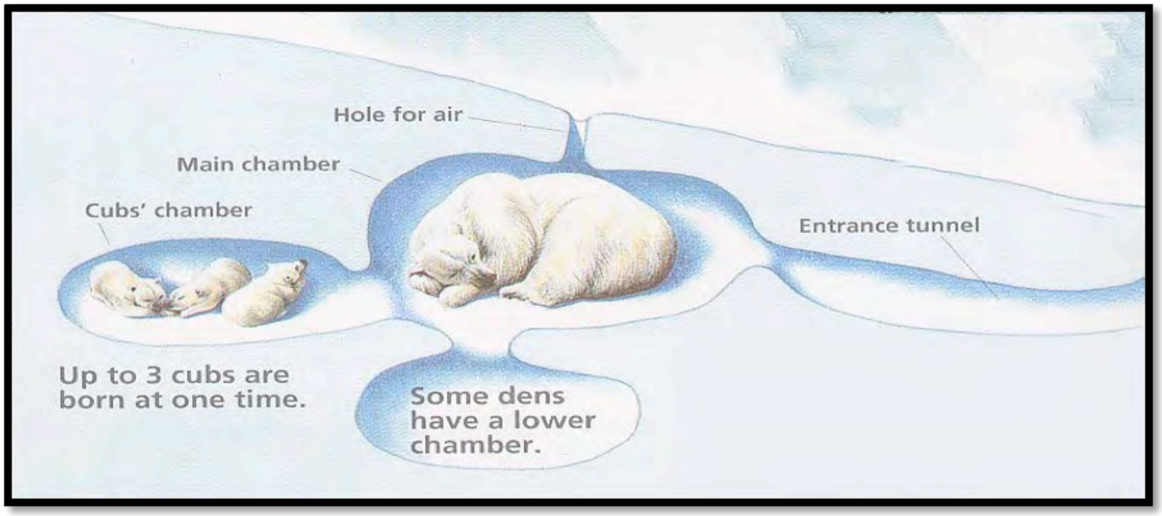

Fig. 3: The structure of a maternity den that a mother polar bear creates in arctic snow drifts (Selden 2008).

A study was done in 2008 to determine the sensitivity of marine mammals to climate change (Laidre 2008). Seven Arctic and four subarctic species, their habitat requirements, and evidence for biological and demographic response to climate change were studied and compared to an index of species sensitivity. Taking into account three main factors: (1) narrowness of distribution and specialization in feeding, (2) seasonal dependence on ice, and (3) reliance on sea ice as a structure for access to prey and predator avoidance. According to the index, the hooded seal, polar bear, and narwhal appear to be the most sensitive polar marine mammal species. The least sensitive were the ringed and bearded seal, primarily due to large distribution and population sizes and flexible habitat requirements. As the climate changes, many species at both the North and South poles are struggling; largely due to their reliance on some form of ice as a habitat or resource to find prey or avoid predators.

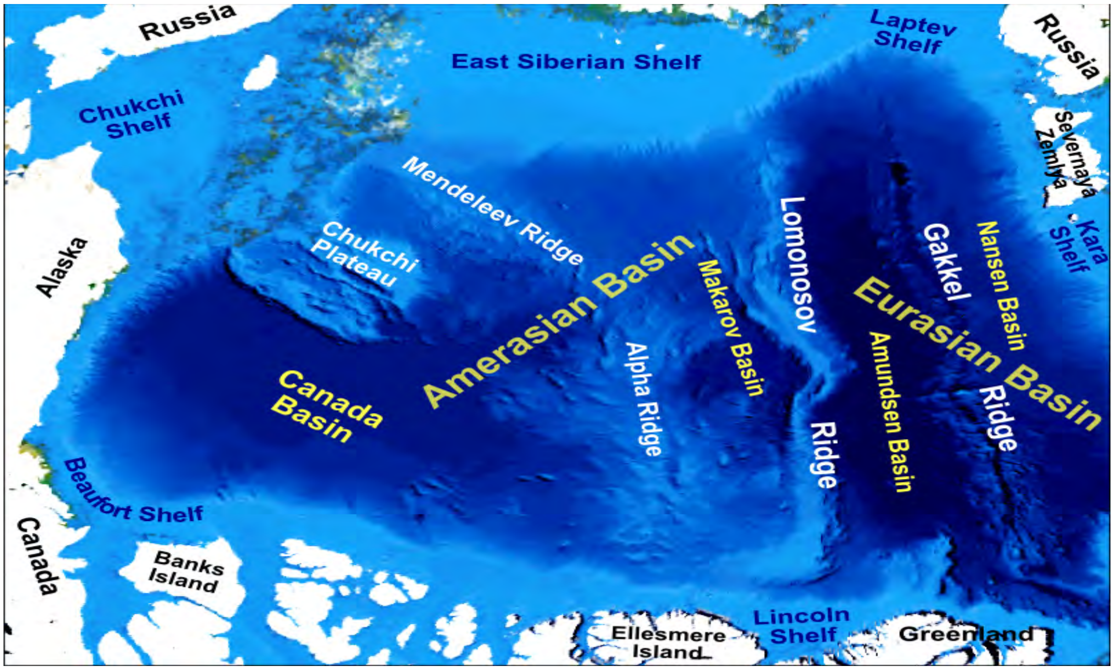

Figure 4: An image depicting large ridges and basins in the Arctic Ocean.

Arctic Ocean

The center of the Arctic Ocean is primarily deep basin, which is cut by several underwater ridges running parallel to each other. The highest is the Lomonosov ridge, which stretches from Greenland to Siberia. This mountain chain rises up to 10,000 feet above the seabed and divides the ocean floor into two main basins. The Eurasian or Nasin basin and the North American. The flattish floor of the basins- called abyssal plains range mostly from 10,000 to 12,000 feet from the surface.

The greatest inflow of water to the Arctic comes from the Atlantic Ocean through the Norwegian Current. The largest outflow is through the East Greenland Current. In the past, the majority of the Arctic water had year- round ice coverage. This has recently changed due to a warming climate (Green 2006).

For a long period, it was thought that organisms could not withstand the extreme temperatures of the deep sea in polar regions. Although benthic areas in the Arctic are still very difficult to study due to their harsh conditions, diverse benthic communities, that have adapted to subzero temperatures and dark spaces, have been found (Bluhm 2002). Some shelf areas with benthic life such as worms, bivalves and crustaceans have been more closely studied to determine the ecology of these deep sea creatures. The primary adaptation that these animals have in common is a low metabolic rate; this causes the organisms to work at slower speed but enables them to spend less energy. This reduction allows them to tolerate such a taxing environment. Recent research indicates that the diversity of species richness in deep Arctic waters may rival that of tropical coral reefs.

Glacial Habitats

At first glance, ice structures seem to simply be barren blocks of frozen water. When taking a closer look, however, scientists have found that there are thriving populations living within the ice in both the Arctic and Antarctic. Sea ice is critical to polar ecosystems in several ways: (1) it provides a habitat for photosynthetic microorganisms and nursing grounds for small invertebrates and fish; (2) as the ice melts in the warmer season, releasing organisms into the surface water, a shallow mixture forms which fosters large, ice-edge blooms that are important to the overall productivity of polar seas; and (3) ice acts as transportation between habitats for microorganisms (Krembs 2011).

Figure 5: Brittle stars have been found to dominate vast areas of the investigated Arctic sea floor (Bluhm, 2002).

When sea ice forms, small spaces between the ice crystals remain and are filled with a salty solution called brine. Sea ice consists of a mixture of ice crystals and brine channels, which form a three-dimensional network of tubes with diameters of a few micrometers to several cm. These ice-specific ecosystems are the home to bacteria, viruses, unicellular algae, diatom chains, worms and small crustaceans. Juvenile stages of zooplankton and meroplanktonic larvae of benthic organisms also enter brine channels to feed on the rich, ice-bottom community and hide from pelagic predators (Gradinger 2002).

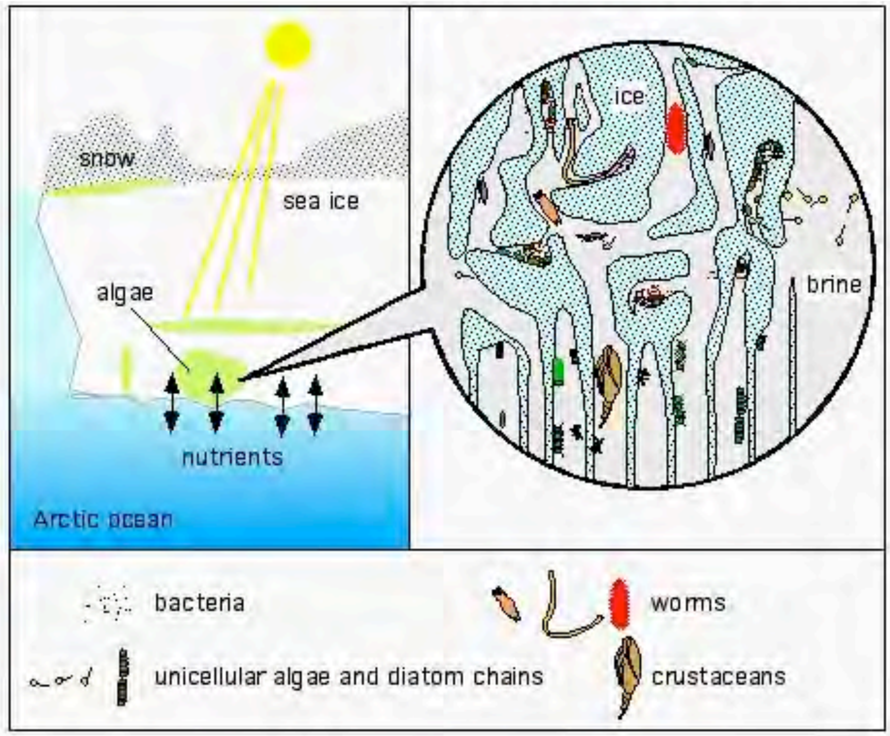

Figure 6: Brine channels are intricate structure formed by space between crystalizing ice crystals (Krembs 2011).

Unicellular algae is the main primary producer in this environment; several hundred species of unicellular algae have been discovered in this area. All organisms living in ice habitats must tolerate a wide range of environmental conditions and light intensity. As ice forms and melts, the salinity and temperature of the area can change at a rapid pace.

Antarctic

Antarctica is known to be the coldest, driest, and windiest continent on Earth. It lacks typical fluvial habitats such as rivers or estuaries and has very few intertidal mudflats. Birds and marine mammals are the primary groups that utilize the Antarctic continent.

Although penguins are the most commonly known bird residing in the


Figure 7: Communities of phytoplankton form diatom mats on the bottom of submerged icebergs. These are thought to be substantial feeding grounds for krill populations in polar regions. (Hogslund 2015)

Antarctic, there are many other species of birds such as prion, fulmar, petrels and Kerguelen blue that live in Antarctica (Ainley 1992). The different species of birds have unique habits where they nest during the breeding season. The Antarctic prion, for example, breeds on the Antarctic islands in the Southern Ocean where they nest on slopes under grass tussocks or rock crevices (Birdlife International 2016). Antarctic petrels nest on snow-free cliffs and rock faces primarily in coastal areas or on offshore islands. This species can be found along the entire Antarctic coastline. Penguins which generally have a more communal system of nesting, still maintain different habitats within the continent's coasts. King penguins form colonies on relatively fat beaches with no snow or ice but that have easy access to the sea. Chinstrap penguins, while also forming breeding colonies do so in ice-free areas of the rocky coasts.

Pinnipeds are a group of marine mammals that partially inhabit the Antarctic continent; the rest of the time is spent in the ocean. Fur seals, Southern Elephant seals, Leopard seals and Weddell seals are the four species that can be found on Antarctica and its surrounding islands (NOAA 2014). Each species has its own ecological niche so there is rarely interspecies competition. Several pinniped species use Antarctica's ice-free beaches to breed and give birth to young, while, others use different ice substrates. The increase in temperature has caused much concern for these animals, and others that need to breathe air, largely due to the amount of melting sea ice. Ice is an essential substrate for marine mammals; pinnipeds use ice as a platform for hauling out, whelping, molting, as well as for sub-ice foraging. Without ice, the basic lifestyle of these animals would be uprooted.

The Southern ocean

The southern ocean extends northward from the coasts of Antarctica to 60 degrees south. The depth is 4,000-5,000 meters in most areas; its lowest point is 7,235m deep at the end of the south Sandwich trench (Spilsbury 2015). The ocean floor contains a shallower continental shelf that has a depth ranging from 400-800m. This is the world's fourth largest body of water and varies in temperature from about 10 to -2 degrees Celsius. The ocean area from about latitude 40 south to the Antarctic Circle has the strongest average winds found anywhere on Earth; in winter the ocean freezes outward to 65 degrees south latitude in the Pacific sector and 55 degrees south latitude in the Atlantic

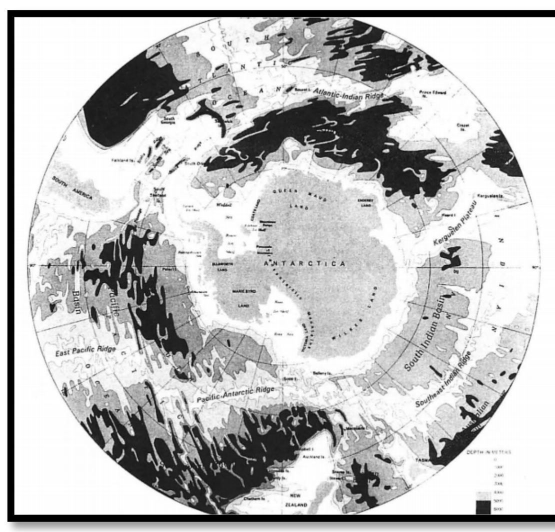

Figure 8: A map showing the major bathymetric contours around Antarctica. The depth scale is in eight shades of grey, and covers the range from 0-IOOO m (palest), 7·8,000 m (darkest). Note the extensive areas of deep water within the Southern Ocean (Young 2015).

sector. The extraordinary wind lowers surface temperatures well below 0 degrees Celsius. Cyclonic storms travel eastward around the continent due to the temperature contrast between ice and open ocean.

The Antarctic Circumpolar Current (ACC) is the world's largest ocean current, transporting 130 million cubic meters of water per second - 100 times the flow of all the world's rivers. The current is circumpolar due to the lack of land masses connecting with Antarctica and travels west to east around the continent. Associated with the ACC is the Antarctic Convergence, where the cold, Antarctic waters meet the warmer waters flowing in from connecting oceans. The convergence creates a zone of upwelling that nurtures high levels of phytoplankton and essentially sustains a much larger, diverse food chain of fish, whales, seals, and birds, which inhabit the Southern Ocean (Young 2015).

Antarctic Benthos

Similar to the Arctic, the depths of the Southern Ocean are difficult to study due to intense temperatures and ice coverage. Most of the Southern ocean overlies the abyssal plain; and the continental shelves are extremely deep.

In comparison to tropical and temperate regions, decapods, bivalves and teleost fishes are poorly represented in the southern ocean benthic community. Echinoderms and many suspension feeding groups, however, are rich and diverse. Over 4,100 benthic species have been recorded in the southern ocean. Within Antarctica, many species appear to have circumpolar distributions and established biogeographic divisions into continental Antarctica, Antarctic Peninsula and sub-Antarctic regions. This brings up many evolutionary questions about species living in the Southern Ocean that have yet to be answered (Clarke 2003).

It is clear that the poles possess very challenging living conditions for any organism. However, life exists and thrives in all polar ecosystems. The adaptations of polar animals to withstand these environments are nothing short of amazing.

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Biodiversity: Endangered and Invasive species in Polar Regions

By: Alexandria Makucewicz
Edited by: Rebecca Hudak and Briar Bragdon

Early scientific research, which proposed that as the latitude increase a decrease occurred regarding biodiversity. It was hypothesized that polar regions contained the lowest amount of species richness and diversity. Current research has disproved this theory, on the contrary polar regions contain some of the highest levels of diversity than temperate and tropical zones and average a higher diversity overall. While Arctic and Antarctic regions differ in the levels of respective species (terrestrial, aquatic, and marine) both include endemic species. These species have become a focus of scientists as research explores the rising negative effects of global climate change. Species in polar regions are becoming threatened and effects of invasive species brought by climate changes and increased tourism is a topic of discussion with increasing concern.

Antarctic Biodiversity

Antarctic is host to 8,806 known species from over 1,300 families. Currently all known taxa found in the Antarctic (occurring south of the polar front) are identified in the Register for the Marine Species database, otherwise known as RAMS (Griffiths 2010). Antarctic has been identified to have fifteen distinct ecoregions (regions of distinct geography, species assemblage, communities and environmental conditions), eight of which are along the Southern Ocean Islands (Chown et al. 2007). Species represented in the database are a culmination of organism from these varied ecosystems, including the seafloor, water column, and the sea ice. From these systems are meio-, macro-, megazoobenthos, micro and macro phytobenthos, phytoplankton, zooplankton, and nekton (Griffiths. 2010). The Antarctic is also known for its endemic species, which range from 50 to 97% (Chown et al. 2015). Endemic species are rare, described as being unique to a specific region. Many endemic species of the Antarctic are so rare they have only been spotted once or twice (Griffiths, 2010). Of these organisms: sponges, tubeworms, amphipods, mollusks, isopods, sea spiders, and notothenioid fish fall within this category (Chown et al. 2007).

Biodiversity is defined as the amount of variation between species within a given region, whereas species richness is the abundance of a particular species. The higher the diversity the more stable an ecosystem. The benthic and deep sea regions have an unexpectedly high diversity in Antarctic, having the highest diversity at present (Griffiths 2010 and Rogers 2007). In contrast, terrestrial areas have relatively lower diversity in regards to higher plant and animal life when compared to non-polar regions. The terrestrial flora system is mainly composed of mosses, liverworms, lichens and is home to only two flowering plants: the Antarctic hair grass (*Deschampsia antarctica*) and the Antarctic pearlwort (*Colobanthus quitensis*) (Rogers 2007). Terrestrial fauna is richer in diversity than terrestrial flora, however, this does not extend to all taxa (Griffiths 2010). Terrestrial fauna is largely dominated by nematodes, tardigrades, rotifers, and microarthropods (including springtails, mites, and insects) (Rogers. 2007). Substantial diversity is present amongst lichens, bryophytes, invertebrates, peracarid crustaceans, pycnogonids and microbiota

Taxonomic group	No. species[1]	State of knowledge	No. experts
Domain Archaea	0	1	1
Domain Bacteria (including Cyanobacteria)	0	1	2
Domain Eukarya			
Kingdom Chromista	256	1	1
Phaeophyta	0	1	
Kingdom Plantae			
Chlorophyta	24	4	1
Rhodophyta	70	4	1
Angiospermae	0	5	
Kingdom Protoctista (Protozoa)			
Dinomastigota (Dinoflagellata)	75	3	1
Foraminifera	179	5	2
Kingdom Animalia			
Porifera	267	4	1
Cnidaria	459	3	2
Platyhelminthes	125	5	1
Mollusca	740	3	6
Annelida	536	4	3
Crustacea	2,900	4	15
Bryozoa	316	3	1
Echinodermata	565	5	6
Urochordata (Tunicata)	114	2	1
Other invertebrates	586	3	
Vertebrata (Pisces)	314	4	6
Other vertebrates	284	3	6
SUB-TOTAL	7,810		
TOTAL REGIONAL DIVERSITY[2]	>8,200		

[1]From the Register of Antarctic Marine Species.
[2]Total regional diversity including all taxonomic groups as reported in the Register of Antarctic Marine Species.
State of Knowledge 5 = very well-known (>80% described, ID guides <20 years old, and current taxonomic expertise); 4 = well-known (>70% described, ID guides <50 years old, some taxonomic expertise), 3 = poorly known (<50% species described, ID guides old or incomplete, no present expertise within region), 2 = very poorly known (only few species recorded, no ID guides, no expertise), 1 = unknown (no species recorded, no ID guides, no expertise).
doi:10.1371/journal.pone.0011683.t001

Table 1. Taken from Griffiths (2010). Taxonomic deconstruction containing the Antarctic area study expertise with estimated populations of illustrated species per taxon.

(Chown et al. 2015 and Rogers 2007). Benthic invertebrates have a higher level of genetic differentiation when compared to pelagic species (Rogers. 2007). The highest overall diversity is observed in viruses, which live within the aquatic systems present in the ice (Chown et al. 2007). Species with the highest richness in Antarctic are bryozoans, sponges, amphipods (Griffiths. 2010), pycnogonids, and most hexacorals (Chown et al. 2015). Gastropods, isopods, and bivalve mollusks have a lower than average species richness when compared to shelf life in temperate and tropical regions. Fish and decapod crustaceans are absent in species richness (Griffiths. 2010).

Extensive research has been done on organisms inhabiting the Antarctic. Species that are best represented by scientific research and give an accurate representation of species presence included penguins, seals, albatrosses (*Chordate sp.*), mollusks, echinoderms, tardigrades, nematodes, springtails, and mites (Griffiths, 2010). Species that are underrepresented by research are fish (of the nematode phylum), ascidians, planktonic arthropods, barnacles, sponges, and sharks (Griffiths 2010 and Rogers 2007). Antarctic provides numerous challenges to researchers and proves difficult in conducting research. Intertidal areas, underneath floating ice shelves, and the deep sea are especially difficult areas to accomplish research and are still largely unsampled. Because of the hindrances that Antarctica possesses, benthic and pelagic areas demonstrate high degrees of patchiness, regardless of the widespread research (Griffiths, 2010). Additionally these issues extend to other regions, where species become underrepresented, their abundance becomes questionable and other species remain undiscovered. Scientists predicted that 17,000 species may exist on the shelf alone (Griffiths. 2010).

Technological advances are making these issues easier, with this advancement has come molecular genetics. Molecular genetics are establishing previously morphemically similar species to be genetically distinct, defined as a cryptic species (Griffiths, 2010). There are a higher proportion of cryptic species in the polar regions. The Antarctic region is home to a multitude of cryptic species given level of reproductive isolation between species. Evidence of this cryptic speciation is represented by isopods, echinoderms and sea slugs. Additionally, some invertebrate groups, such as echinoids and amphipods, have been thought to hold a degree of cryptic speciation (Chown et al. 2015).

Arctic Biodiversity

Similarly to the Antarctic the Arctic is comprised of a higher level of diversity than temperate and tropical regions. The Arctic has approximately 5,900 flora species, of which .7% are flowering plants (angiosperms), 1.6% are cone-bearing (gymnosperms), 4% are bryophytes, and 11% are lichens (Callaghan et al. 2004). The Arctic, while having lower terrestrial flora diversity, in comparison to temperate and tropical region, has a much higher diversity than Antarctica. Of the Arctic flora species more than twice the amount is composed of cryptograms, which include mosses, liverworts, lichens, and algae, than there are vascular plants. About 40% of vascular plants, boreal species, exist primarily along large rivers based on the treeline of the sub-arctic border. While diversity is lower, individual communities have a similar to higher diversity amongst themselves like communities in other regions (Callaghan et al. 2004).

Arctic fauna is 2% of the world's total biodiversity and is twice as diverse as the flora beyond the tree-line. Primitive groups, such as the springtails make up 6% of the world's total. There are 315 known vertebrate species, of which 75 are mammals, 2 are reptiles and 5 are amphibians, portrayed in Table 1 (Callaghan et al. 2004). Large, vagile marine mammals like the walrus, beluga whale, and harbor seals show distinct subgroups, whereas the narwhal demonstrated extremely low genetic diversity (Weider and Hobæk 2000). Insects, however, make up the most diverse group of organisms within the Arctic. In reference to the 240 bird species listed almost 450 species bred in the Arctic region, not all of which are defined as permanent residents (Callaghan et al. 2004). Without a clear definition of what should be considered an Arctic resident and the difficulty in studying migratory birds it is impossible to estimate the number of species present. Other organisms, like microbes, are under-represented in their numbers. Current research suggests that microbes, including prokaryotes, have the highest diversity in the Arctic region. In contrast Fungi, and in particular, yeast, have an extremely low species diversity when compared to other regions and are relatively rare. The aquatic fungi *Chytridiales* and *Saprolegniales* have higher diversity but are not endemic and are believed to reflect annual migration patterns. Yet, common fungi like *Aspergillus* and higher level fungi, such as *Basidiomycets*, have a much lower diversity. In comparison subarctic and temperate regions have almost 10 times the number of species differentiation. Sharing this low diversity is also tundra algae, which show reduced diversity from temperate regions (Callaghan et al. 2004).

The Arctic has a higher overall number of known species, totaling over 14,000. The known species of the Antarctic is approximated around 8,000. The number of animals present in the Arctic is greater,

Taxon								
Animals			Plants			Fungi		
Group	Number of species	% of world biota	Group	Number of species	% of world biota	Group	Number of species	% of world biota
Mammals	75	1.7	Angiosperms	1735	0.7	Fungi	2500	2.3
Birds	240	2.9	*Monocotyledons*	*399*	*0.6*			
Insects	3300	0.4	*Dycotyledons*	*1336*	*0.7*			
Diptera	*1600*	*0.9*	Gymnosperms	12	1.6			
Beetles	*450*	*0.1*	Pteridophytes	62	0.6			
Butterflies	*400*	*0.3*	Mosses	600	4.1			
Hymenoptera	*450*	*0.2*	Liverworts	250	2.5			
Others	*400*		Lichens	2000	11.0			
Springtails	400	6.0	Algae	1200	3.3			
Spiders	300	1.7						
Mites	700	1.9						
Other Groups*	600	—						
Total Estimate	6000	—		5859	3			

*Amphibians & reptiles (7 species), Centipedes (10 species), terrestrial Molluscs (3 species), Oligochaetes (earth worms and enchytraeids) (70 species), and Nematodes (~500 species).

Table 2. Arctic estimates of biodiversity based on species richness compared to world biota. Arctic defined as beyond latitudinal tree line. Taken from Callaghan et al. (2004).

listing about 6000, while the Antarctic has around 7,000. The same is true of plant life, where the total for the Arctic is around 5,800 and 90 for the Antarctic. Individual species may fluctuate, but overall the Arctic tends to have greater diversity over Antarctica. However, the Antarctic is less studied and much of the biodiversity still remains unknown. It is possible that as research continues more accurate and detailed comparisons can be made between Arctic and Antarctic territories.

Invasive Species

To classify as an invasive species an organism must become established within the region and be present through their entire lift cycle. There have been numerous reported sightings of both adult and larval species in the Antarctic region, but none have been in more than one stage of their life cycle (Griffiths 2010). Nearly 200 foreign species of fungi, terrestrial plants, invertebrates, and vertebrates have been colonizing the Antarctic and surrounding areas in recent decades (Ricciardi 2008). Some more notable invaders include macroalgae in the South Shetland Islands and in the Northern Antarctic Peninsula (Griffiths 2010). Additionally the Salmonella virus had been identified in some penguin species (Ricciardi 2008) and some subantarctic crab species have been found slowly migrating closer to Antarctic waters. Crabs are one of the leading indicator species for climate change (Dvoretsky et al. 2015).

There are roughly 60 invasive vascular plant species in the Arctic, in which 28-37 have been recognized as established in the region. The leading cause of terrestrial plant invasion has occurred through seed introduction through tourism (Tolvanen and Kangas, 2015). Also of concern, is the snow crab (*Chionoecetes opilio*) and the king crab (*Lopholithodes Mandtii*). These organisms are expected to drive competition as they continue to migrate north towards the Arctic and have shown to have drastic effects on commercial fishing. Invasive species pose a threat in that they compete for natural resources, introduce diseases and can cause hybridization (Dvoretsky et al. 2015). Much of the research done in recent years has been less focused on which species are invading the Arctic and directed towards the causes and creating preventative measures. The warming of the Arctic region from global climate changed has made the Arctic more accessible to invasive species and threatens polar diversity. Invasions have become the second leading cause of species extinction (Tolvanen and Kangas 2015).

Endangerment and Conservation

Every region has the risk of organisms being placed on conservation lists and while all regions should be concerned with the detriment that extinction causes to an ecosystem, the threat to polar regions is increased because of the number of endemic and cryptic species. Several different classifications exist to identify the level of concern. The status of least concern is considered a population with the lowest risk. These species are generally abundant, diverse, and have stable populations. Near threatened is the increased likelihood that a species will become endangered. threatened or vulnerable indicates that a species population is no longer stable and has an even greater likelihood of become endangered. Endangered organisms are of increased concern and have the possibility of becoming extinct. Critically endangered is the highest risk a species can ascertain before becoming extinct. It is likely that most organisms that reach this level will eventually become extinct (IUCN. Updated 2015).

Currently listed on conservation organizations, such as the International Union for the Conservation of Nature Red List, 44 Antarctic species have a conservation status. These range from least concern to critically endangered. Mammals have 15 species on the list, birds have 25, and crustaceans have 4 (not listed in Table 3). Only two species are listed as endangered, they are the Black-browed albatross (*Thalassarche melanophrys*) and the Blue whale (*Balaenoptera musculus*). Currently there are no recorded extinctions in Antarctica; however, considering scientific research is still attempting to discover species our knowledge on this subject is limited. Many conservation efforts exist to aid these species, but conservation has also begun to target additional species not listed with concern. Species such as Krill (*Euphausia superba*), Antarctic toothfish (*Dissostichus mawsoni*) Patagonian toothfish (*D. eleginoides*), and mackerel icefish (*Champsocephalus gunnari*) are beginning to be more closely monitored (Griffiths, 2010). These organisms are an integral part of commercial fisheries and growing apprehension surrounds these creatures. Furthermore, there are 67 specially protected areas in the Antarctic, including 7 Antarctic Specially Managed Areas. Between the United States and Canada approximately 60 species found in the Arctic are listed between least concern to critically endangered, see Table 4. Databases that collect and report on Arctic endangered wildlife include the World Wildlife Fund (WWF), the International Union for Conservation of Nature (IUCN), the Canadian Encyclopedia for endangered animals, and the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). It is important to note that even with scientific research, the increased conservation efforts and growing interest of the public there is still insufficient data available regarding numerous species. In addition to the difficultly of tracking various species, nations residing in the Arctic are largely independent when it comes to their respective Arctic territories. This makes it increasingly difficult to gather accurate information and develop a solution to the growing endangerment issues. Fewer species actually make it to the critically endangered list, fewer than those listed in the Antarctic, there are a greater number listed in the Antarctic as threatened and are

Common Name	Scientific Name	Status	Population est.	Pop. trend
Southern Right **Whale**	Eubalaena australis	Vulnerable	7.500-8,000	Increasing
Sei **Whale**	Balaenoptera borealis	Endangered	30,000	?
Blue **Whale**	Balaenoptera musculus	Endangered	10,000-25,000	Increasing
Fin **Whale**	Balaenoptera physalus	Endangered	80,000	?
Humpback **Whale**	Megaptera novaeangliae	Least concern	30,000-40,000	Increasing
Magellanic **Penguin**	Spheniscus magellanicus	Near threatened	1.3 million pairs	Decreasing
Emperor **Penguin**	Aptenodytes forsteri	Near threatened	595,000	Stable
King **Penguin**	Aptenodytes patagonicus	Least concern	2 million pairs	Increasing
Rockhopper **Penguin**	Eudyptes chrysocome	Vulnerable	1.23 million pairs	Decreasing
Macaroni **Penguin**	Eudyptes chrysolophus	Vulnerable	6.3 million pairs	Decreasing
Adelie **Penguin**	Pygoscelis adeliae	Near threatened	2.37 million pairs	Increasing
Chinstrap **Penguin**	Pygoscelis antarcticus	Least concern	8 million	Increasing
Gentoo **Penguin**	Pygoscelis papua	Near threatened	387,000 pairs	Decreasing
Amsterdam **Albatross**	Diomedea amsterdamensis	Critically endangered	170	Decreasing
Antipodean **Albatross**	Diomedea antipodensis	Vulnerable	44,500	Decreasing
Tristan **Albatross**	Diomedea dabbenena	Critically endangered	7,100	Decreasing
Southern Royal **Albatross**	Diomedea epomophora	Vulnerable	27,200	Stable
Wandering **Albatross**	Diomedea exulans	Vulnerable	20,100	Decreasing
Northern Royal **Albatross**	Diomedea sanfordi	Endangered	25,000	Decreasing
Sooty **Albatross**	Phoebetria fusca	Endangered	30,000	Decreasing
Buller's **Albatross**	Thalassarche bulleri	Near threatened	64,000	Stable
Indian Yellow-nosed **Albatross**	Thalassarche carteri	Endangered	160,000	Decreasing
Shy **Albatross**	Thalassarche cauta	Near threatened	60,000-70,000	?
Grey-headed **Albatross**	Thalassarche chrysostoma	Endangered	250,000	Decreasing
Chatham **Albatross**	Thalassarche eremita	Vulnerable	16,000	Increasing
Campbell **Albatross**	Thalassarche impavida	Vulnerable	24,600	Increasing
Salvin's **Albatross**	Thalassarche salvini	Vulnerable	90,000	?
White-capped **Albatross**	Thalassarche steadi	Near threatened	200,000	Decreasing
White-bellied **Storm Petrel**	Fregetta grallaria grallaria	Least concern	300,000	Decreasing
Antarctic **Tern**	Sterna vittata	Least concern	140,000	?
Subantarctic **Fur Seal**	Arctocephalus tropicalis	Least concern	310,000	Increasing
Imperial **Shag**	Phalacrocorax atriceps	Least concern	?	?
Southern **Elephant Seal**	Mirounga leonina	Least concern	650,000	?
Blue **Petrel**	Halobaena caerulea	Least concern	3,000,000	Stable
Southern **Giant Petrel**	Macronectes giganteus	Least concern	150,000	Increasing
Northern **Giant Petrel**	Macronectes halli	Least concern	17,000-21,000	Increasing
Soft-plumaged **Petrel**	Pterodroma mollis	Least concern	5,000,000	Stable
Kermadec **Petrel**	Pterodroma neglecta	Least concern	150,000-200,000	Decreasing
Abbott's **Booby**	Papasula abbotti	Endangered	9,000	Decreasing

Table 3. List of endangered species, with respective conservations statuses and population trends. Taken from WWF Antarctic conservation list.

trending towards greater concern. Conservation efforts become further exacerbated because the Arctic is especially susceptible due to slow vegetation re-growth (Tolvanen and Kangas, 2015). It is important to note conservation status of species are always changing, and that the species in the tables provided may change at any time as more information is collected and the public is updated. More research needs to be conducted on a larger scale and a more diverse variety of organisms examined, to include those beyond bird, mammals, and terrestrial plants.

It is clear that more research is necessary regarding polar region biodiversity and that as more species are uncovered scientists will have a better understanding of polar environments. Our comprehension of the Arctic and Antarctic is crucial to worldwide topics, such as global warming, conservation and the possible tie of extremophiles to life on other planets. Although there is still far to go it may be most helpful to look to the past and discover some of the creatures that came before us and the environments which they inhabited.

Common name	**Scientific Name**	**Conservation Status**
Beluga Whale	*Delphinapterus leucas*	Near threatened
Bowhead Whale	*Balaena mysticetus*	Least concern
Blue Whale	*Balaenoptera musculus*	Endangered
Fin Whale	*Balaenoptera physalus*	Endangered
Sei Whale	*Balaenoptera borealis*	Endangered
North Atlantic Right Whale	*Eubalaena glacialis*	Endangered
Common Minke Whale	*Balaenoptera acutorostrata*	Least concern
Gray Whale	*Eschrichtius robustus*	Least concern
Narwhal	*Monodon monoceros*	Near threatened
Walrus	*Odobenus rosmarus*	Threatened
Harbor porpoise	*Phocoena phocoena*	Threatened
Greenland Shark	*Somniosus microcephalus*	Near Threatened
Sea Mink	*Neovison macrodon*	Extinct
Peary Caribou	*Rangifer tarandus*	Endangered (CA), Least concern (US)
Grizzly Bear	*Ursus arctos*	Least concern
Polar Bear	*Ursus maritimus*	Vulnerable
Wolverine	*Gulo gulo*	Least concern
Short-eared owl	*Asio flammeus*	Least concern
Harlequin Duck	*Histrionicus histrionicus*	Least concern
Tundra Peregrine Falcon	*Falco peregrinus*	Least concern
Anatum Peregrine Falcon	*Falco peregrinus*	Least concern
Eskimo Curlew	*Numenius borealis*	Critically endangered
Ivory Gull	*Pagophila eburnea*	Near threatened
Ross Gull	*Rhodostethia rosea*	Least concern
Great Auk	*Pinguinus impennis*	Extinct
Atlantic Cod	*Gadus morhua*	Vulnerable
Bering wolffish	*Anarhichas orientalis*	Vulnerable

Table 4. List of Arctic endangered species and respective conservation statuses. Reports compiled from IUCN and COSEWIC. Some discrepancy between species exists in reference to status. Continued on Table 5.

Common Name	**Species Name**	**Conservation Status**
Northern wolffish	*Anarhichas denticulatus*	Threatened
Blackline prickleback	*Acantholumpenus mackayi*	Vulnerable
Fourhorn sculpin	*Triglopsis quadricornis*	Least concern
Pacific Salmon	*Oncorhynchus nerka*	Least concern
Arctic tern	*Sterna paradisaea*	Least concern
Long-tailed Jaeger	*Stercorarius longicaudus*	Least concern
Parasitic Jaeger	*Stercorarius parasiticus*	Least concern
Arctic Jaeger	*Stercorarius parasiticus*	Least concern
Ruddy turnstone	*Arenaria interpres*	Least concern
Wood bison	*Bison bison athabascae*	Threatened
Barren ground caribou	*Rangifer tarandus groenlandicus*	Threatened
Woodland caribou	*Rangifer tarandus caribou*	Endangered
Arctic Skate	*Amblyraja hyperborea*	Least concern
Arctic dwarf birch	*Betula nana*	Least concern
Arctic reedgrass	*Calamagrostis coarctata*	Least concern
Gray wolf	*Canis lupus*	Least concern
Arctic crisco	*Coregonus autumnalis*	Least concern
Palearctic collard lemming	*Dicrostonyx torquatus*	Least concern
Arctic Loon	*Gavia arctica*	Least concern
Arctic Herring gull	*Larus smithsonianus*	Least concern
Rock Ptarmigan	*Lagopus muta*	Least Concern
Arctic hare	*Lepus arcticus*	Least concern
Mountain hare	*Lepus timidus*	Least concern
Arctic lamprey	*Lethenteron camtschaticum*	Least concern
Christmas flounder	*Liopsetta glacialis*	Least concern
Arctic warbler	*Phylloscopus borealis*	Least concern
Arctic-alpine Pea Clam	*Pisidium conventus*	Least concern
Arctic Alkali Grass	*Puccinellia arctica*	Least concern
Arctic char	*Salvelinus alpinus*	Least concern
Arctic shrew	*Sorex arcticus*	Least concern
Arctic ground squirrel	*Spermophilus parryii*	Least concern
Arctic graylings	*Thymallus arcticus*	Least concern
Arctic fox	*Vulpes lagopus*	Least concern

Table 5. Continued from Table 4. List of Arctic endangered species and respective conservation statuses. Reports compiled from IUCN and COSEWIC. Some discrepancy between species exist in reference to status.

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Extinct Species and Fossils

By Halie Pruitt and Emily Johnson
Edited by Ashley Breault and Jennifer Gamble

Antarctica

Antarctica has not always been the cold, dry, windy continent it is today. When Antarctica was part of the super continent Gondwana, it was fully vegetated with much of the plant and animal life found on the rest of the supercontinent. 400 million years ago, Gondwana began to move dramatically and the present day continent of Antarctica moved south towards the pole.

Around this time animal life on the continent began to evolve and the carbon dioxide levels in the atmosphere were estimated to be around 15 to 20 times higher than current levels. The oxygen levels began to increase and once the oxygen hit the stratosphere, it was converted to ozone. The ozone provided the protection from UV rays that were needed for life on earth to evolve. The plant life from the oceans then moved to the land, and the land animals evolved to feed on these plants (Australia Department of the Environment).

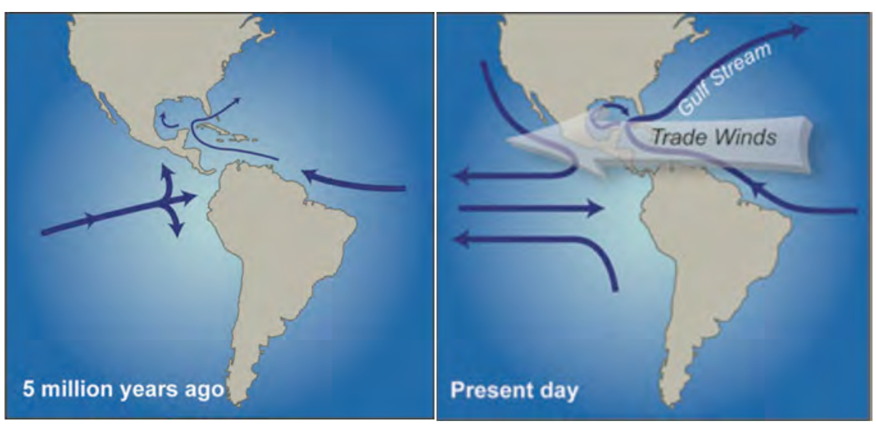


Fig 1. The closure of the Isthmus of Panama, which may have contributed to extinction events in Antarctica (Haug, 2004).

55 million years ago Antarctica became isolated from Australia, which it had been connected to in the supercontinent Gondwana. Many fossils found from before this time shows this connection due to similar fossils being found on both continents. 30 million years ago the Antarctic Circumpolar Current began to evolve and strengthen, creating the modern isolated environment that is Antarctica today. A major extinction event occurred only 2 to 3 years ago that may have been part of a global event, but also correlates with the closure of the Isthmus of Panama. The closure caused the flow of water from the Atlantic to the Pacific to stop, the Gulf Stream to form, and glaciation to occur (Haug, 2004).

Antarctic Fossil Record

Only 5% of the Antarctic landmass is exposed for fossils to be discovered, the rest being covered in ice. Nevertheless, many fossils have been found that show what life was like on Antarctica millions of years ago before major extinction events occurred. What has been found suggests the connection to Australia and a very different climate that could support the species which fossils were found of.

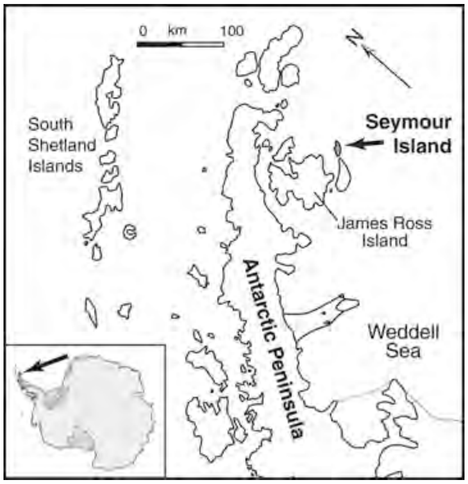


Fig 2. The Antarctic Peninsula, highlighting the location of the South Shetland Islands, Seymour Island, and James Ross Island (Ivany, 2008).

The U.S. scientist James Eights found the first Antarctic fossil on King George Island of the South Shetland Islands in 1829. The fossil fragment, a log with preserved growth rings, did not seem significant enough to Eights for him to collect it, but he referred to it in an 1833 report published by the New York Albany Institute on the natural history of the South Shetland Islands (Stillwell & Long, 2011). After this discovery, more than 60 years passed before the first collection of fossils from Antarctica were formally documented.

One of the most important sites for Antarctic fossil records is Seymour Island off of the Antarctic Peninsula. The island is a treasure trove of fossils, representing an array of different environments (Australia Department of the Environment). The island has been focused on during studies involving fossils from part of the much warmer Eocene period when the biota of the continent was much more diverse.

Another important site for fossil discovery in Antarctica is Marine Plain in the Vestfold Hills of East Antarctica, which holds a large diversity of fossils from 4.5-4.1 million years ago. Fossil dolphins and whales have been found in this area, some being almost complete skeletons (Australia Department of the Environment).

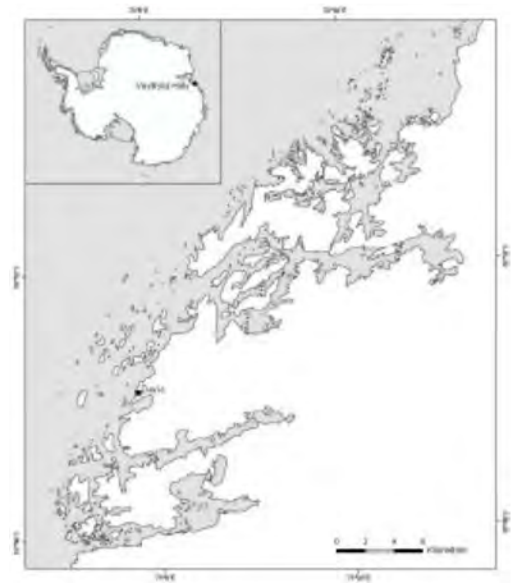


Fig 3. The Vestfold hills where Marine Plain is located (https://data.aad.gov.au/aadc/mapcat/list_view.cfm?page=3&list_id=14).

Flora

The vegetation cover of Antarctica lasted until at least 35 million years ago (Australia Department of the Environment). Studies have suggested that the flora across Gondwana was relatively uniform during the Early Cretaceous and some species were widely distributed, but there were also distinguishable differences between eastern and western Gondwana flora (Cantrill & Poole, 2012).

Devonian plants from around 400 million years ago have been well preserved in white sandstone. A macroscopic plant fossil of the stems of the psilophyte *Hostinella* that has been found from the Devonian age suggests that the Early Devonian flora of Antarctica was similar to other land plant communities throughout the supercontinent (Contrill & Poole, 2012).

Other lycopsids and psilophytes fossils have been found from this period as well.

The vegetation of the mid-Cretaceous period was initially dominated by ferns and evergreen and deciduous gymnosperms. There were Polar forests filled with evergreen conifer trees that were highly productive with trees exceeding heights of 40 m. Cool temperate rainforests comprised of bryophytes, lycophytes, ferns and conifers also occupied the region at this time (Riffenburg, 2007).

Large oval fossil leaves of the extinct tree, *Glossopteris*, are commonly found in Antarctica as well as South America. Some of the *Glossopteris* specimens found have dated back to 280-300 million years ago. These trees, extant during the Late Permian after the melting of the great Gondwana ice sheets, were adapted to living in the cool, wet climate of this period. After the extinction of these plants due to the warming of the climate into the Triassic period (around 245 million years ago), plants with thick, waxy leaves dominated the area. These plants were able to thrive in the new, dry conditions (Riffenburgh, 2007).

Fish

Fossil fishes in the Antarctic are known from Devonian, Jurassic, Cretaceous and early Tertiary deposits. The Devonian fish fauna all belong to families that are now extinct. The fish fauna includes agnathans, placoderms, acanthodians, chondrichthyans and osteichthyans. The only known fish fauna from the Jurassic period is a species of neopterygian from a now extinct family, Archaeomaenidae. Fossil fishes from the Cretaceous and Tertiary species found in the Antarctic are from families now extinct in the Antarctic, but found in other regions of the world (Eastman & Grande, 1989).

Reptiles and Dinosaurs

Many fossils and skeletons from marine reptiles and even dinosaurs have been found in Antarctic, further supporting the idea that the climate used to be much warmer and suitable for these species to thrive.

One of the first dinosaur remains found in Antarctica was the *Cryolophosaurus ellioti*, a 7-m long carnivorous theropod dinosaur that is unique to Antarctica who lived during the Early Jurassic period. This species was part of the group of the youngest vertebrate fauna found in Antarctica. Along with the remains of the *Cryolophosaurus*, two other scavenging theropods were found from the teeth marks on the *Cryolophosaurus*, most likely due to scavenging. The remains of an herbivorous prosauropod was also found with the remains and was most likely being fed on by the *Cryolophosaurus*. Findings of remains other small-to-medium sized species within the remains of the *Cryolophosaurus* suggest that it was the king carnivore at the top of the food chain (Stillwell & Long, 2011).

In the same region this theropod was discovered, the remains of a true sauropod (part of a group of long necked, long tailed herbivores) were also found (Riffenburgh, 2007). The group of dinosaur fossils found in this region represents the only known Jurassic dinosaurs from Antarctica (Stillwell & Long, 2011).

Vertebrate fossils from the Late Cretaceous period have been found on several islands off the Antarctic Peninsula including plesiosaurs (extinct marine reptiles with long necks) and mosasaurs (extinct marine reptiles similar to modern lizards) (Riffenburgh, 2007).

Fragments from a nodosaurid, belonging to a group of armored herbivores related to the ankylosaurs, have been found in Antarctica as well as a small hypsilophodontids, a small herbivorous ornithopod (Riffenburgh, 2007).

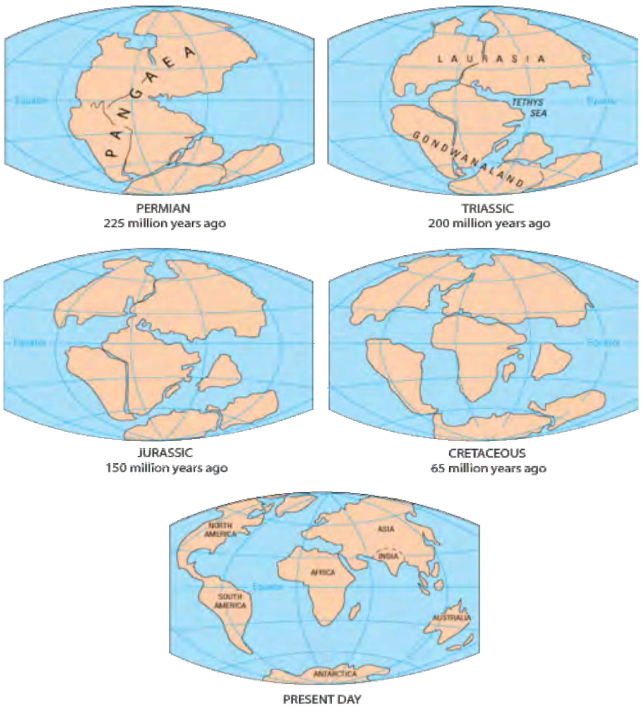


Figure 4: This image shows the spreading of the super continent, Pangea, into smaller supercontinents—eventually resulting in the earth present day http://i.livescience.com/images/i/000/047/334/original/Pangaea.jpg?1365037770

Arctic Prehistory

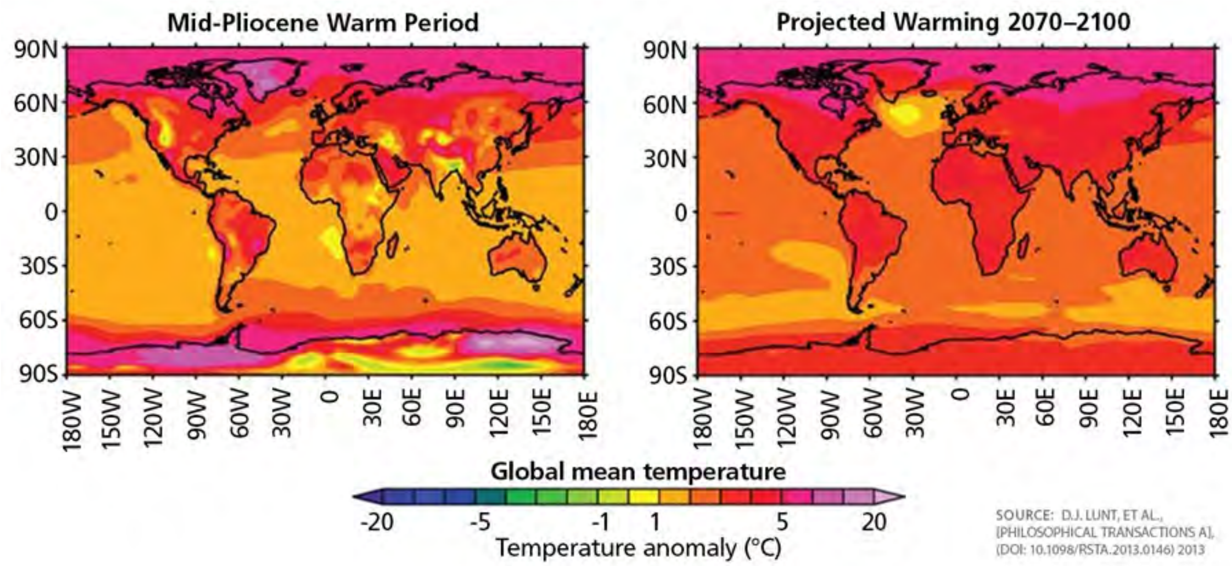
As we previously looked at the separation of the supercontinent Gondwanaland, we find that there has been less physical movement and separation of the northern continent, Laurasia. As indicated by figure 1, Laurasia simply stretched out and spread away from each other, without separating until after the Cretaceous period, where you can clearly see the formed land bridge that allowed passage of certain organisms across what is now Alaska and Russia (Kahlke 2015). We find that much of the organisms from the Cretaceous period are the same, or related, species-- just as fossil records show the existence of similar plants between Australia and the Antarctic. For this reason, and the "highly fragmentary and widely scattered" (Gangloff 1998) fossil record of the Jurassic period, this section will focus primarily on the Mid-late Cretaceous period into the Cenozoic period.

The present day Arctic has shifted northerly throughout millions of years, where previously 55 million years ago the Arctic temperatures rose to subtropical levels (23 C), 49 million years ago the Arctic was green, with fresh surface water and large amounts of fern covering the water, and Ice in the Arctic Ocean found about 45 million years ago, Lush forests on land.

Looking back, even, to 3.5 Mya, the mid Pliocene era was considered a warming period. The average temperature was 2-3 C higher than we experience today, as well as having the same concentrations of carbon dioxide in the atmosphere. The global temperature during the Pliocene actually rose 3 C, and is considered a good representation of what our future climate might look like. (Rybczynski 2012).

The increased temperatures allowed for a diversity of organisms in the arctic, much different than today's arctic population. Looking at Ellesmere Island, a Canadian island on the west coast of Greenland, today is covered with ankle-high tufts of cotton grass and mossy ground cover. 3.5 MYA, however, the land was covered by boreal forest grazed by mammals that would not be sustained by the modern day arctic climate. In studying this area, researchers found bone fragments from Gigantic High Arctic Camel, *Paracamelus* (Rybczynski 2012). Camels, llamas and alpacas, had evolved in North America before spreading to South America, Asia and eventually Africa. However, this fossil was found 745 miles farther north than other previously found relatives. Camels, and their relatives, thrive in the deserts of Africa and have specific adaptations for surviving there, and yet we have a species of camel found that experienced below freezing temperatures and 6 months of total darkness. Although scientists believe they may have found the first forest dwelling camel, the collagen fingerprints and fossils bear a striking resemblance to the modern day species of camels, indicating that these are not as distant relatives as originally perceived. Furthermore, the presence of these camel remains is evidence of this warmer climate in the arctic during the Pliocene era.

In a similar vein, the last place scientists expected to find the fossil of a tropical freshwater turtle was in the Arctic. The finding of this Asian turtle indicates that these animals migrated from Asia to North America not by circumventing Alaska, as originally thought, but straight across freshwater seas and physically floating in the dense and warm salty water of the Arctic Ocean. These turtles were able to successfully cross without extreme stress due to the frequent volcanic eruptions which created islands, allowing them to hop across the Bering Strait (Tarduno 2006). This research not only solved the passage of this turtle, and several other transatlantic animal crossings, but it also is evidence that a rapid influx of carbon dioxide from these volcanic sites some 90 million years ago was the likely cause of a super-greenhouse effect that created extraordinary heat in the polar region. There's evidence that this volcanic activity happened all around the planet — not just the Arctic. If it all happened on a short enough timescale, it could cause a

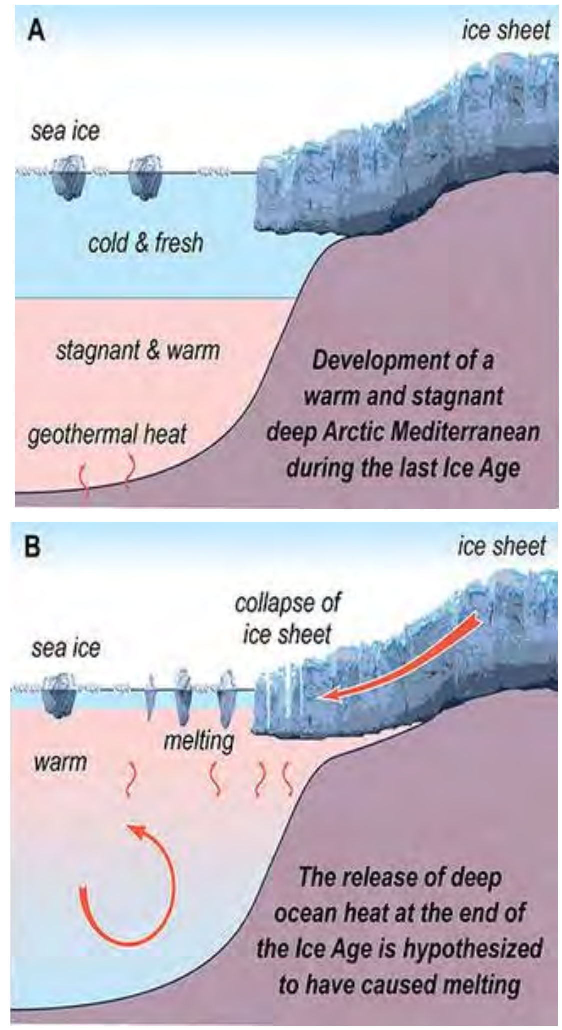


super-greenhouse effect. "It's a key question for the future, because we are headed for a Pliocene era."

While the presence of these mammals and tropical species indicates a warmer climate, the discovery of Ankylosaurs, Pachycephalosaurs, and *Ugrunaaluk kuukpikensis* in this northern climate indicates a biological phenomenon. Ugrunaaluk fossils were found in the riverbed of an Alaskan river, much higher than the paleo arctic circle. Although Arctic Alaska was covered in trees because Earth's climate was much warmer as a whole, because it was so far north, the species likely contended with months of winter darkness. Even if it wasn't as cold as a modern-day winter, these giant lizards are not meant to live in cold climates and Ugrunaaluk is one of the only dinosaurs found to withstand this climate. They lived in a climate which most likely experienced snow and must have had mammal like adaptations in order to survive the temperature change (Hirotsugu 2016)

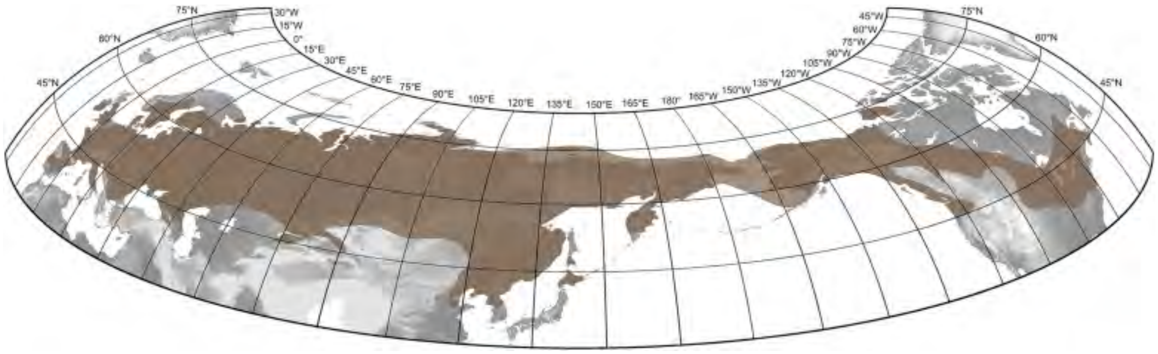
Today, the ocean is cooled by the atmosphere during winter, producing large volumes of dense water that sink and flush through the deep Arctic Mediterranean. However, in contrast to the vigorous circulation of today, the research found that during the last Ice Age, the deep Arctic Mediterranean became like a giant stagnant pond, with deep waters not being replenished for up to 10,000 years. This is thought to have been caused by the thick and extensive layer of sea ice and fresh water that covered much of the Arctic Mediterranean during the Ice Age, preventing the atmosphere from cooling and densifying the underlying ocean.

This study highlights the important impact that changes in ocean circulation can have on climate, due to the ocean's capacity to redistribute vast quantities of heat around the globe. For example, scientists are currently concerned that ongoing changes in ocean circulation may result in warmer



subsurface water that will cause enhanced melting and retreat of certain ice sheets in Greenland and Antarctica. "To help predict the role of the ocean in future climate change, it is useful to investigate how ocean circulation changed in the past and what the associated climate effects were" (Thornalley 2015)

Returning to mammals, two crucial discoveries were found in Russia; Young Wooly Mammoth was found preserved in Arctic soil for 42,000 years and Remains of Young Wooly Rhino preserved in Arctic ice for 10,000 years. Researchers began to look specifically at the geographic extension of Late Pleistocene Mammoths.



The figure above shows the full extent of the wooly mammoth distribution. This distribution is impacted by the configuration of inland glaciers, high mountain chains, semi-deserts and deserts, and marine shorelines at year-round open water surface, The exposure of continental shelf regions and the replacement of tundra-steppe by extended grasslands. Despite the limiting factors mentioned, woolly mammoths enjoyed an enormous geographic extension during the Late Pleistocene. When we look at the geographical distribution of a species as a measure of its success, Late Pleistocene *Mammoth* was one of the most successful large herbivores of the Holarctic Mammoth Fauna. Only the morphologically quite diverse *Bison priscus* group occupied a comparably large, and in many places identical, distribution area during the last glacial period (Kahlke 1999). The woolly mammoth rightly proved itself as a palaeoecological characteristic species and a worthy namesake for the most cold-adapted large mammal assemblages in Earth's history, the Mammoth Fauna.

Bridging out from the fossil record, the arctic has seen the death of species in recent history. The Little Ice Age may have reduced the population of the Great Auk by exposing more of their breeding islands to predation by Polar Bears, but massive exploitation for their down drastically reduced the population. By the mid-16th century, the nesting colonies along the European side of the Atlantic were nearly all eliminated by humans killing this bird for its down, which was used to make pillows. With its increasing rarity, specimens of the Great Auk and its eggs became collectible and highly prized by rich Europeans, and the loss of a large number of its eggs to collection contributed to the demise of the species.

If we look at the demise of this species, we can compare it to the future of the current species in the arctic. The following list shows the species in the arctic that are in threat of extinction:

- Arctic fox
- Polar bear
- Pacific walrus
- Four species of ice seal – ringed, bearded, harp and ribbon
- Four species of whale – grey, beluga, bowhead and narwhal
- Sea butterfly
- Three species of seabirds – Kittlitz’s murrelet, spectacled eider and ivory gull

These species are under threat due to anthropogenic effects in an exacerbated warming period that we are experiencing now. If there is not a change in the way that the world operates around climate change, soon these species, and countless others around the globe, will be lost along with the wooly mammoths and the dinosaurs.

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Evolution

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Editors: Sharlene Maynard, Erin Mohr

Evolution:

The concept of evolution is not new, but the study of it in a polar context has many similarities and differences to evolution across the globe. To begin with, we will discuss the major types of evolution, divergent, convergent, and parallel, and how they as similar and different to evolution in non-polar areas. Divergent evolution occurs when one parent species evolves into two independent species, and is the type that is most typically thought of when the word evolution is heard. An example of this would be one species of fish over time diverging to become two different types of fish. Convergent evolution occurs when two unrelated species develop the same characteristics to deal with similar environments. This can be seen in sharks and whales that have both independently developed countershading with white bellies that blend in with the sky when seen from

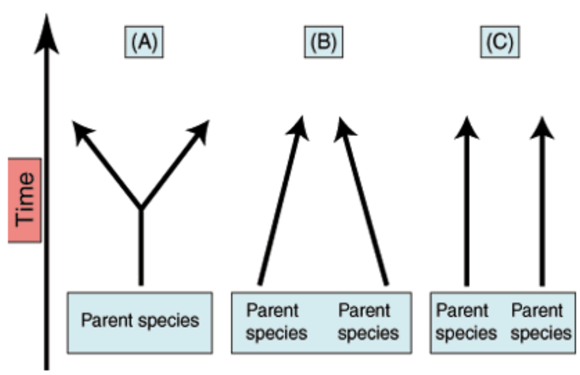

Figure 1: Types of evolution. A) Divergent, B) Convergent, C) Parallel (sparknotes.com)

below, and dark backs that blend in with the deep ocean when seen from above. Parallel evolution occurs when two unrelated species separately evolve in the same way in response to a changing environment. This would be seen in the leaves of trees. Very similar shapes evolved over time despite the animals not deriving from the same ancestor. This chapter will discuss all of these different types of evolution and how they manifest at the poles. Figure 1 is a visual representation of how these types of evolution occur.

Polar Endemism:

Another important concept we will discuss is polar endemism. Endemism refers to how many animals from a certain territory are only found in that location. For example, the polar bear is endemic to the Arctic because it is found nowhere else in the world, but the killer whale is not, because it has many different populations around the globe that are not limited to one location. Antarctica has many more endemic species than the Arctic, and this is closely tied to the age of the area. The Antarctic ecosystem has been geographically isolated by the Antarctic Circumpolar Current (ACC) for 22 million years, while the Arctic ecosystem has only existed for 0.7-2.0 million years. Additionally, the Arctic is not as strictly defined as the Antarctic, which has been mentioned before, and there are no clear boundaries separating the Arctic from the subarctic. Because the Arctic ecosystem has been around for a shorter time, and animals are less restricted from leaving, there has been more gene flow between the Arctic and the subarctic, and there has not been enough time for a significant portion of the animals in the Arctic to evolve so that they cannot live outside the Arctic. Conversely, the Antarctic has had lots of time for new species to evolve, and has been geographically isolated for a very long period of time, allowing many species to evolve so that they cannot withstand living outside of the Antarctic. In a study comparing endemism in the Arctic and

Antarctic among marine fish species, Antarctica had a high species endemism of 88%, while the Arctic had a low species endemism of only 20-25%. Additionally, 12% of the fish families in Antarctic are endemic, while 0% of the arctic families are endemic (Eastman 1999). This is important because it lends evidence to the idea that the Antarctic will have more endemic species than the Arctic.

Divergent Evolution:

Divergent evolution in Antarctica has largely been driven by the Antarctic Circumpolar Current (ACC), which is a difficult geographic barrier for species to traverse, and can cause speciation. An example of this is *Gigartina skottsbergi*, a type of red algae. This type of algae is found in South America as well as in Antarctica. Genetic analysis of members of this species on the Antarctic Peninsula and the tip of South America found no common alleles between the two locations, and a 31 base pair difference between the Antarctic allele and the dominant South American allele. The next largest difference in number of base pairs different is a 12 base pair indel. An indel is short for an insertion or deletion, which means that at some point an additional nucleic acid was added or deleted from the DNA strand, altering the coding sequence for the next twelve base pairs. The 31 base pair difference between Antarctica and South America does not have any indels, so having 31 base pair differences is significantly different from the population in South America. This could mean that this species has diverged to become two distinct species, which could only have been discovered through genetic analysis. The Antarctic Circumpolar Current was the barrier that allowed these species to diverge so drastically (Billard 2015).

Another great example of divergent evolution is the Antarctic Ice Fish. As Antarctica moved south and got colder, most temperate fish species did not survive. However, one species did, and underwent adaptive radiation, fathering over 100 species endemic to Antarctica. Adaptive radiation is a form of divergent evolution in which one species diverges many times in a short period, creating many distinct species. This was also driven by the Antarctic Circumpolar current, as well as the cooling temperatures. As the ACC developed, it limited flow between the temperate waters to the north, and the polar waters to the south. This allowed the Antarctic waters to become extremely cold, causing many species of fish to die. The only species that could keep up evolutionarily with the cooling temperatures (McClintock et.al. 2008) evolved several neat adaptations, including antifreeze proteins (Jia and Davies 2002) and a loss of hemoglobin (Verde et.al. 2008), which will both be discussed in future chapters. These fish were the only inhabitants south of the ACC, and northern fish could not cross the ACC to live in the cold polar waters, so the Antarctic ice fish diverged to inhabit many different niches, and 97% of them are endemic to Antarctica (Eastman 1999, McClintock et.al. 2008).

To contrast the high amount of speciation in the Antarctic, an example of divergent evolution in the Arctic is the polar bear. Polar bears are most closely related to brown bears and grizzlies, which eat primarily vegetation with the occasional animal. However, polar bears diet consists almost entirely of fatty seals and other animals. The genetic differences between these two animals are mostly concerned with fat processing, and polar bears are much better at transferring fat from the bloodstream into the body cells, which prevents arterial clogs (Pennisi 2014). Polar bears developed this feature and diverged from brown bears roughly 600,000 years ago.

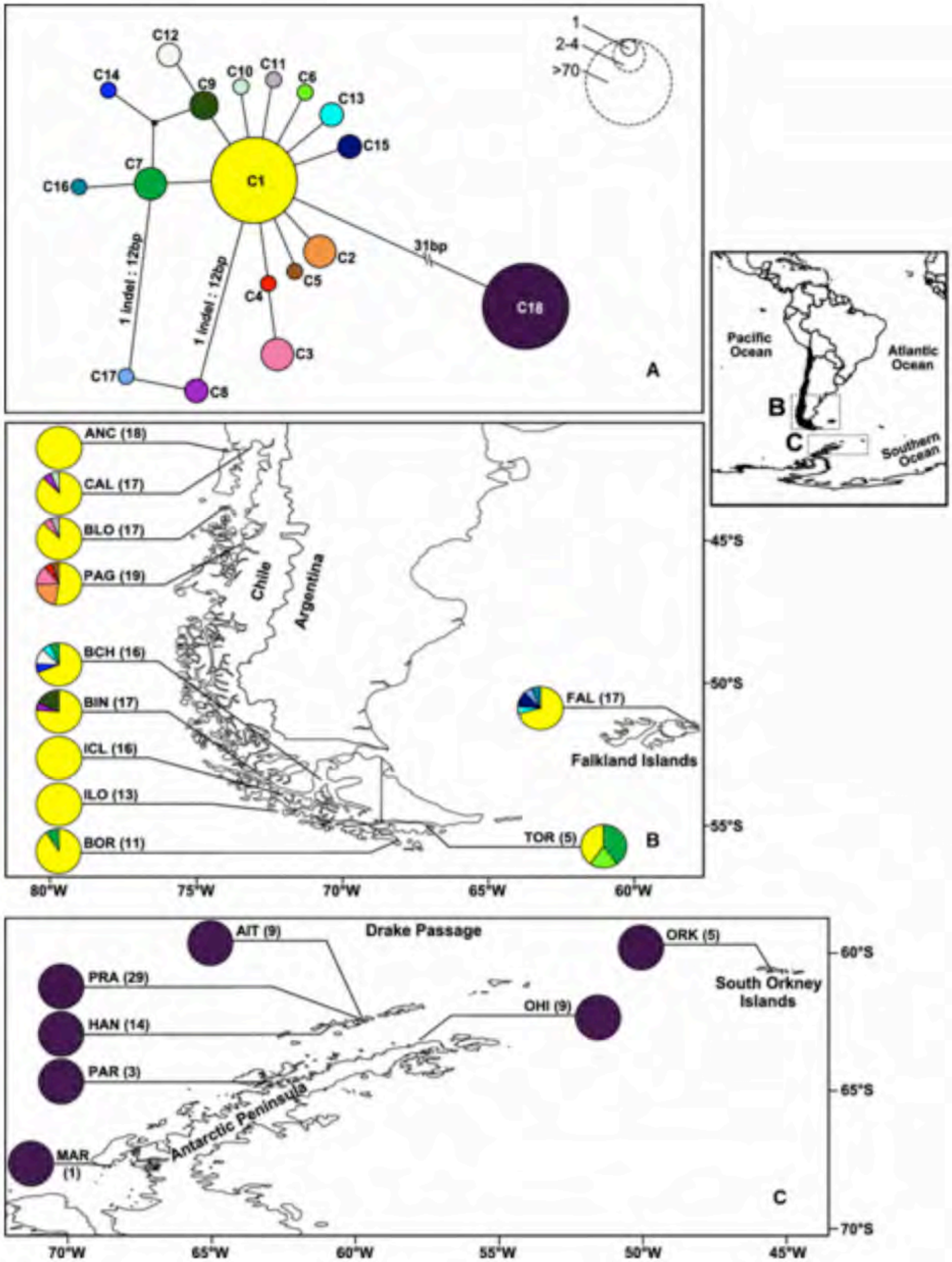

Figure 2: Alleles in the red algae *G. skottsbergi*. The top image shows the different alleles present in this species and how many base pair changes separate them. The bottom two pictures show the geographic distribution of these alleles, and what concentrations they were found in at each site (Billard 2015).

However, because the polar bear was not geographically isolated from the brown bear in lower latitudes, it could still mate with the brown bear, and a lot of hybridization occurred with the Irish Brown, an extinct lineage. During the last glacial period, around 45,000 years ago, brown bears moved towards the coast, where they found polar bears, and hybridized, causing their DNA to mix with the polar bears. Modern polar bears now have DNA from the extinct Irish brown bear, which can be visualized in figure 3. Today, climate change is causing the ice sheets that polar bears depend on to melt, and the polar bears are being forced inland. Because of this, they may encounter brown bears and hybridize again, which will have a negative impact on the conservation of the polar bear (Hailer et.al. 2012, Pennisi 2011).

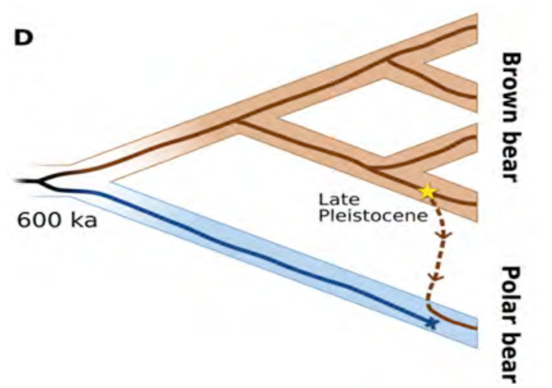

Figure 3: Polar bears diverged from brown bears 600,000 years ago and hybridized with Irish brown bears 45,000 years ago (Hailer et.al. 2012).

In the Arctic, there may be possibilities for a range distribution change with the changing climate, but in the Antarctic, the isolation due to the Antarctic Circumpolar Current may cause many species to die as they cannot escape the warming temperatures or adapt quickly enough.

Convergent Evolution:

Polar areas are a good place to study convergent evolution because they have similar environmental conditions, but are very geographically isolated. The Arctic and Antarctic are both very cold and dominated by ice, but are extremely far apart, with few animals travelling to both areas. The classic example of convergent evolution occurring across these two ecosystems is that of anti-freeze proteins. Anti-freeze proteins evolved to prevent ice crystals from forming in cells and lysing them, or cutting them open. What is clear about these molecules is that they evolved several different times in polar regions, in vastly different animals, and from different genetic sources. Animals in both the Antarctic and the Arctic evolved these to respond to the same external pressure: sub-zero temperatures (Jia and Davies 2002). Anti-freeze proteins will be discussed more thoroughly in the chapter “Anti-freeze proteins”.

Parallel Evolution:

Parallel evolution is very similar to Convergent evolution, but it occurs when two similar species evolve in the same way to respond to environmental pressures. An example of parallel evolution at the poles occurred when Antarctica moved south and lost all of the crabs and other durophagous predators, or predators that can crack shells. These animals could not tolerate the cold and became extinct in Antarctica. When looking at the fossil record of Antarctica, we can see the durophagous predators living with molluscs with thick shells. However, after the durophagous predators disappeared, there was no need for a thick shell, and over time, it became more energetically efficient to not produce shells, and the modern animals living in Antarctica have very thin and brittle shells. This trait is present in all types of molluscs, including snails, clams, and brachiopods, and evolved the same trait in response to the same pressures. This is different from convergent evolution because the animals originally stemmed from the same source. However, this trait evolved independently in all of these related animals in response to the same pressure (McClintock et.al. 2008). Figure 4 shows an example of two chitons, a type of mollusc with hard plates, one from Antarctica, and one from the Gulf of Maine. The chiton from the Gulf of Maine has thick, well-developed plates that cover all of its body. In contrast, the chiton from Antarctica has reduced plates with gaps between them that are very brittle.

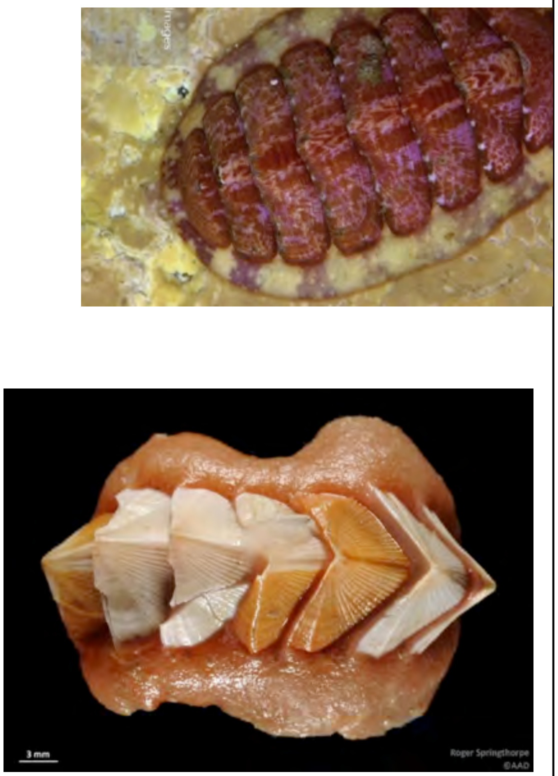

Figure 4: Top image- chiton from the Gulf of Maine (yooniqimages.com).
Bottom image- chiton from Antarctica showing thin, reduced shells (antarctica.gov.au).

Molecular Slowdown Hypothesis:

When studying polar evolution, another important consideration is the molecular slow-down hypothesis. This hypothesis states that evolution is slower at the poles due to the colder temperatures. The main driver of evolution is nucleotide substitution, when a nucleotide that was not coded for gets inserted, or deleted. Colder temperatures lead to a slower metabolism, and slower moving molecules, so nucleotide substitution happens at a slower rate. This is particularly evident in endotherms, where there is a higher body temperature and metabolism happens faster, speeding up evolution. In ectotherms and animals with lower body temperatures, it occurs more slowly (Held 2001). There is some evidence to support this hypothesis, including a study involving Antarctic Ice Fish, but other evidence contradicts it (Verde et.al. 2008, Held 2001). Polar areas are an ideal place to study this hypothesis because temperatures have been consistently cold for millions of years. This is a consideration when looking at polar evolution, but the evidence is controversial, and needs more study.

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An Investigation of Antarctic Icefish Adaptiveness

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Edited by: Briar Bragdon and Rebecca Hudak

Introduction

Antarctica is nearly entirely made up of the greatest latitude land on Earth. The Southern Ocean, which surrounds this continent, is distinguished from other oceans and defined by the Antarctic Circumpolar Current (ACC), an immensely powerful eastward flow. Naturally, antarctic waters are the coldest and most thermally stable environment in the world. Near the Ross Ice Shelf, sea temperatures hover around -1.9°C (Littlepage 1965), with sea temperatures near the peninsula fluctuating between 1.5°C in the summer and -1.8°C in the winter (DeWitt 1971). This thermal consistency has been coupled with well mixed dissolved oxygen levels near saturation for the past 10-14 million years. This time frame aligns with the radiation of Notothenioids, an order of fishes which accounts for 35% of all fish species and 90% of the fish biomass in Antarctica. Researchers propose this order's adaptive radiation was possible because of the relative isolation of Southern Ocean waters, their stable temperatures, and reduced interspecific competition associated with ice cover (Sidell and O'Brien 2006).

Hemoglobin and myoglobin loss

Oxygen solubility in seawater increases with decreasing temperatures, providing a very oxygen-rich antarctic environment, enhanced by thermal stability. Hemoglobin (Hb) is a red pigmented oxygen binding protein found in the bloodstream of most animals, including the red-blooded notothenioid fishes. In these species, Hb aids in the transportation of oxygen from the gills to the rest of the body. Red-blooded notothenioid fishes are able to downregulate the expression of their genes for Hb expression in response to decreasing temperatures. Belonging to this order, icefish make up the family Cannichthyidae, their lineage diverging approximately 2-5.5 million years ago (MYA) (Figure 1). This divergence was marked by a loss of Hb in the blood. In contrast to other notothenioids, icefish have lost Hb expression entirely through the deletion of genes that code for its major components, α-globin and β-globin (Sidell and O'Brien 2006).

Figure 1. The blackfin icefish (*Chaenocephalus aceratus*), belonging to the Cannichthyidae family, lacks expression of both hemoglobin (Hb) and myoglobin (Mb) (Arkive 2016).

As a result of the absence of Hb, icefish blood has less than 10% of the oxygen carrying capacity of red-blooded notothenioids. To compensate for this, cannichthyids have larger hearts, greater capillary diameter, a fourfold greater blood volume, and a four to fivefold greater cardiac output than other notothenioids (Figure 2). These physiological adaptations coupled with a comparatively low activity budget and metabolic rate allow for adequate oxygen delivery to the body (Sidell and O'Brien 2006).

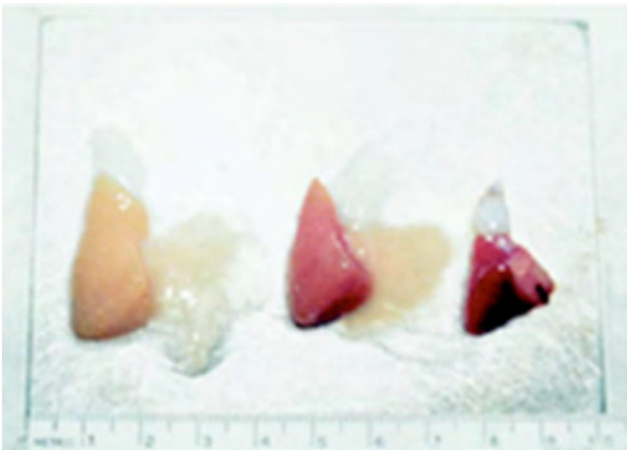

Figure 2. Heart sizes and colors are compared for three notothenioid fishes: A Hb and Mb lacking species, the blackfin icefish *Chaenocephalus aceratus* (Left), a Mb expressing icefish *Chionodraco rastrospinosus* (Center), and a red-blooded notothenioid fish *Notothenia coriiceps* (Right) (Sidell and O'Brien 2006).

Myoglobin (Mb) is an oxygen binding protein found in the muscle fibers of most animals, including notothenioid fishes. In addition to the loss of Hb expression, six of the sixteen known icefish do not express Mb in their heart muscle (Figure 3). The loss of this expression occurred independently four times, each caused by a different type of mutation in different locations on the genome (Sidell and O'Brien 2006). Unlike the synaptomorphic loss of Hb within the

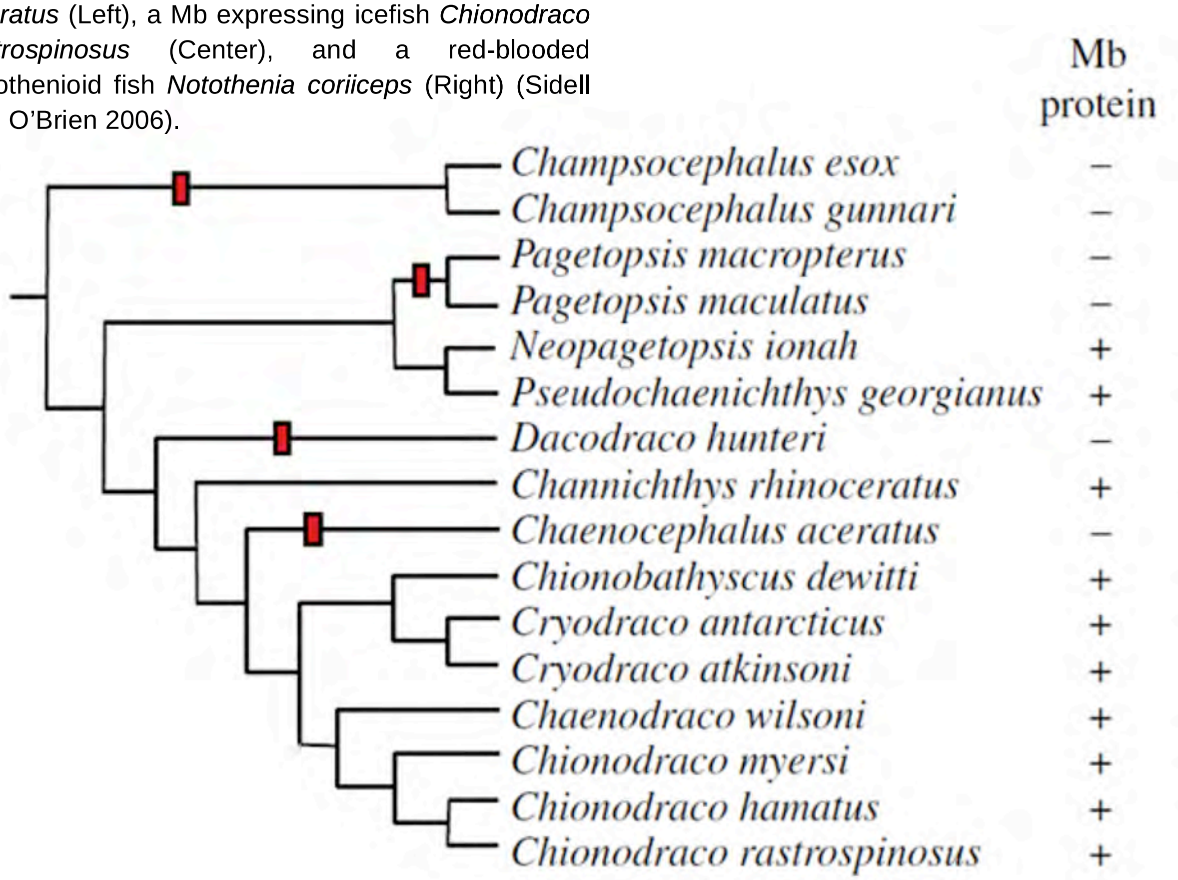

Figure 3. Phylogenetic tree of the Cannichthyidae family with corresponding icefish myoglobin (Mb) expression. Red bars represent independent mutational events of the lineage that led to a loss of Mb expression (Sidell and O'Brien 2006).

icefish family, Mb expression varies on a species level. Furthermore, the loss of this oxygen binding protein has occurred through different genetic and evolutionary mechanisms.

Adaptive value

Researchers initially proposed that the loss of both Hb and in some species Mb must be of some adaptive value to the icefish. In accordance with theories on evolution, the increase or decrease in expression of a particular trait or characteristic must correlate to greater reproductive fitness and survivability of the species. Indeed, the loss of Hb reduces the viscosity of the icefish blood, a potential source of energy conservation. However, it has been shown that because these hemoglobinless fishes have a greater blood volume through their circulatory system, they actually expend twice the cardiac energy per unit time than red-blooded notothenioids. This inefficiency corresponds to 22% of icefish resting metabolic rate being attributed to cardiac function. This outrageous percentage of energy devoted to the circulatory system is well over four times greater than that seen in temperate water fishes. Thus, the loss of Hb and Mb in this family appears to be disadvantageous and has been cited as a "Disaptation," or a detrimental mutation (Sidell and O'Brien 2006).

Researchers have speculated that the disadvantaged icefish are able to persist within their environment due to the highly oxygen saturated waters associated with the cold, thermally stable sea temperatures. For this reason, the icefish were thought to survive without needing oxygen binding proteins. However, this theory is negated when analyzing the large energy expenditure associated with their cardiac output. It is however critical to note that the synaptomorphic loss of Hb and different mutations associated with Mb loss in some species are ultimately sublethal. Furthermore, icefish may thrive in antarctic waters due to a biodiversity crash occurring around the time of notothenioid radiation. This, coupled with antarctic ice sheets reducing habitat availability for other species, may explain the reduced interspecific niche competition (Sidell and O'Brien 2006).

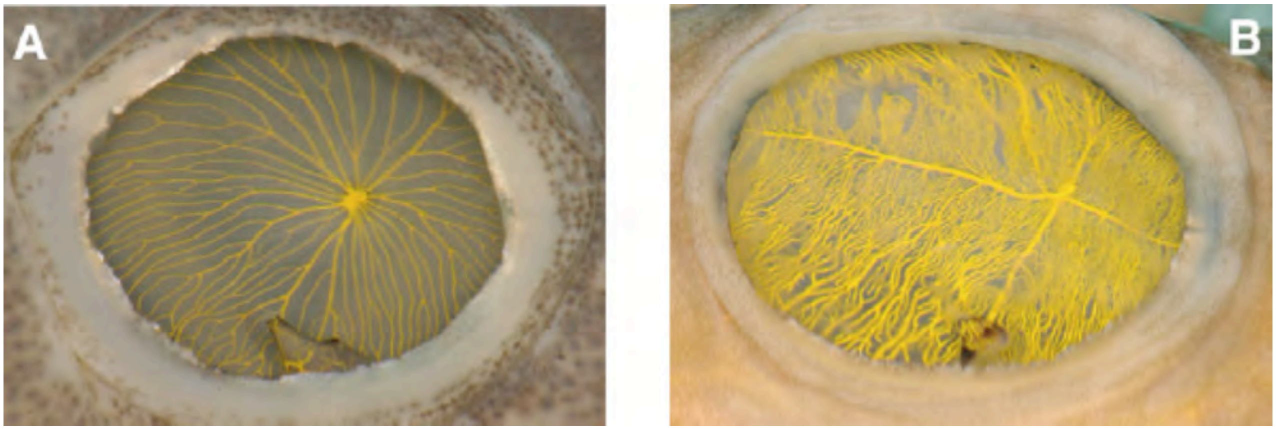

Figure 5. Retinal vasculature of (A) *Pagothenia borchgrevinki*, a hemoglobin expressing nototheniid and (B) the blackfin icefish, *Chaenocephalus aceratus,* a hemoglobin lacking fish (Sidell and O'Brien 2006).

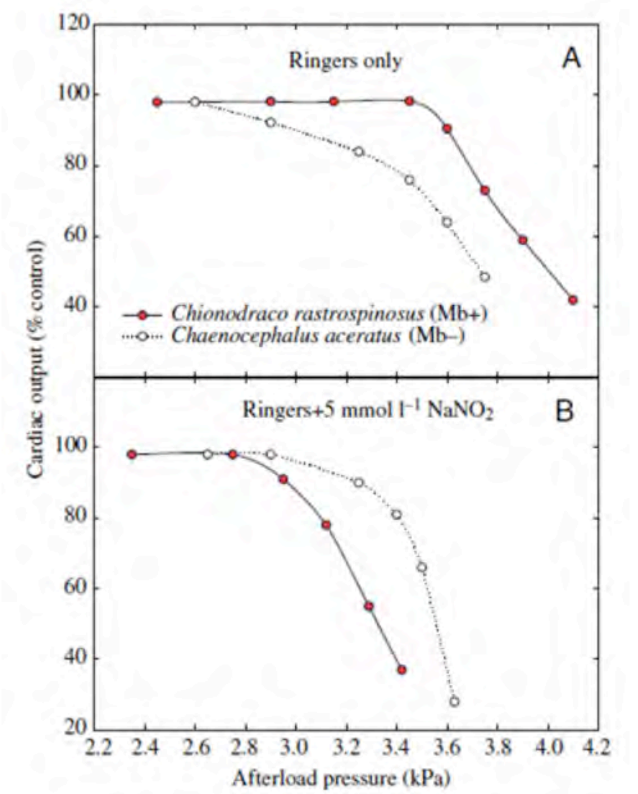

Figure 4. The cardiac output (% control) over afterload pressure (kPa) under normal conditions (A) and under sodium nitrite exposure, which inhibits Mb function (B) of two Channichtyid species is displayed: *Chionodraco rastrospinosus*, a Mb expressing species (Red dots), and the blackfin icefish, *Chaenocephalus aceratus*, a Mb lacking species (White dots) (Sidell and O'Brien 2006).

For whatever reason, icefish have lost Hb expression (and some Mb expression) throughout their evolution as a family. Red-blooded notothenioids are able to more efficiently distribute the oxygen needed for metabolic functions throughout the body. However, when myoglobin expression is hindered, their cardiac output decreases dramatically. In contrast, icefish are able to maintain somewhat constant cardiac output, suggesting that they must be using other physiological mechanisms to successfully transport oxygen throughout the body (Figure 4) (Sidell and O'Brien 2006).

Other mechanisms for oxygen delivery

Along with the modified cardiovascular physiology displayed by the channichthyids, these fish have also shown to have two other distinguishable differences. These differences include enhanced vascular densities and altered structural and ultrastructural features of the heart muscle. Antarctic icefish have large lumenal diameters of the microvasculature to go along with their large blood volume. Previous studies have shown that the capillary bore of hemoglobinless icefishes is two to three times greater than that of their red-blooded relatives. In recent studies,

Species	Hb/Mb	O_2 Diffusion distance through tissue (μm)[a]	Mitochondrial volume density [$V_{v,mit}$, *f* %)][b]
Gobionotothen gibberifrons	+/+	9.82±1.37	15.87±0.74
Chionodraco rastrospinosus	-/+	6.20±0.86	20.10±0.74
Chaenocephalus aceratus	-/-	6.23±0.41	36.53±2.07

Table 1. Structural and ultrastructural features of the heart muscle from three Antarctic notothenioid fishes (Sidell and O'Brien 2006).

researchers have discovered that there is a large difference in the vascular densities within the retina of the eyes, which are highly aerobic, of fish that produce hemoglobin and those that do not (Figure 5) Researchers found that the vascular densities of the hemoglobinless icefish were much larger than those notothenioid species that do express hemoglobin. The larger vascular densities seen in the hemoglobinless fish effectively reduce the diffusion distance for oxygen. This also makes certain that the retinal tissue of animals whose blood has reduced oxygen carrying capacity is properly oxygenated.

When researchers compared the structural features of hearts of three notothenioid fishes that all differed in their expression of oxygen-binding proteins, they found striking differences (Table 1). The three species involved in the study included *Gobionotothen gibberifrons* (expresses both hemoglobin and myoglobin)*, Chiondraco rastrospinosus* (lacks hemoglobin, but expresses cardiac myoglobin)*, and Chaenocephalus aceratus* (lacks both hemoglobin and myoglobin). Researchers found that the hearts of both *C. rastrospinosus* and *C. aceratus*, which both lack hemoglobin were more spongy than the hemoglobin expressing heart of *G. gibberifrons.* These spongy hearts had an average shorter diffusion distance that oxygen has to move between lumenal blood and tissues. Mitochondrial densities are also dependent on whether or not the individual expresses hemoglobin and myoglobin. While studying these three species, researchers found that the loss of hemoglobin results in only a small (~4%) increase in the mitochondrial densities. When both hemoglobin and myoglobin are lost, the mitochrondrial densities are increased by a greater amount (~16%). The increase in mitochondrial density in icefish that lack hemoglobin and myoglobin act as an important pathway for oxygen and enhance its delivery. Based on these findings, researchers concluded that the loss of hemoglobin and myoglobin originally started the evolution of secondary cardiovascular traits (Sidell and O'Brien 2006).

Role of hemoglobin and myoglobin as nitric oxide-oxygenases

Recent studies have shown that hemoglobin and myoglobin have other purposes besides oxygen storage and transport proteins. These proteins are also able to metabolize nitric oxide. As nitric oxide oxygenases, these proteins use oxygen to convert nitric oxide to nitrate. If the animal is lacking these proteins, it will have an enhanced sensitivity to nitric oxide. Nitric oxide has many functions including acting as a vasodilator and enhancing blood flow and oxygen delivery to the tissues. Nitric oxide is also responsible for stimulating and maintaining high densities of mitochondria in the tissues. As a result of not having hemoglobin and myoglobin as nitric oxide metabolizers, icefish have a build-up of nitric oxide in their bodies. It is hypothesized that the elevated levels of nitric oxide give the icefish their unique characteristics including their larger mitochondria, muscle fibers, and hearts (Sidell and O'Brien 2006).

Case study

The study "Oxygen uptake and circulation by a hemoglobinless Antarctic fish (*Chaenocephalus aceratus)* compared with three red-blooded Antarctic fish" set out to examine the factors that affect the oxygen exchange of the *C. aceratus*. Researchers compared the oxygen uptake and circulation of *C. aceratus* to three red blooded fish, *Notothenia gibberifrons, Parachaenichthys charcoti,* and *Notothenia neglecta.* After capture, all of the fish were anesthetized and a polythene tube was inserted into the ventral aorta, the dorsal aorta, buccal cavity, blood vessels, and the opercular chamber in order to measure certain parameters. These parameters included oxygen consumption, blood pressure, buccal cavity pressure, and breathing movements. After recovering from the surgeries, the fish were placed into containers that acted as respirators. The fish were kept in the respirometers for a period of anywhere between two and ten days with observations and measurements being made frequently throughout this time. After observing the fish, researchers found that *C. aceratus* had large opercular pumps, however these were normal for a benthic fish such as this one. They also found that the gill arches of this species are long and had a large gill array, allowing a large amount of water to flow through with low resistance. A low buccal cavity pressure was measured due to the slow breathing movements in *C. aceratus.* When compared to the three red-blooded fish, researchers found that *C. aceratus* had a much lower blood oxygen capacity, but had the largest heart that pumped three to four times as much blood as the red-blooded fish. Even though *C. aceratus* pumps the most blood, this species was found to have the lowest oxygen transporting capacity when resting. Researchers also noticed that the resting oxygen consumption of all four species was similar. Overall, researchers concluded that the only advantage that the red-blooded fish had over the icefish was that they are more resistant to hypoxia. However, with the waters of Antarctica being relatively oxygen rich, this does not seem to be a real threat to icefish.

Conclusion

The Channichthyidae family, or Antarctic icefishes, display unique physiological characteristics not seen in any other fish species. Their loss of hemoglobin and in some species, myoglobin, has lead researchers to further study the function of these two oxygen binding and transporting proteins. The loss of these proteins has led to higher energetic costs for circulating blood, and an overall reduction in cardiac performance. Therefore, the losses of such important proteins must have caused the icefish to evolve modified cardiovascular systems in order to properly deliver oxygen throughout the body. It is suggested that the loss of hemoglobin and myoglobin and the nitric oxide oxygenase properties they possess has led to the development of the modified cardiovascular systems and the unique characteristics that the icefish have. Studying icefish has lead scientist to learn of the importance of hemoglobin and myoglobin and what occurs when these proteins are missing. Researchers are continuing to study the role of nitric oxide in icefish and how elevated levels of nitric oxide within the icefish are leading to their unique characteristics (Sidell and O'Brien 2006).

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Ice Binding Proteins

By: Bailey Bush, Katie Kennedy
Edited by: Alex Makucewicz, Sharlene Maynard

Ice binding proteins, often classified as antifreeze proteins, are a class of polypeptide that are produced by certain vertebrates, fungi, plants, and bacteria that live in areas of extreme cold. These proteins are essential to organisms living in both the Arctic and Antarctic. Antifreeze proteins (AFPs) stop the growth of ice crystals inside of an organism, allowing them to live in subzero temperatures. There are many, different variations to ice binding proteins that are still being studied by researchers. Although humans have not yet discovered all of the protein's mechanisms and uses, it it certain that these proteins are necessary for many organisms to withstand polar climates.

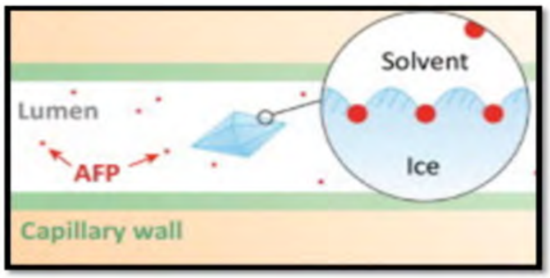


Figure 1: IBF proteins attach to ice crystals within an organism's blood stream. The adhesion of the proteins form curved patterns on the ice surface which help lower the freezing point and stop ice growth (Davis 2014).

As the proteins bind to the ice crystals, it forms a microcurvature design in the surface of the ice (seen in figure 1). Thermodynamically speaking, it is more difficult for water to bind onto a curved surface than a flat one. The adhesion to the ice, along with a process called thermal hysteresis, and the curved structure created in the ice, lower the freezing point of the ice structure. The lowered freezing point in the organism makes it more difficult for ice to grow. All of these aspects together allow organisms to maintain and expel ice crystals from their body (Davies 2014).

Thermal hysteresis is defined as the separation of melting and freezing point. This process widens the gap between melting and freezing temperatures and maintains ice crystals in a structure that neither grows nor melts (Davies 2014).

Variations of Ice Binding Proteins

The majority of ice binding proteins are found within a creature's blood stream. However, several species of microorganisms are known to expel the proteins through their skin rather than maintaining them inside the body (Cheng 1998). In this case, the proteins are maintaining a small habitat within the ice by not allowing the ice to

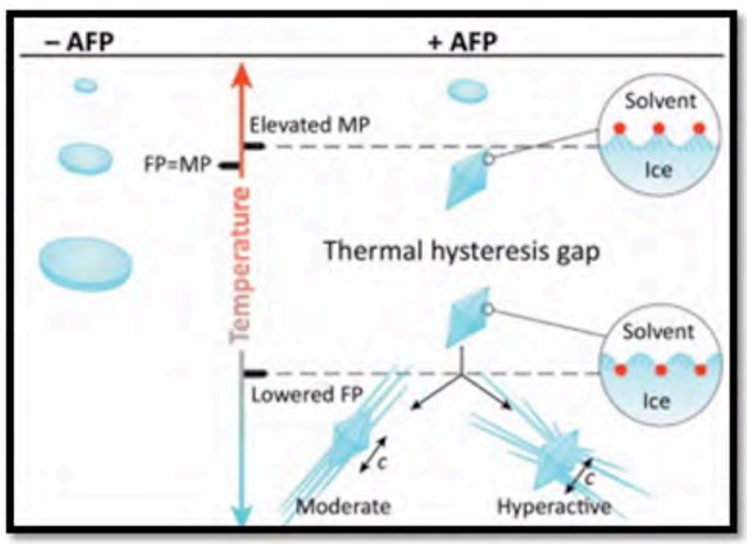


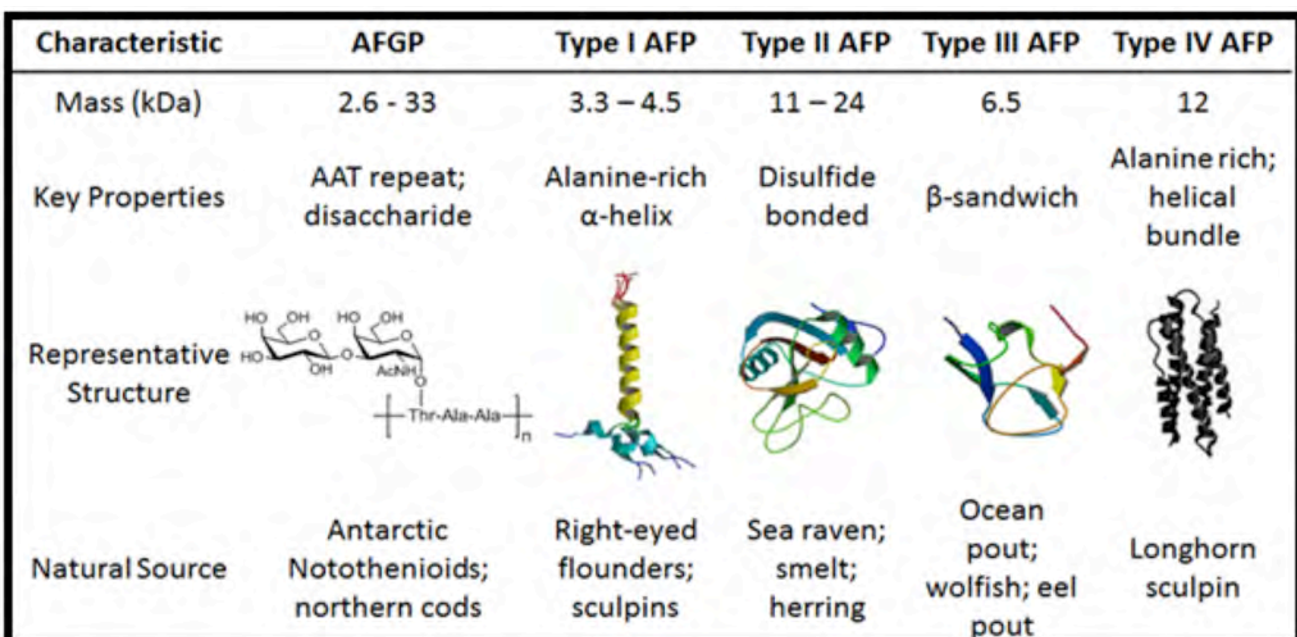
Figure 2: Without IBPs (left side of the temperature scale) the melting and freezing point are the same. In the presence of IBPs (right side of temperature scale) the proteins create a thermal hysteresis gap separating the two temperature points and allowing the ice crystals to remain in their current state without growing or melting (Davis 2014).

form around the organism.

There are large variations to ice binding proteins which make them beneficial in polar habitats and to many different organisms. The large variations, however, also makes it more difficult to study and categorize AFPs.

Resistance proteins, a specific form of AFPs, are found in various, polar plant species. Rather than avoiding internal freezing all together, this type of protein attaches to ice structures and limit their growth to maintain a size that is not harmful to the organism. Avoidance proteins, on the other hand, are a type of protein that are used to keep body fluids in a liquid state. They are primarily found in fish and insects. These proteins bind to ice structures to limit their growth, but are also responsible for expelling the ice crystals out of the body. Researchers have yet to determine the mechanism which removes ice crystals from an organism’s body. There are two groups of AFPs within the avoidance category: (1) Antifreeze Glycoproteins (AFGPs) and (2) Antifreeze Proteins, which are broken down into four subcategories, labeled 1-4 in order of their discovery. Glycoproteins are found in antarctic notothenioids and northern cod. The structure of these proteins have various numbers of tripeptide (Ala-Ala-Thr) repeats where the Thr is linked to a disaccharide group. The first of the AFP subcategories is found in flat fish, and has an a-helical structure with three or four folds of an eleven residue repeat. The second type is found in raven, smelt and herring, and is differentiated by a disulfide bond. The third group is a globular protein that is found in eel pouts and wolf fish. Lastly, the fourth is a helical bundle that is found in longhorn sculpin (Cheng 1998).

The production of antifreeze proteins varies with species, climate, and season. Many species that use AFPs are on a seasonal cycle of protein production. Growth hormones regulate plasma AFP production. If the organism does not need to produce proteins all year long, the hormones will repress AFP transcription through summer months when the climate is warmer. The amount of AFP gene copies also fluctuates depending on the species and the



Characteristic	AFGP	Type I AFP	Type II AFP	Type III AFP	Type IV AFP
Mass (kDa)	2.6 - 33	3.3 – 4.5	11 – 24	6.5	12
Key Properties	AAT repeat; disaccharide	Alanine-rich α-helix	Disulfide bonded	β-sandwich	Alanine rich; helical bundle
Representative Structure					
Natural Source	Antarctic Notothenioids; northern cods	Right-eyed flounders; sculpins	Sea raven; smelt; herring	Ocean pout; wolfish; eel pout	Longhorn sculpin

Figure 3: There is a large variety of antifreeze proteins. Proteins are different in all aspects, including chemical and physical structure and the natural sources they are found in (Capicciotti et al. 2013).

atmosphere. A fish living in Antarctica, for example, would most likely have more copies of protein genes and produce them for longer seasons than an organism living on the southern tip of Greenland (Fletcher 2001).

Potential Uses of Antifreeze Proteins

Research on the benefits and possible uses of antifreeze proteins is still being done, however, there are already several well-known types of AFPs that are regularly implemented for human use. Proteins have been used in frozen foods, such as ice cream, to maintain textures and prevent recrystallization. They are also used for frozen preservation; the proteins reduce drip to minimize protein loss, as well as inhibit recrystallization during thawing, storage, or transportation (Griffith 1995). Antifreeze proteins can also be used to advance the field of aquaculture by allowing for the freezing and long term storage of important fish egg stock. This could allow for much more flexibility when it comes to storing eggs from particularly successful stocks for use in subsequent years. It would also allow for the easy storage and shipment of stocks between the suppliers and the aquaculture farms (Young, Fletcher 2008).

Discovery of Antifreeze Proteins

Antifreeze proteins were first discovered by Arthur DeVries in the late 1960's (Logsdon, Doolittle 1997). He was able to conclude that the freeze resistance exhibited by some fish was due to certain glycoproteins in their blood. He conducted his experiment on the Antarctic toothfish, *Dissostichus mawsoni.* He was able to prove that the antifreeze glycoproteins, found in the species blood serum, were derived from a gene which coded pancreatic trypsinogen. A small region of this gene between the first intron and second exon was expanded and duplicated 41 times, (Figure 4) (Logsdon, Doolittle 1997). The new gene still had the same end segments as the trypsinogen gene, which it had mutated from and was still produced in the pancreas. Its first function,

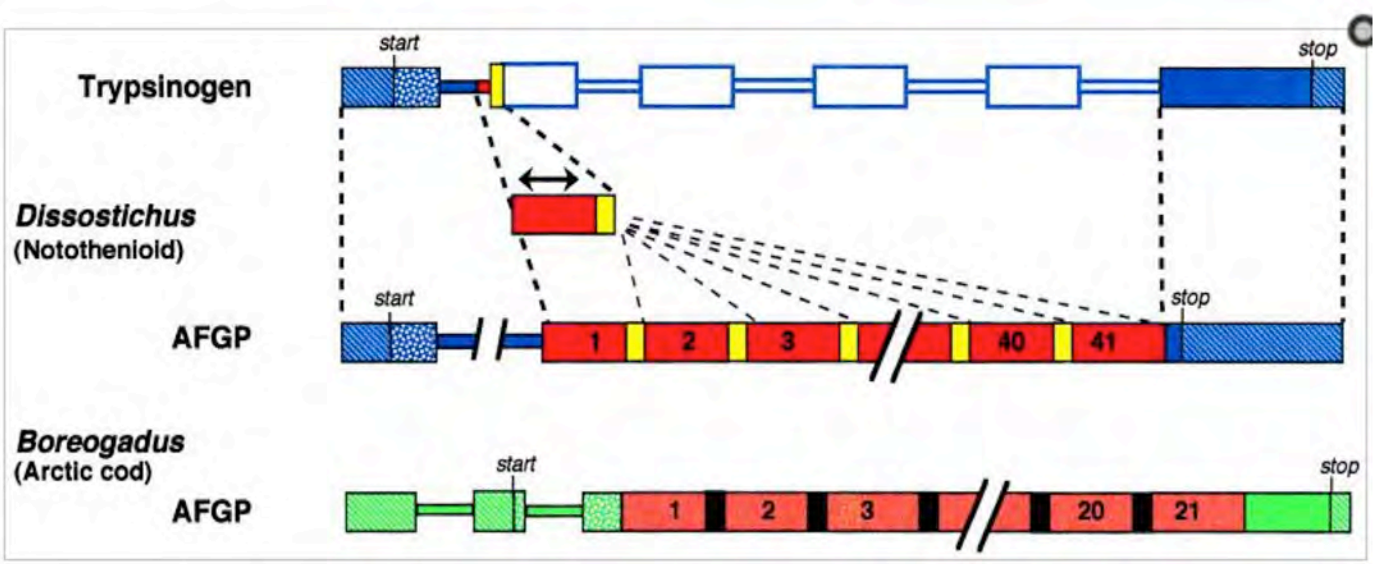


Figure 4
Comparison of gene structures and their sequence similarities. The regions shown represent genomic regions encompassed by sequenced cDNAs. Exons are shown as large boxes; introns are shown as thinner boxes; inferred initiation and termination codons are indicated. (Logsdon, Doolittle 1997)

after evolution, was to keep the intestinal fluids of the species from freezing. It was later adopted by the liver and spread throughout the blood serum (Logsdon, Doolittle 1997). This study was revolutionary in its discovery of antifreeze proteins. It began a new field of study and solved the mystery surrounding the freeze resistance of many species.

The freezing of the Arctic and Antarctic Oceans, which happened around 14 million years ago, is thought to be the main event which triggered the evolution of antifreeze proteins. Since the freeze, 4 distinct types of antifreeze proteins have evolved in species (Logsdon, Doolittle 1997). Many of these different proteins evolved the same ways across species. Antifreeze glycoproteins evolved in both Antarctic toothfish and Arctic cod. These two species are thought to have shared a common ancestor around 40 million years ago (Figure 5). However, the freezing of the polar oceans happened approximately 14 million years (Logsdon, Doolittle 1997). This suggests that even though both species shared a common ancestor, the evolution of the same antifreeze glycoproteins happened separately.

Case Study: Superheated Ice

Since their discovery in the 1960s, antifreeze proteins have become a topic of interest for scientists in both of the poles. Many experiments testing the extent of their effectiveness on changing the melting and freezing points of liquids have been published in the last five decades. One such study, conducted by DeVries and several of his colleagues, explored the existence of superheated ice in the blood of Antarctic notothenioid fish. They discovered that ice can be heated past its usual melting point due to a side effect of antifreeze proteins. This phenomenon is seen in ice crystals which have been stabilized by antifreeze proteins. The proteins work by surrounding the ice crystals, so that it can no longer form covalent bonds with other water molecules.

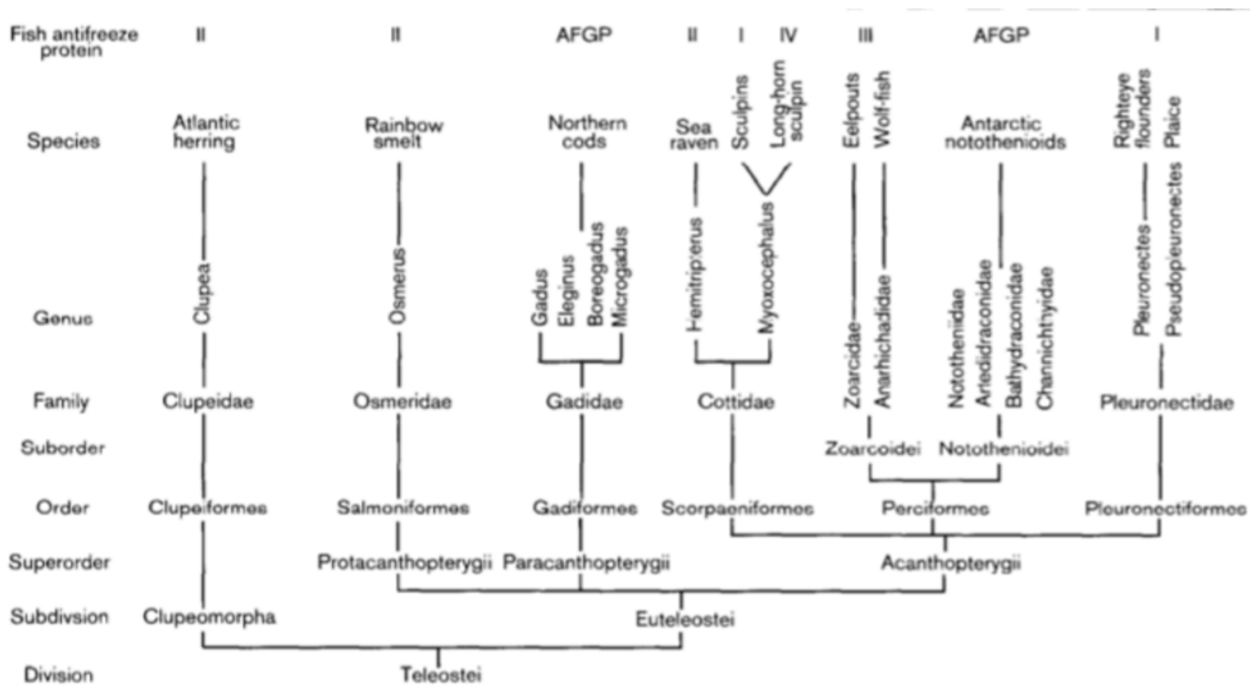


Figure 5
Evolutionary relationship of antifreeze bearing fish. Type of antifreeze proteins shown at top. (Cheng 1998)

This stops the crystal from getting any bigger and stops the complete freezing of an organism's body fluids (DeVries 2014). The stabilized crystals have a decreased melting point, but they also gain an increased melting point due to the presence of the proteins. This increased melting point could form a problem, due to a build-up of stabilized ice crystals in an organism's blood. A large amount of stabilized ice crystals could still be fatal to the organism, which leads scientist to believe that these organisms have a way of disposing of the ice.

DeVries experiment was conducted to learn the extent of the raised melting point of stabilized ice and test the hypothesis that the ice buildup could melt during warmth of the Antarctic summer (DeVries 2014). The hypothesis was tested by obtaining the melting point of the stabilized ice and comparing it to seasonal pelagic temperatures from the McMurdo Sound. Scientist produced a serum which shared many of the same properties as the notothenioid fishes blood. They then tested the serum to find the freezing and melting point in the absence of antifreeze proteins. They found the freezing point with of the pure serum to be -1.04℃. They then added a collection of antifreeze proteins taken from several different species of notothenioid fish. They found that the serum which contained the antifreeze proteins exhibited a lowering of the freezing point to -2.54℃ and raising of the melting point to .32℃ (Figure 6) (DeVries 2014). Their tests of the benthic water temperatures in the McMurdo sound during the summer showed average water temperatures well below .32℃. These results disproved their hypothesis and lead them to believe that the organisms must decrease the amount of stabilized ice crystals in their bodies by some internal mechanism.

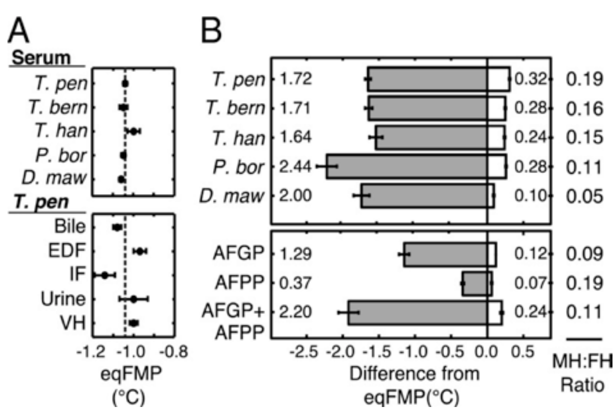


Figure 6
Freezing and Melting Point Equilibrium (eqFMP) of pure serum (A) compared to the eqFMP of the antifreeze serum (B). (DeVries 2014)

Case Study: Practical Use in Frozen Foods

Another study addressed the potential uses of antifreeze proteins found in winter flounder embryos. These proteins could be used to cryofreeze and store fish eggs from many different commercially and scientifically important species (Young, Fletcher 2008). In the past, cryofreezing and long term storage of fish eggs has been impossible, due to the eggs high sensitivity to cold. The eggs cells would burst during the freezing or defrosting processes, due to a buildup of ice crystals and the embryos would die. Recent studies involving the embryos of winter flounder have revealed that the embryos still exhibit signs of growth even after the defrosting process. Since grown winter flounder produce three different types of antifreeze proteins, scientist believe that this cold tolerance could be due to the production of antifreeze proteins by the embryos. An experiment was conducted to discover which, if any, of these antifreeze proteins were produced by the embryos (Young, Fletcher 2008). Scientists also wanted to determine if these antifreeze proteins could be adopted by the embryos of other fish species to help them survive cryogenic freezing.

To discover whether these embryos produced antifreeze proteins, scientist fertilized a batch of winter flounder eggs and tested them for the presence of antifreeze proteins. None were found immediately after fertilization; however, tests conducted 4, 8 and 11 days post fertilization showed low antifreeze protein activity. They then performed reverse transcriptase-polymerase chain reaction analysis of the antifreeze proteins mRNA (Young, Fletcher 2008). This revealed seven different genes for skin type antifreeze proteins which were translated into four different types of antifreeze proteins. These findings could lead to an effective way to cryofreeze and store fish eggs from many different species, which could help both the aquaculture and food industries with stock preservation and storage durations.

Case Study: Relationship of Moss and Bacteria

This study explored the partnership of an Antarctic moss and a specialized type of epiphytic bacteria. Liquid samples of the moss were frozen in storage for several years. The samples showed strong pitting activity suggesting the presence of antifreeze proteins. At first, it was thought that the Antarctic moss *Bryum argenteum* had simply evolved antifreeze proteins of its own. It used these proteins to create fissures and pitting in the ice surrounding it throughout the Antarctic winter. The pitting and fissures give the moss the ability to continue to respire as well as take in nutrients even when covered in ice, allowing it to continue growing year round.

The scientists named the protein DUF3494 and then used Metagenomic analysis to reveal that the antifreeze proteins from the sample were of bacterial origin. This discovery led them to develop the hypothesis that the moss housed epiphytic bacteria which secreted the antifreeze proteins. They tested this theory by taking a stored sample of the moss and using it to grow a new sample under aseptic lab conditions. This new sample showed no signs of producing antifreeze proteins, proving that the antifreeze proteins present

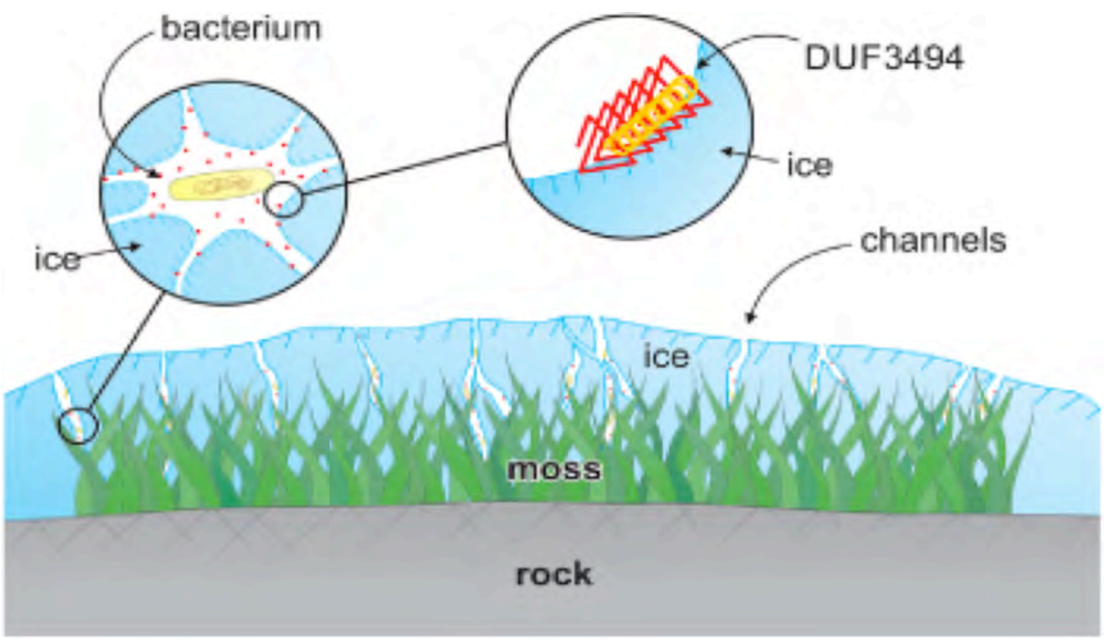


Figure 7
Antifreeze proteins (DUF3494) secreted by epiphytic bacteria living on moss might alter the texture of surrounding ice to keep pits, fissures and channels open for respiration. (Davis 2016)

were produced by another organism (Davis 2016).

This experiment serves to raise many new questions about the way that Antarctic plants have adapted to deal with the cold. Is *Bryum argenteum* a special case or are there many other species that deal with the freezing temperatures of the Antarctic in this way?

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Cool Polar Critters

Ashley Breault and Jen Gamble
Edited by Abigail Rhodes and Gwen Pelletier

Polar regions are known as extreme environments but despite their challenging characteristics, many marine and terrestrial species thrive in these areas. It is interesting to study the variety of life in the Arctic and the Antarctic to learn about how different species have adapted to living under such harsh conditions. The creatures found in these regions play an important part in the polar ecosystems, and in the global ecosystem as well.

Animals in the Arctic

Figure 1. Narwhale, *M. monoceros,* swimming.

http://blogs.mtlakes.org/weirdanimals/files/2014/01/Narwhal3.jpgde5cc6d8-5985-4214-b9dd-36d7af50965aLarge.jpg

Figure 2. Map of the arctic shows the sea ice extent, the distribution of Narwhals in both the summer and winter, and their seasonal movements using the Conservation of Arctic Flora and Fauna (CAFF) definition of the Arctic.
http://www.worldwildlife.org/species/narwhal

Narwhals

Narwhals are one of the many animals that call the Arctic waters their home. *Monodon monoceros,* the scientific name for this toothed whale, lives in the Arctic waters of Canada, Greenland, Norway and Russia. The ice shelves in these areas change size based on the season, with more ice in the winter months and less ice in the summer months. Due to this changing ice shelf size, narwhals can spend up to 5 months under sea ice during the winter, occasionally breaking through the ice with their tusks to breathe (Narwhal 2016). Narwhals are otherwise known as the 'unicorn of the sea' for this prominent tusk.

A narwhal's tusk has other functions besides breaking through the ice. The tusks, which are actually enlarged front teeth, can be up to 10 feet long. Though most narwhals have one tusk, it is possible for an individual to have two tusks, or none. These giant teeth are very sensitive, with up to 10 million nerve endings, and are thought to play a role in male dominance and mating behaviors. Adult narwhals can weigh up to 4,200 pounds and can grow up to 17 feet long. These large animals primarily eat Greenland halibut, Atlantic and Polar cod, squid, shrimp. As a narwhal eat and grows, they change coloration. A newborn baby is blue-gray, juveniles are blue-black, adults are mottled gray, and older adults are nearly all white (Narwhal 2016).

Because these majestic creatures live in such a delicate environment that is being greatly affected by climate change, narwhals are facing their own threats and environmental problems. With the increased interest of oil and gas development in Arctic waters, comes an increased risk for the narwhals. Not only is the oil drilling a health risk for the animals with the fear of leaked oil in the environment, but it also comes with the concern of more boat traffic that happens with the further development. A surge in shipping vessels leads to an increased likelihood of collisions as well as increased noise pollution that negatively impacts all marine mammals. Climate change also causes increasing ocean temperatures and melting ice, which impacts narwhals. Because these creatures are only found in these waters, if the environment changes drastically enough, they will have nowhere else to go (Narwhal 2016).

These animals need protecting for a few reasons. As an arctic whale, the narwhal is at the top of the food chain for the marine environment, meaning not many other organisms try to eat them. As a top predator, they help to regulate the populations of the organisms they eat, and if narwhals were to disappear, those populations of prey would drastically change, altering the whole food web. Narwhals are also very culturally important to many indigenous communities of the Arctic, used as a food source and trading good. For many different cultural and environmental reasons, they need protecting (Narwhal 2016).

Figure 3. A walrus sitting on the ice.
http://www.walrus-world.com/

Walruses

Walruses are another marine mammal that call the Arctic their home. These massive relatives of seals are divided into two subspecies of walrus based on where they are geographically found. The Atlantic Walruses live in northeastern Canada to Greenland, where as the Pacific Walruses are found in the northern seas near Russia and Alaska.

Walruses are best known for, and identified by, their large tusks. These tusks are actually large teeth, similar to Narwhals. These canine teeth can grow to be up to 3 feet long and are found on both males and females. The tusks are used to haul themselves out of the water and help them get back onto the ice, break holes in the ice if they need access to the surface to breath, and are used by males to mark territory and to protect females and their young during mating and birthing seasons (Walrus 2016). Each Walrus also has between 400 and 700

Figure 4. Map of the distribution of the two subspecies of walruses. The purple areas represent where the Atlantic populations are found and the pink areas represent where the Pacific populations are found.
http://www.canadiangeographic.ca/kids/animal-facts/images/walrus_range.jpg

whiskers that resemble mustaches, which are used to find food on the ocean floor (Walrus Information 2016). Though these creatures look like they could hunt and kill other large mammals using their tusks, they primarily feed on clams, mussels, and other benthic shellfish, making those whiskers very helpful on the dark seafloor under the ice (Fact Sheet 2016).

Walruses have another adaptation that allows them to live in such a cold environment. The mating season for walruses stretches from December to March and gestation lasts between 15-16 months, which usually results in one offspring, though twins have been recorded. These babies can weigh between 99 and 165 pounds and grow quickly off their mother's milk (Fact Sheet 2016). These huge animals then grow to be between 7.25 and 11.5 feet long and can weigh up to 1.5 tons. Their bodies are surrounded by a layer of blubber, or layer of fat, that allows them to stay warm while swimming in the cold arctic waters (Walrus 2016). This layer of fat can be more than 4 inches thick. They also have a very thick layer of skin that helps to protect them from the cold and from predators (Walrus Information 2016). The fur on walruses changes as they get older. As juveniles, they are brown-gray, but as they get older they become brown-red. Their skin also changes color based on the temperature and sun exposure due to the changing size of blood vessels in the skin (Walrus 2016).

In the past, walruses have been in jeopardy of becoming endangered, but because of early conservation efforts, they have been able to stay off that ever-growing list. The prevention of the sale of ivory, the substance their tusks are made of, has helped these creatures make a comeback. Another issue that is of concern for the Walrus is climate change and the loss of sea ice. Because these animals rely so heavily on the ice as a habitat, a significant loss of ice would be detrimental to the walrus populations. The ice is where these animals rest after long dives and where their young are born. An increase in water temperature could also limit their food sources and their livable locations (Walrus Information 2016).

Greenland Shark

Figure 5. Greenland Shark, *S. microcephalus*, swimming.
http://www.arkive.org/greenland-shark/somniosus-microcephalus/image-G59813.html

The Greenland Shark, *Somniosus microcephalus*, is a large and slow sleeper shark. It is identified by its two reduced and spineless dorsal fins, a short rounded snout and five small gill slits. Its average maximum length is around 7 meters and it has brown to grey to black skin covered in dark lines or white spots (Widescreen). There is little known about their growth, due to their lack of calcified bands in the vertebral column. Most shark species have calcified vertebral columns with new bands forming each year of growth. The Greenland Shark vertebral columns are made of homogenous cartilage, making vertebral band studies impossible (MacNeil et al. 2012).

This shark prefers warmer, inshore waters, such as shallow bays and river mouths, during the winter, and offshore deep water, 180-550 meters, during the summer. *S. microcephalus* can be found in the Northern

Atlantic Ocean and throughout the Arctic Ocean (Widescreen).

Figure 7. Map of the geographic range of Greenland Shark (*S. microcephalus*)
http://maps.iucnredlist.org/map.html?id=60213

The diet of the Greenland Shark consists primarily of molluscs, but they will also consume seabirds, crustaceans, carrion, offal, large active fish, seals and cetaceans (Widescreen). Due to the habitat and range of the Greenland shark, there is not much that is know about their reproduction. Most studies are based on fewer than 50 individuals. Females are thought to reach maturity at 450cm and males are thought to reach maturity at around 300cm (Yano et al. 2007).

The three main modes of reproduction in sharks are oviparity, aplacental viviparity and placental viviparity. Oviparity is the most prehistoric form and is defined by the mother laying an egg case on the seafloor. Aplacental and placental vivparity requires more maternal input, as well as live birth. Aplacental viviparity has a soft case formed around the pup in the uterus of the mother, the baby sharks feed on a yolk sac that is attached to them, and the mother acts as the egg case. There can be multiple pups in the uterus per birthing event, each pup in its own soft case. Placental vivparity is when the mother has a physical connection to the pup, she acts as the egg case and the food supply. This is the most modern and advanced form of reproduction. There is debate as to whether Greenland Sharks are viviparious or oviparous, having evidence for both. There have been females found with numerous fertilized eggs in the uterus, indicating that they are capable of producing yolk-dependent offspring. Gestation period and the size of pups at birth is still unknown (MacNeil et al. 2012).

The IUCN Red List, a comprehensive inventory of the global conservation status of biological species, has *Somniosus microcephalus* listed as Near Threatened. The biggest threat to these animals is human interaction. Historically, the Greenland Shark was targeted for its oil-rich livers. This species has also been used as a food source for dogsledders and their dogs. In addition to this, they are subject to bycatch in deep water trawl nets and longlines (Kyne et al. 2006).

There is an interesting parasite that is found on the eyes of Greenland Sharks. It is the large copepod *Ommatokoita elongate*. The parasite attaches to the eye of the shark and proceeds to eat the cornea, eventually rendering the shark blind. The interesting aspects of this parasite are that it is an ectoparasite, a parasite

Figure 6. Greenland Shark swimming with the ectoparasite visible on the eye.
http://www.arkive.org/greenland-shark/somniosus-microcephalus/image-G59814.html

that attaches to the exterior of its host, and it is found on between 98-100% of caught individuals. It is also a surprisingly large size, with females reaching lengths of 4-6cm when egg sac is formed (MacNeil et al. 2012). Since these sharks are primarily benthic and slow moving, losing their eyesight is not a major hindrance to their fitness. They have a well-developed olfactory system that helps compensate for their lack of vision (MacNeil et al. 2012). The meat of the Greenland Shark is toxic when raw, inducing a drunk-like state in the consumer. The meat only becomes edible once it has dried.

S. microcephalus was historically harvested for the oil in their livers for export to Europe. They also were a significant species hunted by the Inuit people for a food source. Now, their biggest threat is bycatch. The main fisheries that results in their bycatch are Greenland Halibut (*Reinhardtius hippoglossoides)* and Northern Shrimp (*Pandalus borealis*) (MacNeil et al. 2012).

There are not currently conservation measures in place for *S. microcephalus* due to the lack of information that is known about them.

Arctic Fox

The Arctic Fox, *Vulpes lagopus*, is an idyllic species in the Arctic. It is prized primarily for its fur. There are two forms of the Arctic Fox, blue and white. They are still considered the same species. Both forms have variation in coat color depending on the season. The white form has brownish fur on its upper side and greyish on the underside. In the winter this changes to a pure white all over. The blue form is a darker brown to black in the summer, transitioning to light brown with a bluish sheen in the winter. Their average length is 46-68cm with an average shoulder height of 28cm. They are a relatively small species, weighing between 1.4-9g (Widescreen).

The Arctic Fox has some adaptations that allow it to survive in the harsh conditions of the Arctic. Their inner ears and the pads of their feet are furry and they have a small, short nose. These adaptations help to reduce heat loss. They also have increased bloodflow to their feet, since that is the part that is closest to the ice and snow (Widescreen).

The two forms of this fox have slightly different habitats that they prefer, however, both are found circumpolar throughout the Arctic. The white form prefers the open and treeless plains, while the blue form prefers the coastal and shrubby areas. Their range increases with pack ice. When there is a significant amount of pack ice, the foxes have been seen as far north as the North Pole, in the Gulf of Alaska and the southern tip of Hudson Bay, Canada.

V. lagopus is a scavenger species. They have been found to consume seabirds, ptarmigan, fish, marine invertebrates and marine mammals, however, their primary prey are lemmings. Diet consists on what is available in the current habitat that they are living in or passing through. They also have the ability to slow their metabolic rate when food is scarce, in order to maintain their highly active lifestyle.

Figure 7. White form of an Arctic fox in the snow.
http://www.arkive.org/arctic-fox/vulpes-lagopus/image-G54175.html

Figure 8. White and blue forms of the Arctic fox.
http://www.arkive.org/arctic-fox/vulpes-lagopus/image-G139962.html

Figure 9. A white form of an Arctic Fox with its summer coat.
http://www.arkive.org/arctic-fox/vulpes-lagopus/image-G58107.html

Figure 10. A blue form of an Arctic Fox with its summer coat.
http://www.arkive.org/arctic-fox/vulpes-lagopus/image-G58219.html

The breeding season for *V. lagopus* is February to May. Gestation is 51-54 days, resulting in the pups being born between April and July. The litter size depends on the food availability for the mother. The normal litter size range is 5-10 pups, but an extreme case was seen of a 19 pup litter. This occurred when there was a surplus of food. The pups are raised in the dens by both parents, as well as some helper adults from previous generations of that family. After the pups are born, the mother will stay and provide most care until the pups are more independent. The father is the main food provider at this time. After the pups are independent, which is around 8-10 weeks, the mother will begin hunting again, so both parents are providing food (Widescreen).

During the breeding season, *V. lagopus* is very territorial. They mark their territory with urine and have unique vocalizations and body postures to assert themselves as dominant. *V. lagopus* is the number one terrestrial game specie in the Arctic states. They are prized for their fur primarily, however, they are also consumed (Widescreen). There is also concern that there is increasing pollution of their gene pool. Arctic foxes are being captured and raised for pets, and some of the captive individuals

Figure 11. Bioclimatic zones that the Arctic is broken up into.
http://www.eoearth.org/view/article/150179/

have bred with the wild individuals (Widescreen).

The Arctic Fox is a key species in the Arctic. Its habitat of boreal forest, and competition with the Red Fox (*Vulpes vulpes*) make it a target species to study in terms of effect of climate change. *V. lagopus* can be found in the boreal forests of the arctic where they have competition currently with the Red Fox (*Vulpes vulpes*). With these connections, the IUCN Red List has flagged *V. lagopus* as a key species to monitor and study to understand how the Arctic will react to climate change.

Figure 12. Map of the geographic range of the Arctic Fox (*L. vulpes*).
http://maps.iucnredlist.org/map.html?id=899

The IUCN Red List has *Vulpes lagopus* listed as least concern, however, there are some populations that have historically struggled. Populations in Sweden, Finland and Norway consisted of 40 adults in 1998. As a result of the SEFALO+ conservation plan devised by Sweden, Finland and Norway, by 2008 there were roughly 200 individuals (Saving the Endagered...2016). The healthier populations are controlled by well-enforced laws and permit requirements for trapping and fur trade. The main Arctic states that this is regulated in are Greenland, Svalbard, Canada, Russia and Alaska.

Rock Ptarmigan

Figure 13. Mating pair of Rock Ptarmigans with summer plumage.
http://www.arkive.org/ptarmigan/lagopus-muta/image-A20587.html

Lagopus muta, the Rock Ptarmigan is a member of the Grouse family. Its body is stocky and round, often described as chicken-like. They are identified from other ptarmigan, such as the Willow Ptarmigan (*Lagopus lagopus*) by its black square-shaped tail. This is the only species of Ptarmigan that have the solid black tail year round. They also have feathers on their feet that extend to the tip of their toes during the winter and to the base of the toes in the summer. This helps prevent heat loss (Gough et al. 1998).

There is some sexual dimorphism within this species. Males have a red comb over their eye and their body is barred with dark brown-black, depending on the molt stage. Females do not have the red comb, they have lighter brown bars and black spotting. Male and females both have white wings and legs and a black tail. This is their summer plumage. In the fall their plumage turns to pure white, except the tail, which remains black. The transition back to summer plumage begins in the spring; males start molting earlier than females (Gough et al. 1998).

The Rock Ptarmigan is found throughout the Arctic from Canada, Alaska, southeast and west coasts of Greenland as well as northern Russia. *L. muta* prefers to remain above the timberline where it is primarily rocky. In the summer, they migrate south to the dry, open tundra. Some move to shrubby areas (Gough et al. 1998).

L. muta is a relatively flightless bird. They eat primarily buds, seeds and leaves, but they will also eat a few insects. Mating for *L. muta* begins in May (Cotter 1998) with an egg incubation period of 21-24 days, producing an average clutch size of 7-9 chicks. The chicks

Figure 15. Rock Ptarmigan nest with seven brown speckled eggs in it.
http://www.arkive.org/ptarmigan/lagopus-muta/image-A17743.html

Figure 16. Rock Ptarmigan chick in low brush with insect in mouth.
http://www.arkive.org/ptarmigan/lagopus-muta/image-A20572.html

Figure 14. Map of the geographic range of Rock Ptarmigan (*L. muta*).

will then fledge between 10-12 days.

The current global population of *L. muta* is around eight million. As a result, *L. muta* is listed as least concern by the IUCN Red List. The main predator of the Rock Ptarmigan is the Golden Eagle (*Aquila chrysaetos*). In addition to predation, they are also subject to human hunting for food and habitat loss due to grazing by sheep and mountain tourism, such as ski resorts. The Rock Ptarmigan is an important species to study because of the extreme environment in which they live. With the threat of humans growing for this species, as well as climate change, it is crucial that we understand how they will interact and adapt to a changing environment (BirdLife International 2015).

Animals in the Antarctic

Colossal Squid

The Colossal Squid, *Mesonychoteuthis hamiltoni*, also known as the Cranch Squid, is the largest, most elusive squid species. This species can reach lengths up to 14m with a mantle width of two to four meters and an

Figure 17. Image of a colossal squid being hauled up by a fishing vessel.

http://upload.wikimedia.org/wikipedia/en/6/61/Colossal_squid_caught_in_february_2007.jpg

estimated weight of 150kg. They also have the largest eyes of the animal kingdom reaching 25cm in diameter. They are different from the similar species of Giant Squid, *Architeuthis dux* (Bouchet and Gofas 2015), in that *M. hamiltoni* has 25 rotating hooks in two rows at the end of their tentacles, *A. dux* do not have these hooks (Colossal Squid 2015).

Figure 18. Close up image of the rotating hooks that are present on the end of the tentacles.
http://collections.tepap.govt.nz/APICollection/media/84220/640

M. hamiltoni is a deep water squid, adults spend most of their time at depths greater than 1000m while juveniles have been found at depths above 1000m and the paralarvae, the free-floating larval stage of cephalopods, are found at depths between 20-500m. They are found circumpolar to Antarctica from 40° latitude south (Colossal Squid 2015). There has been no evidence thus far indicating that *M. hamiltoni* participates in diel vertical migration (Barratt and Allcock 2014). Diel vertical migration is the vertical movement within the water column on a daily basis. An example is the Humboldt Squid (*Dosidicus gigas*) which remains at deeper depths during the day and migrates towards the surface to feed at night.

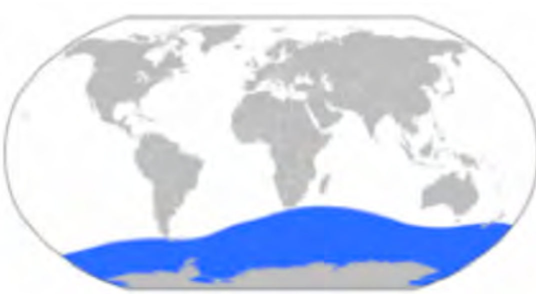

Figure 19. Map of the geographic range of the Colossal Squid (*M. hamiltoni*).
https://en.wikipedia.org/wiki/Colossal_squid

M. hamiltoni eats primarily mesopelagic fish and squid (Barratt and Allcock 2014) and they consume about 0.03kg or prey items per day (Roda et al. 2010). According to Roda et al. 2010, the amount of prey items that they consume per day does not vary depending on what depth of the water column they are in. Due to the elusive nature of *M. hamiltoni*, there is still significant life history research that has not been completed. There is little to nothing known about their reproductive habits.

The main threat for this species is bycatch, they get hauled up from deep water trawls and longlines of commercial fishing boats. The predators of *M. hamiltoni* are longfinned pilot whales (*Globicephala melas*), southern elephant seals (*Mirounga leonina*), southern bottlenosed whales (*Hyperoodon planifrons*), albatross (Family *Diomedeidae*) and Patagonian toothfish (*Dissostichus eleginoides*) (Barratt and Allcock 2014).

M. hamiltoni is an important species to understand because they are so unique and elusive. More research needs to be done with this species in order to gain a better understanding of how it lives. There are no current conservation plans in place for this species due to the lack of data on the.

Figure 20. Crabeater seal, L. carcinophaga, sitting on the ice.
http://www.antarctica.gov.au/about-antarctica/wildlife/animals/seals-and-sea-lions/crabeater-seals

Crabeater Seals

Crabeater seals, *Lobodon carcinophaga*, are the most abundant seal species in the southern ocean and one of the marine mammal species that calls the Antarctic home. These animals live all around the coast of continental Antarctica but have been found as far north as the southernmost points of South America, Africa, Australia, Tasmania, and New Zealand (Crabeater Seal Wildscreen Arkive). Crabeater seals feed primarily on krill, which make up around 95% of their diet, as well as cephalopods, fish, and crustaceans. Due to their primary food source being krill, Crabeater seals have specially designed teeth perfect for taking in large gulps of seawater and krill and filtering out the water (see figure 21) (Crabeater seals 2010). The main predators of Crabeater seals are Leopard seals and Killer Whales.

Figure 21. A Crabeater seal skull and teeth. These teeth are perfectly designed to strain out water, allowing Crabeater seals to eat as much krill as possible.
http://tywkiwdbi.blogspot.com/2012/03/serrated-teeth-of-crabeater-seal.html

Crabeater seals can grow to up to 8.5 feet long and can weigh up to 660 pounds. Some seals have been found to live up to 40 years old. They are brown-gray in color and their flippers are darker in color and marked with spots. Their coloration varies depending on the time of year and they molt their darker fur in January/February, turning a lighter color the following summer (Crabeater Seal NOAA Fisheries).

Crabeater seals are considered of least concern on the International Union for the Conservation of Nature (IUCN) Red List. Even though they are not threatened or endangered, Crabeater seals still face many threats to their populations. These threats include the commercial harvest of krill, diseases, and increased water temperatures and decreased pack ice caused by climate change. Diseases can cause mass die offs in the populations at a single time and are caused by increased tourism and climate change. The loss of pack ice is hazardous to these seals because the ice is utilized for breeding, nesting, avoiding predators, and as the habitat for its food sources. Thankfully, Crabeater seals are protected by the Antarctic Treaty and the Convention for the Conservation of Antarctic Seals, which has helped the populations maintain healthy numbers (Crabeater Seal Wildscreen Arkive).

Snowy Sheathbill

Figure 22. Snowy Sheathbill
http://www.arkive.org/snowy-sheathbill/chionis-albus/image-G84633.html

Snowy Sheathbills, *Chionis albus*, are small Antarctic birds found along the rocky coastlines of the Antarctic Peninsula and on several island of the Scotia Arc Island system. These birds may be found further north in southern parts of Chile and Argentina, but prefer the colder regions of the Antarctic. Weighing only 1 to 2 pounds and having a wingspan of 75-

80 cm, these small birds have a broad conical shaped bill with a horny sheath that partly covers their nostrils. This strong bill is their most identifiable trait. They have strong legs and unwebbed feet, making them better at gathering food on land rather than at sea. Snowy Sheathbills also have a thick underlayer of

Figure 23. Map of the distribution of Snowy Sheathbills along the rocky coastline of the Antarctic Peninsula all the way to the southern tip of South America.
http://www.mbgnet.net/salt/sandy/animals/imageRVK.gif

feathers that insulates them from the cold Antarctic air (Snowy Sheathbill 2016).

Snowy Sheathbills can be found around piles of kelp washed up on beaches or in grasses and bogs on the islands. This is where they tend to scavenge for food, whether it is human trash and leftover food or small invertebrates tangled in the washed up seaweeds. These birds are such scavengers that they have even been known to eat the umbilical cord of seal pups while being birthed on beaches. Snowy Sheathbills will eat just about anything, including other animal feces, trash, animal remains, whatever they can find that day (Fang E 2010).

Due to the fact that Snowy Sheathbills will eat just about everything, one of the threats these birds face is poisoning from pollution. Chemicals from human waste and trash can be hazardous to these birds if not regulated in some way. Another threat that was once an issue but no longer seems to be of much concern is human hunting. These birds used to be hunted but when there was no real economic value to them, the hunting stopped. Human interactions have since then been limited, though these birds will not shy away from people if it means food. These birds are considered to be of least concern on the IUCN Red List. The only well studied predator of the Snowy Sheathbill are Brown Skuas that have been known to dive at Sheathbill chicks (Snowy Sheathbill 2016).

Tardigrades

Figure 24. A Tardigrade sitting on lichen.
https://www.washingtonpost.com/news/speaking-of-science/wp-content/uploads/sites/36/2015/04/11b.-Tardigrade_SciSource_BS9660_final2.jpg

Tardigrades, also known as Waterbears, are small microscopic invertebrates that are capable of living in extreme environments. *Acutuncus antarcticus*, the Antarctic species of Tardigrades, live in the marine environment amongst other benthic invertebrates (Tsujimoto M 2016). There are currently 400 known species worldwide, 140 of which are marine species, though scientists predict there are thousands more yet to be discovered. These different species can vary in color, ranging from orange or red to green, like the Antarctic species. These bizarre animals have an outer layer made of chitin, proteins, and lipids, and have four pairs of legs each with 4 to 8 claws used for grasping their food and the surface. They can grow up to 1 mm long and can easily be seen with a microscope (Lindahl K, Balser S. 1999).

The most interesting aspect of Tardigrades are their ability to live in just about any environment, including the extreme cold of Antarctica. Tardigrades can undergo anhydrobiosis, meaning they replace the water in their cells with a specific sugar. They lower them metabolic rate to 0.01% of their normal rate and they curl into a small ball called a Tun. Tardigrades do this when they are in an environment void of water. They can survive for years in the Tun phase and when re-exposed to water, will rehydrate themselves and go on to live a normal life. Another adaptation that Tardigrades have is the ability to undergo cryptobiosis when the environment is cold. Cryptobiosis is when the Tardigrade stops all metabolic processes, all reproduction, all development, and all repair. Tardigrades can survive -200° C and the freezing and thawing process. They can also withstand change in salinity, pressure, and oxygen availability. This is especially useful for the Antarctic species

Figure 25. A comparison of a Tardigrade fully hydrated and a Tun, the dehydrated version of a Tardigrade. https://s-media-cache-ak0.pinimg.com/236x/7b/f4/3a/7bf43a2c48449f8e902fccfc2a38af93.jpg

(Mullen L 2002).

Tardigrades also have other adaptations that allow them to withstand levels of radiation that are 100 times more lethal to humans and animals. Because of all these different adaptations that allow Tardigrades to live in such extreme environments, scientists have looked into the lifestyles of these little animals to predict what life on other planets could be like. Scientists have also looked into sending Tardigrades into space to see if they could survive for extended periods of time (Mullen L 2002). One study in 2007 pushed the Tardigrades adaptations to the limits and exposed dehydrated Tuns to the vacuum and solar radiation of outer space for 10 days. Upon their return they rehydrated the animals and the majority of the specimen, around 63%, came back to life and went on to reproduce. This was a huge step for science and understanding the way life on other planets might work (Stromberg J 2012).

Back here on earth, Tardigrades can live just about anywhere, though they prefer areas where moss or lichen is available. They have two stylets used to pierce their prey, which can be anything from plants and bacteria to other Tardigrades and rotifers. The few known predators include Amoebas, Nematodes, and other Tardigrades. Besides the organisms that eat them, Tardigrades do not have very many threats (Mullen L 2002).

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Species Interactions

This section discusses the ecology, inter- and intraspecific interactions, and life histories of organisms living in polar regions. Specific examples are drawn from various niches in arctic and antarctic communities.

Primary Production

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Edited by Alexandra Makucewicz
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Introduction

Primary production is the process of converting light energy into chemical energy which fuels the biological processes of photosynthetic organisms. In polar regions, the majority of the primary production occurs below the sea ice in the form of algal communities (Lizotte 2001). Global climate change is causing the sea ice to melt, threatening the essential primary production process.

Globally, primary production is highest in coastal waters and at the poles. High primary production in coastal waters is due to precipitation and runoff from inland waterways. Production at the poles is generally attributed to the colder, more nutrient-rich water found there. Other factors that affect production levels are upwelling, sea-ice coverage and the amount of available light for use in photosynthesis, or PAR (photosynthetically active radiation) (Priddle et al. 1992).

As in other climates, polar region productivity levels vary throughout the year. Productivity in these areas rises and falls along with the sea ice coverage. Figure 1, illustrates seasonal change in polar communities, and shows that there is more ice coverage April through May, more open water June through August, and then ice begins to form again in September. There is also a productivity difference based on the age of the sea ice. First year ice is the seasonal ice that is only present no more than one year before melting, reaching a thickness of 0.3-2m (NSIDC 2016). Figure 1 shows the correlation between first-year ice and the type of dominant primary producers. When there is more first-year ice, sub-ice algae communities are dominant. When there is less first-year ice and more open water, phytoplankton is dominant.

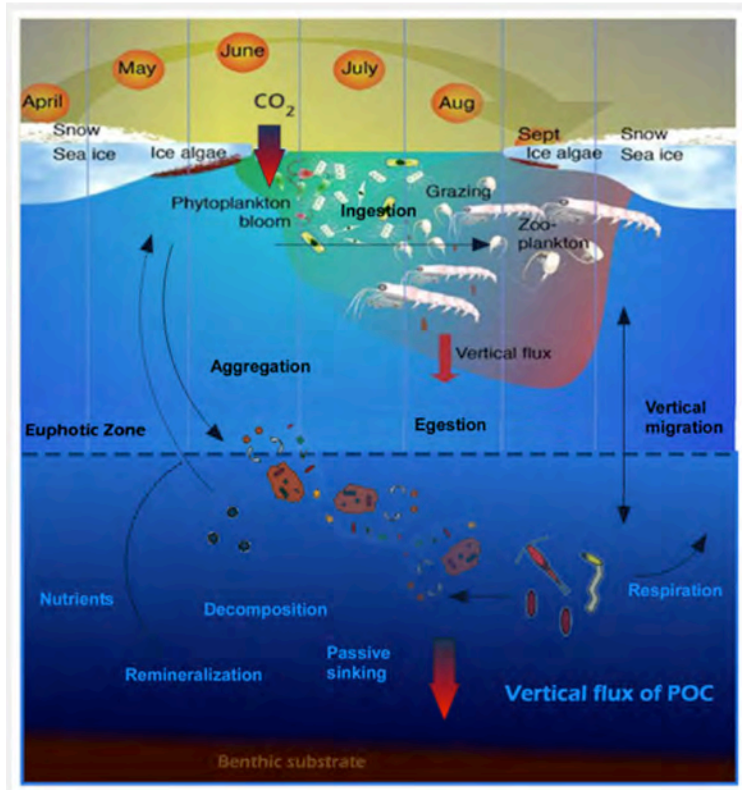


Figure 1. This figure shows the trend of the marine ecosystem throughout the year from maximum ice coverage to the next season of maximum ice coverage. There is maximum ice coverage between September and April. Ice begins to melt in May and re-form in September. When there is more open water, phytoplankton are in high abundance. When there is more first-year ice, the sub-ice algae communities are in high abundance. This figure also shows the factors affecting primary production, such as grazing, vertical mixing and sinking. (http://neba.arcticresponsetechnology.org/report/chapter-1/13/)

Nutrient Sources and Limiting Factors

In the Arctic, there is significantly more ocean than land. The nutrient sources in this area for phytoplankton are runoff, sediment deposition from rivers, and falling dead organic matter called marine snow. In the Antarctic, the main source of nutrients for marine photosynthetic organisms is runoff from melting ice and marine snow. Antarctica does not have rivers, so river runoff and sediment deposition are not contributing factors in this region.

There are two types of limiting factors in primary production: physical and chemical. The physical parameters are PAR, vertical mixing of the water column, grazing by zooplankton and other organisms, sea ice coverage and UV radiation (Priddle et al. 1992). The chemical parameters are inorganic chemicals such as nitrogen, phosphorus, silica and iron with nitrogen being the most significant.

Phytoplankton needs sunlight in order to create energy, but there is variety in the wavelengths that make-up sunlight. Different wavelengths of light correspond with different types of light. The wavelengths of light that correspond to PAR are 400-700nm (Mottus et al.). More available sunlight increases PAR levels, and therefore production.

Vertical mixing within the water column is another important parameter because phytoplankton and algae are passive swimmers carried along with the movement of water. Melting sea ice adds more freshwater to the water column resulting in vertical mixing.. This influx increases the stratification of the water, carrying phytoplankton to depths where there is insufficient light. Low light reduces photosynthesis, which reduces primary production levels. Figure 2 shows the correlation between sea ice coverage and primary production in the Arctic.

Sinking is also a significant event that affects the primary production levels. A majority of the marine primary producers in Polar regions are found below sea ice., in large sub-ice algal communities that attach to the underside of the ice sheets forming mats (Lizotte 2001). When the ice sinks, the algal community sinks as well, below the reach of adequate sunlight. Sub-ice algal mats are also subject to grazing by zooplankton and are a top food source for krill.

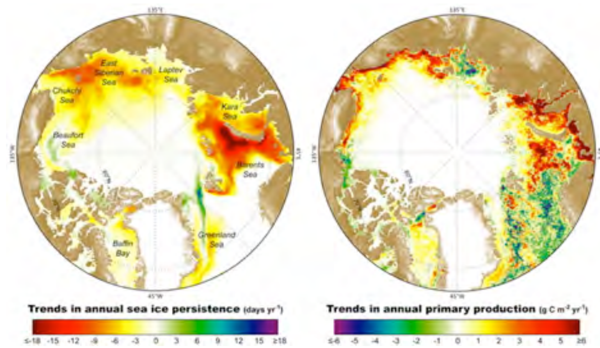


Figure 2. This figure shows the correlation between sea ice coverage and primary production in the Arctic. (Frey et al. 2011)

The chemical nutrients iron, nitrogen, phosphorus and silica are important in determining the ocean's productivity. Silica is essential to many types of phytoplankton because their exoskeletons made of silica. The Southern Ocean accounts for 80% of the biogenic silica (Rivikin and Putt 1987). Much of the ocean's nitrogen is found in the nitriocline level of the water column. As the sea ice melts, the nitrocline moves deeper within the water column, approaching depths where there is insufficient light for photosynthesis (Frey et Al. 2015).

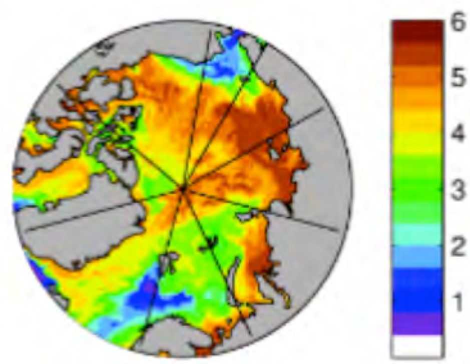


Figure 3. Average annual short-wave UV Radiation for the summer in the Arctic (Popova et aL. 2010).

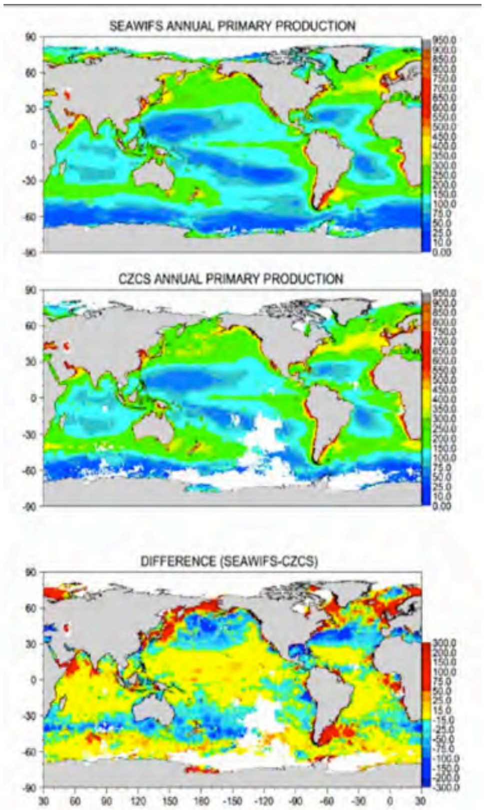


Figure 4. Global distribution of primary production. (Gregg et al. 2003)

The Arctic and the Antarctic are each polar regions. The two regions share some nutrient resources and some limiting factors that differentiate them from warmer climates, but they also differ in some respects. Primary producer species differ somewhat between the two poles, but more significantly from other ecosystem types. Warmer waters have fewer available nutrients resulting in lower primary production. In temperate regions, there are more temperature fluctuations and mixing, which leads to more seasonal trends in productivity. Table shows the different types of ecosystems and their average world net primary production in pedagrams of organic matter. Figure shows the global distribution of primary production.

Distribution

Primary producer distribution fluctuates based on the contributing factors present. The steepest increase in chlorophyll-a production was between 2003 and 2015, but there was also a 30% increase in net primary production between 1998 and 2012 (Frey et Al. 2015). The Arctic inflow shelves account for 75% of the annual primary production, and also accounts for 50% of the primary production in the Arctic Ocean (Frey et al. 2015). Abnormally

Arctic:

Primary producers

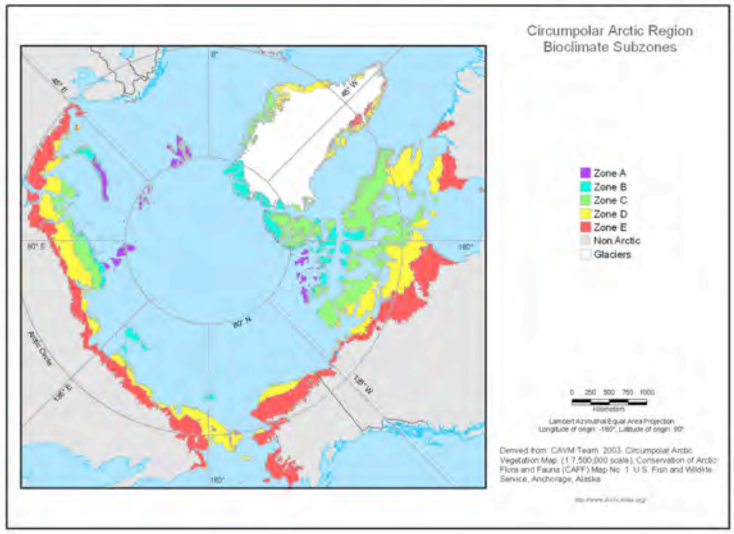
In the Arctic, there are both terrestrial and marine primary producers. Perhaps surprisingly, there are 1,700 plant species in the arctic, primarily dwarf shrubs, mosses and grasses (Fries-Gaither 2009). The Arctic is divided up into bioclimatic zones (Figure 5), defined differently by different scientists. There are different types of producers in each zone. Mosses dominate the north portion of the Arctic, while herbs and grasses dominate the south. The primary producers found in the Arctic Ocean are phytoplankton and algae. The abundance of these producers is highly variable due to the passive nature of their locomotion.

Ecosystem Type	Surface area (x 10^6 km^2)	NPP (Pg)
Forest	31	48.7
Woodland, grassland, and savanna	37	52.1
Deserts	30	3.1
Arctic-alpine	25	2.1
Cultivated land	16	15.0
Human area	2	0.4
Other terrestrial (chapparral, bogs, swamps, marshes)	6	10.7
Subtotal terrestrial	147	132.1
Lakes and streams	2	0.8
Marine	361	91.6
Subtotal aquatic	363	93.4
Total	**510**	**224.5**

Table 1. The types of ecosystems, their surface area and the net primary production in Pedagrams of organic matter. (The Flow of Energy…2008)

high chlorophyll levels were noted in 2015 in the Bering Sea, Labrador Sea, Barents Sea (May), Fram Strait (June), Siberian Kara Sea, Laptev Sea (July) (Frey et al. 2015).

Primary production levels are highly affected by the seasons, currents and sea ice. In the Arctic, there are usually significant blooms seen in September when there is the least amount of ice coverage. The timing of this bloom is becoming earlier due to climate change. With warmer temperatures, there is less year-round ice. Sea ice melting is causing the blooms to occur in July rather than September (Popova et Al. 2010). The blooms also are a good indicator for water turbidity. Turbidity is the amount of organic and inorganic material suspended in the water column (NOAA 2015). In January, there is minimal turbidity in the Arctic. Recently, turbidity increases towards April and peaks in July, leading to the early blooms. Turbidity decreases again towards October. Phytoplankton levels correlate to turbidity levels. Arctic summer brings a bloom fed by a corresponding spike in turbidity and PAR. Arctic winter brings low to no turbidity, more ice coverage, no bloom.



Arctic Bioclimatic Zonation Approaches			
Arctic Zones	Polunin 1951	Matveyeva 1998	Yurtsev 1994
A	High Arctic	Polar Desert	High Arctic Tundra
B	Middle Arctic	Arctic Tundra	Arctic Tundra; Northern Variant
C		Typical Tundra	Arctic Tundra; Southern Variant
D	Low Arctic		Northern hypo-Arctic Tundra
E		Southern Tundra	Southern hypo-Arctic Tundra

Figure 5. The Arctic's bioclimatic zones with respect to the bordering land, and shows the zonation based on different definitions established by various scientists (Toolik-Arctic Geobobotanical Atlas 2015).

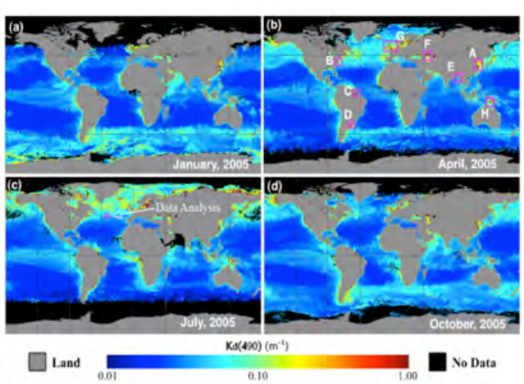


Figure 6. This figure shows the global turbidity trends (Shi and Wang 2010).

Antarctic:

Primary producers

In the Antarctic there are significant numbers of both marine and terrestrial primary producers. The marine contributors are algae and phytoplankton. Phytoplankton accounts for 5% of the annual Antarctic primary production (Lizotte 2001). The terrestrial contributors include a wide variety of low-lying plants such as lichens, mosses, liverworts, macro fungi, and some flowering plants. Some of the plant species are Antarctic Hairgrass (*Deschampsia antarctica*), Antarctic Pearlwort (*Colobanthus quitensis*) and Tussock Grass (*Deschamsia angusta* (Fries-Gaither 2009). Some of the main phytoplankton species are *Thalassiosira spp*., *Corethron cirophilium* and *Nitzchia spp*. There are also several species of phytoplankton found in Antarctica that are in the *Fragilariopsis* genus.

Key Antarctic Ice-Bound Primary Producers		
SIZ Pack Ice Communities	*Fragilariopsis cylindrus*	
	Fragilariopsis curta	
	Phaeocystis Antarctica	
Crack Pools	*Fragilariopsis cylindrus*	
Older Ice	*Fragilariopsis kerguelensis*	
	Dactyliosolen	

Table 2. Key ice-bound primary producers in the Antarctic. SIZ= Seasonal Ice Zone (where ice presence is seasonal compared to year-round) (Lizotte 2010).

Key Antarctic Phytoplankton Species and Abundance		
Location	**Species**	
N. Weddell Sea	*Thalassiosira spp.*	
	Thalassiosira antarctica	
Drake Passage (nearshore) and Bransfield Strait	*Corethron cirophilium*	
Drake Passage (offshore)	*Nitzchia spp.*	
	Rhizosolenia spp.	
	Distephanos speculum	

Table 3. The Antarctic phytoplankton species with their distribution (Sommer 1988).

Distribution

In the Arctic, primary production levels are higher where there is thick snow coverage (Arrigo et al. 1997). When surface snow melts, pools of water form in the packed snow and ice which increases melt and sea ice retreat. The main influences on primary production are sea ice retreat and wind-driven mixing (Taylor et al. 2013). About 60% of the annual Arctic production occurs in November, when there is maximum ice coverage (Arrigo et al. 2013).

In the Antarctic, the Southern Indian Ocean, the Weddell Sea and the Ross Sea combined account for 85% of the annual production levels (Arrigo et al. 2013). On a daily scale, normally the highest production levels occur around noon in early September (Rivkin and Putt 1987). Climate change has shifted the peak to midnight in late October (Rivkin and Putt 1987). The seasonal ice zone accounts for about 63-70 Tg C yr^{-1} (Tg C $year^{-1}$= teragrams of carbon / years) annual production while the marginal ice zone accounts for about 36 Tg C yr^{-1} annual production (Lizotte 2010). This supports the finding that there is higher production in the seasonal ice that is more subject to melting. Figures 7 and 8 show the primary productivity in the seasonal ice zone (SIZ) and the sea ice surface communities respectively.

There are more blooms in the Antarctic than the Arctic. In the Antarctic, there is a spring and a summer bloom. In November, there is an increase in light availability, which causes the bloom. The main cause of the shift in bloom presence is melting ice, which cause increased vertical mixing of the water column. According to a study done by Lizotte 2001 there is a bloom the Antarctic summer (January). A rise in turbidity is also seen during this time. Likewise, in what would be the Antarctic spring in October, it can be seen that turbidity increases again, which corresponds to the spring phytoplankton bloom.

Figure 7. Map of Antarctica and Drake Passage (http://www.destination360.com/antarctica/antarctica-map , http://wietelworld.com/Antarctica/Drake%20Passage%20-%20Aitcho%20Island%2028%20December%202007.html).

Effect of Climate Change

The algal communities that make their home on the underside of first-year ice are a main contributor to the production levels in the Antarctic. Scientists predict an increase in primary production with climate change because of more melt leading to more open water. Warming temperatures and more open water will allow phytoplankton and algae to thrive, increasing the productivity levels. A study done in 2010 saw a 90% decrease in phytoplankton in the Antarctic. Contrary to this, in the Arctic, primary production has increased by 20% since 1981 (Lindsey 2011).

Climate change is being studied extensively in order for scientists to make predictions about the effect rising

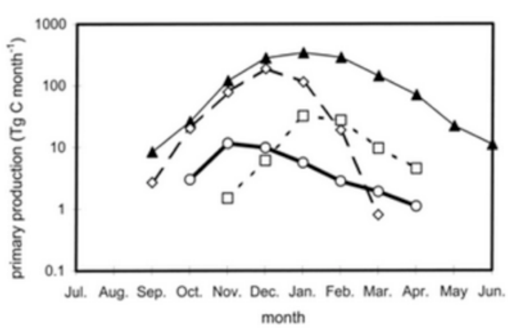


Figure 8. Monthly Antarctic primary production in the Seasonal Ice Zone. Lizotte 2001

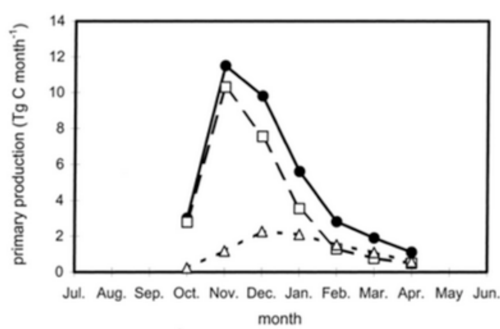


Figure 9. Monthly primary production levels in the sea ice surface communities. Lizotte 2001

temperatures will have on polar regions, and the world. The effect of climate change on primary production globally is still being studied. With general production levels decreasing globally, it is crucial that it is a topic that is continued to be studied in order to proper understand the possible outcomes. Figure and table show the global trends of primary production.

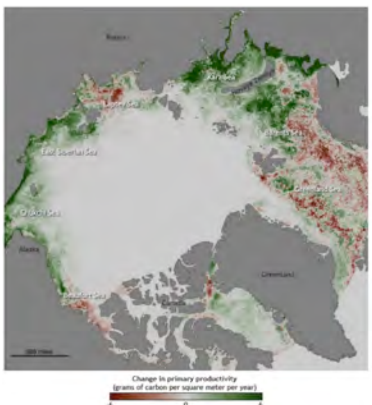


Figure 10. Image shows the change in Arctic productivity between 1998 and 2009. Green shows increase and brown shows decrease (Lindsey 2011).

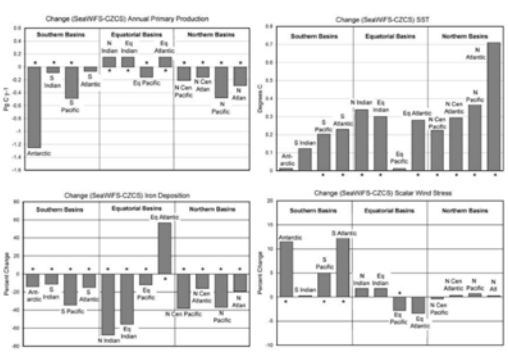


Figure 11.Difference between SeaWiFS (1997-2002) and CZCS (1979-1986) in the 12 major oceanographic basins. (Gregg et al. 2003)

Basin	Area	Change
N. Atlantic	1.83	−6.7%
N. Pacific	2.32	−9.3%
N. Central Atlantic	1.53	−7.0%
N. Central Pacific	3.22	−5.8%
N. Indian	0.46	13.6%
Eq. Atlantic	1.15	6.9%
Eq. Pacific	3.72	−3.0%
Eq. Indian	1.37	8.8%
S. Atlantic	1.20	−3.8%
S. Pacific	2.69	−14.0%
S. Indian	1.77	−4.2%
Antarctic	8.28	−10.4%
Global	29.73	−6.3%

Table 4. Percent change in ocean primary production by basin and surface area basins ($10^7 km^{-2}$). (Gregg et al. 2003)

Summary:

In polar regions, primary production is most closely linked to marine primary producers because of year-round ice coverage. There are similar nutrient sources and primary producers seen in both the Arctic and the Antarctic, but there are also major differences. Current climate change researchers in each polar region seek to determine the effect warmer temperatures and ice-melt will have on the regions and the earth as a whole. Because melting sea ice is a predictable consequence of climate change, and sea ice cover is crucial for polar primary production, and primary producers are an essential part of the food chain, it is essential to understand the effects of climate change on polar regions and their unique ecosystems.

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Images:

Antarctic map
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Dactyliosolen
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Drake Passage map
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Fragilariopsis curta
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Food Webs

Ashley Breault
Edited by Kaitlyn Kennedy and Halie Pruitt

The Arctic and Antarctic may be similar in some ways, but there are also quite a few ways in which they are different. In this chapter we will focus on the food webs of these different regions. Food webs look at the organisms in a specific location and how they are interrelated in their feeding habits. Food webs show which trophic level, or hierarchy in the ecosystem in which all organisms share the same ecological function and have the same nutritional relationship, that a particular organism is at, which help scientists better understand the ecosystem as a whole. By looking at the food webs of these two polar regions, we can take a further look at the similarities and differences between them.

Antarctic Food Webs

Primary Producers and Consumers

At the base of all food webs are primary producers. In the Antarctic, phytoplankton that live in the ocean makes up the biggest source of primary production, though terrestrial plants do make up a small portion of the primary production that occurs. In fact, about 9% of all ocean primary production is done in Antarctic waters by these photosynthesizers (Xavier *et al* 2015).

The few terrestrial plant species in the Antarctic live on the small portion of tundra that exists on the Antarctic Peninsula. It supports two flower place species, mosses, and lichens (Fries-Gaither 2009). Though these terrestrial plants exist, this chapter will mainly focus on the marine primary producers because of their importance to the ecosystem.

The primary phytoplankton that lives in these waters are dinoflagellates, diatoms, and coccolithophores. “Ice algae” – or phytoplankton that live under the ice shelves – are diatoms that are an important food source for organisms of higher trophic levels, including Krill (Xavier *et al* 2015).

Due to the drastic changes in weather and the oceans throughout the year in the Polar Regions, the amount of primary production that occurs varies seasonally. In their summer months (October to March), the Antarctic has 24-hr daylight, whereas their winter (April – September) consists of complete darkness. Because of this season variation, the summer months result in much higher primary productivity than the winter months because of the light that is available (Smith *et al*. 1998). The nutrients available also affect how much primary production will occur, meaning if there are not enough nutrients, then the primary productivity will be low.

This seasonal variation of primary production has an affect on the higher trophic levels that take advantage of the primary producers. The zooplankton that eats the phytoplankton must either be able to handle long periods of time without food, or the zooplankton’s predators must be able to. These zooplankton are the next step in the food web. These small organisms, such as copepods and krill, are important food sources for those organisms of higher trophic levels and are important predators to the phytoplankton (Xavier *et al* 2015).

Antarctic krill, *Euphausia superba*, are the major link between primary producers & vertebrate predators. These krill take advantage of the ice algae under the ice shelves. The sea ice is an important nursery and grazing habitat for the krill because it is protected from predators (Antarctic krill 2016). Studies have shown that there is a correlation between the amount of sea ice and the biomass of krill. More ice has been shown to result in significantly higher krill numbers. Less ice shows significantly lower krill numbers, and higher Salp biomass. Salps are barrel-shaped, planktonic tunicates that live in the water column. They are less nutritious to predators than krill, which makes higher salp biomass detrimental to those higher trophic levels (Xavier *et al* 2015).

The Antarctic krill have a 5-7 year life span and are omnivorous, eating primarily phytoplankton, though may eat smaller zooplankton if needed. They are found between 65° and 75° S latitude. In the Scotia Sea however, they can be found as far north as 53° S latitude. The krill biomass in the Southern Ocean is about 1.5 billion tons, meaning there is a large amount of krill available during the phytoplankton blooms. Their distribution patterns are closely linked to sea ice conditions, and as a result if the amount of ice drastically decreases, the krill biomass will significantly decrease as well (Saba *et al* 2014).

Antarctic krill make up to 95% (by mass) of the diet of Crab-eater Seals and Minke Whales. They make up 50 % or more of the diet of Macaroni Penguins, Black-browed Albatrosses, and Fur Seals. They also make up at least 1% of the diet of many other organisms, including other fish, birds and seals, squids, and other zooplankton (Xavier *et al* 2015).

Though they are not considered a keystone species, krill are very important organisms to this environment and their presences or absence affects many of the higher trophic levels. Because of their significance, scientists are concerned with the rising temperatures and the melting ice and what that affect would have on not only the biomass of the krill, but also the Antarctic food web as a whole (Saba *et al* 2014).

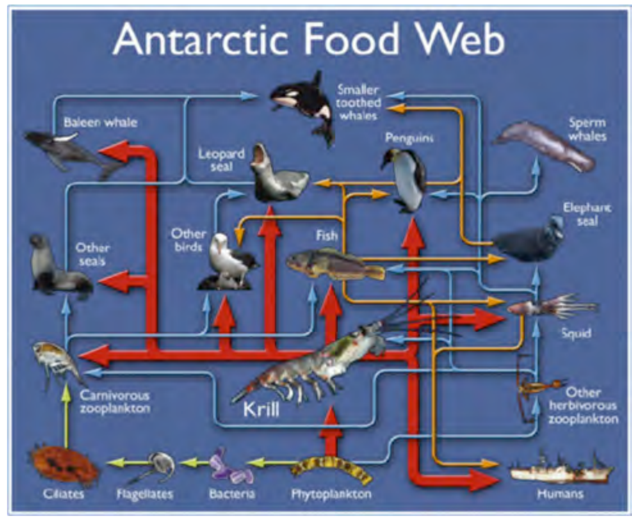

Figure 1. Antarctic food web that emphasizes the importance of krill to other trophic levels. http://coolantarcticabynoah.weebly.com/uploads/1/8/5/2/18528768/4393407.jpg?584

Secondary Consumers

The next trophic level on the food web includes fish, cephalopods, and some marine mammals.

The fish in the Antarctic are a major food source for many organisms. There are more than 200 fish species that call the Southern Ocean home. More than 85% of these species are native to this ocean. Some studies have found that the fish in the Southern Ocean that live deeper than 200 meters are related to species of fish that live in warmer waters around the world but are found at depths greater than 1000 meters and that live on or close to the sea floor.

They have been found to have similar adaptations because the conditions of that of 200 meters deep in the Southern Ocean are so similar to that of 1000 meters deep in many other oceans around the world (Xavier *et al* 2015).

Some specific species of fish include the Antarctic Silverfish, Antarctic Deep Sea Smelt, Antarctic Snaggletooth, and the Lanternfish. The Antarctic Silverfish accounts for about 90% of biomass of mid-water fish in the Southern Ocean (Xavier *et al* 2015).

Cephalopods, including squid, feed primarily on fish and crustaceans. They are eaten by seabirds, seals, whales, and larger fish. There are approximately 70 species of Southern Ocean cephalopods. Many of these species are native to the Antarctic and are only found in this region. These cephalopods only have one reproductive cycle, have lower growth rates, and have greater longevity in comparison to their temperate and tropical relatives (Xavier *et al* 2015).

The Antarctic Colossal Squid is one of the species that is found only in the Southern Ocean. *Mesonychoteuthis hamiltoni* is the largest squid, measuring greater than 14 meters in length. They also have the largest animal eye on earth measuring greater than 28 centimeters. Even though these organisms are so large, they are an important food source for many organisms it the Antarctic. They make up 77% (by mass) of the diet of Sperm Whales, up to 52% of the diet of Sleeper Sharks, and make up about 1% of the diet of Wandering Albatrosses, Patagonian Toothfish, and Southern Elephant Seals (Xavier *et al* 2015).

The marine mammals that feed on lower trophic levels, like krill, are Baleen Whales. The Blue, Fin, Humpback, Minke, Sei, and Southern Right Whales are Baleen whales found in the Antarctic and take advantage of the high krill biomass that exists there. A typical whale's lifespan is generally between 20 and 40 years, though some have been found to live as long as 80 years. All Antarctic whale species migrate throughout their lives. They travel long distances to feed in the cold nutrient rich waters of the Southern Ocean in the summer months and then head north to warmer waters to breed and give birth in the winter months (Whales 2016).

Figure 2. Many of the different organisms that live in the Antarctic. A. Macaroni Penguins, B. Black-browed Albatrosses, c. Leopard Seals, D. Southern Elephant Seals.
http://site.ebrary.com.une.idm.oclc.org/lib/unelib/reader.action?docID=11123066&ppg=229

Tertiary Consumers and Top Predators

Moving up the food web, are the higher trophic levels. These include the top predators found in the Antarctic. All top predators found here are marine, though they live close to or on the continental shelf.

Some of the secondary predators include the Emperor and Adelie penguins and Antarctic Petrels. These birds feed on cephalopods, crustaceans, and small fish.

Weddell Seals also feed on squids, crustaceans, and small fish (Xavier *et al* 2015)

Top predators include Leopard seals, Elephant seals, and Killer whales. Leopard seals feed on penguins and Fur and Elephant Seals. Killer whales feed on Minke Whales, penguins, fish, squid, and seals, making the Killer Whale the top of the food web for the Antarctic, not taking into consideration Human impacts (Xavier *et al* 2015).

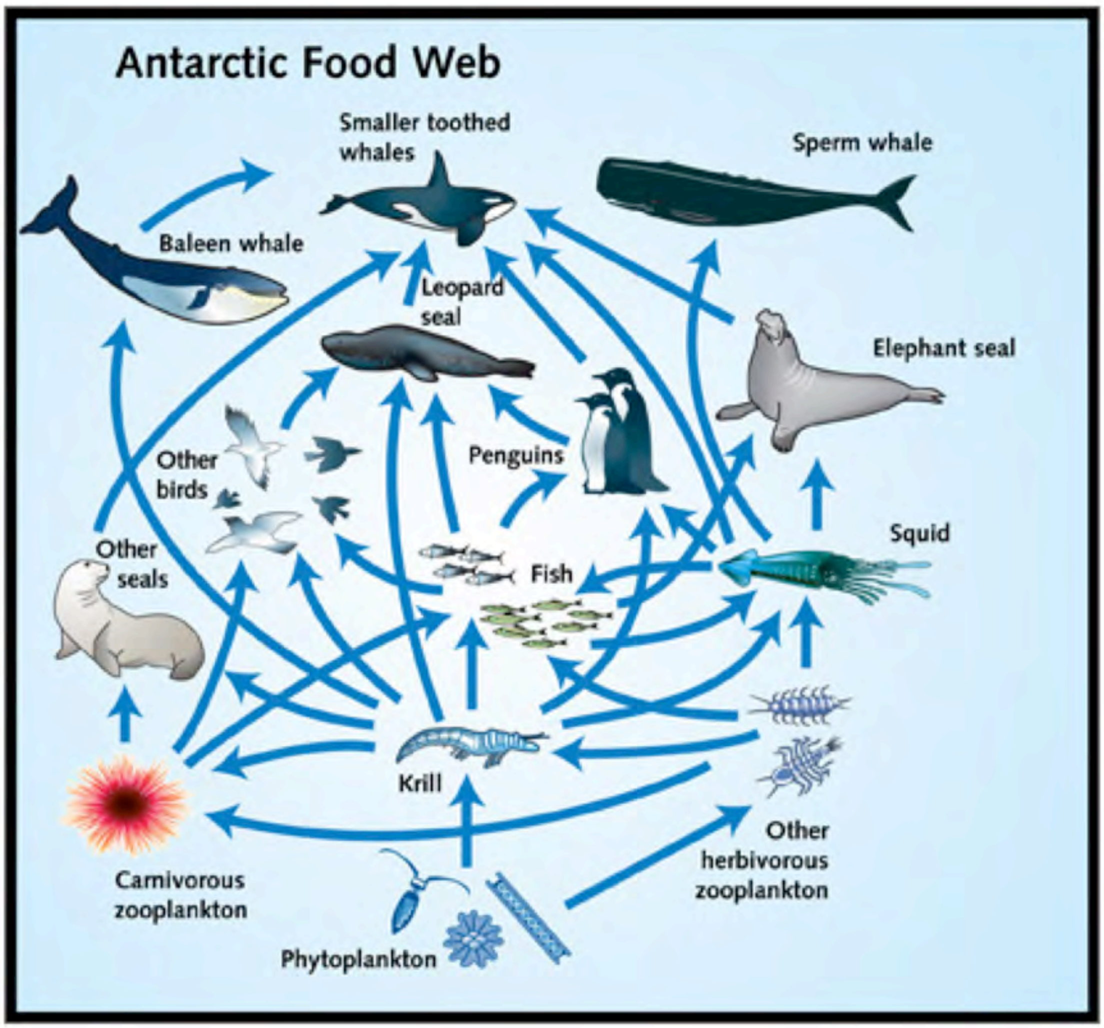

Figure 3. Antarctic food web starting with krill and ending with small toothed and baleen whales.

Figure 4. Arctic tundra is located in the Northern Hemisphere (shown in yellow), and is characterized by being a vast, treeless flat land that has a cold climate, little precipitation, poor nutrients, and a short growing season.

http://beyondpenguins.ehe.osu.edu/issue/tundra-life-in-the-polar-extremes/life-in-the-tundra

Arctic Food Webs

The biggest significant difference in primary production between the polar regions is the availability of terrestrial plants in the Arctic. Due to this presence of a tundra, where the subsoil is permanently frozen though not always covered in snow as seen in Figure 4, there are terrestrial plants to take into consideration and therefore there are two different food webs we can look at: the terrestrial and the marine.

Marine Food Web: Primary Producers and Consumers

Like in Antarctica, the base of the food web starts with primary producers. Phytoplankton, again, are the biggest source of primary production. But in the Arctic, there are many more different terrestiral plants because not all of the land mass is covered in ice. The primary phytoplankton that lives in these waters are dinoflagellates, diatoms, and coccolithophores. Like in the Antarctic, Ice Algae are an important food source for organisms of higher trophic levels, including krill and other zooplankton (Xavier *et al* 2015).

The drastic seasonal variation also affects the Arctic, making primary productivity variable. This means that during their summer months (the Antarctic's winter months), the Arctic is light 24/7, whereas their winter months consists of complete darkness. Due to this seasonal variation, the summer months result in much higher primary productivity than the winter months because of the light that is available. Similar to the Antarctic, the nutrients available also affect how much primary production will occur, meaning if there are not enough nutrients, then the primary productivity will be low (Smith *et al*. 1998).

This seasonal variation of primary production has an affect on the higher trophic levels that take advantage of the primary producers. The zooplankton that eats the phytoplankton must be able to handle long periods of time without food.

After the primary producers (the phytoplankton), are the zooplankton. Krill are one of the main zooplankton in the

Arctic as well, though it doesn't make up as much of the diet of as many organisms as it does in the Antarctic. Instead, there are a wider range of different zooplankton, including pelagic crustaceans and amphipods. These are the main food source for many of the organisms at higher trophic levels (Fries-Gaither *et al* 2009).

Secondary Consumers

The secondary consumers in the Arctic waters include fish, cephalopods, and some marine mammals. The benthic fish feed on the zooplankton and detritus on the sea floor. These include species like Sculpins, Alligatorfish, Flatfishes like Flounders, and Gunnels. There are also many species of pelagic fish that swim in the open ocean and eat smaller fish and zooplankton. These include Cod, Salmon, and Lamprey (Fishes 2009). The cephalopods include squids and octopi and eat small fish and crustaceans. They are eaten by seabirds, seals, whales, larger fish, and marine mammals (Gardiner 2008).

Figure 5. Baby Harp Seal

http://eluxemagazine.com/wp-content/uploads/2014/01/baby-harp-seal-clubbingrelove-planet-whats-going-on-canadas-annual-seal-hunt-gqjmdbtx.jpg

Sea birds also take advantage of the marine organisms they can catch. Kittiwakes, Fulmars, and Gulls eat small fish, zooplankton, squid, and other small birds (Fries-Gaither 2009). Seals, like the Ringed, Bearded, and Harp (as seen in Figure 5), eat fish like Cod, Capelin, benthic fish, crustaceans, and squid.

There are 17 different whale species in the Arctic. These include both Baleen and Toothed Whales. Baleen Whales include Gray, Blue, Fin, Minke, and Bowhead Whales. Their diet consists primarily of krill. The Toothed Whales include Narwhals, Belugas, and Killer Whales. They primarily eat smaller whales, fish, squid, and seals (Arctic Whales 2016).

Top Predators

The top predators for the marine based food web are the Killer Whales, Seabirds (Fulmars, Kittiwakes, and Gulls), Sharks, Arctic Foxes, and Polar Bears.

Killer Whales hunt in pods of up to 40 individuals and prey upon fish and smaller marine mammals (Killer Whale 2016). Sharks, though more common in warmer climates, are found in the Arctic. Theses species of shark include the Greenland shark that preys on whales, polar bears, seals, and fish (Arctic Ocean Ecosystem 2006). Arctic foxes eat Ducks and other small birds and Ringed Seals (Arctic Fox 2016). Polar Bears hunt Ringed and Bearded Seals. Polar Bears are considered a keystone species because the size of their population has a direct and influential impact on the size of the Bearded Seal populations (Galicia *et al* 2015).

Terrestrial Food Web: Primary Producers

The terrestrial food web differs in that instead of starting with the primary production being done by phytoplankton, it is the terrestrial plants that are doing the photosynthesizing. There are 1,700 different species of plants found across the Arctic tundra. These include flowering plants, low shrubs, sedges, grasses, liverworts, lichens, and mosses. Because the tundra is still a difficult place to live, the plants are low growing, have shallow root systems, and are capable of carrying out photosynthesis with low light and cold temperatures (Fries-Gaither 2009).

Primary and Secondary Consumers

The primary consumers consist of animals like Caribou, Lemmings, Artic Hares, and Musk Ox. As herbivores, they live off the grasses, lichens, and marsh plants like liverworts. These animals are then eaten by Brown Bears and Arctic Wolves (Fries-Gaither 2009). The sea birds will also take advantage of the small land organisms they can catch. Snowy Owls are also considered secondary consumers feeding on Lemmings and small birds (Snowy Owl 2016).

Top Predators

Those organisms listed as primary and secondary consumer can fall victim to the top predators of the Arctic. Polar Bears are considered to be *the* top predator for both the marine and terrestrial food webs.

Marine Food Webs:

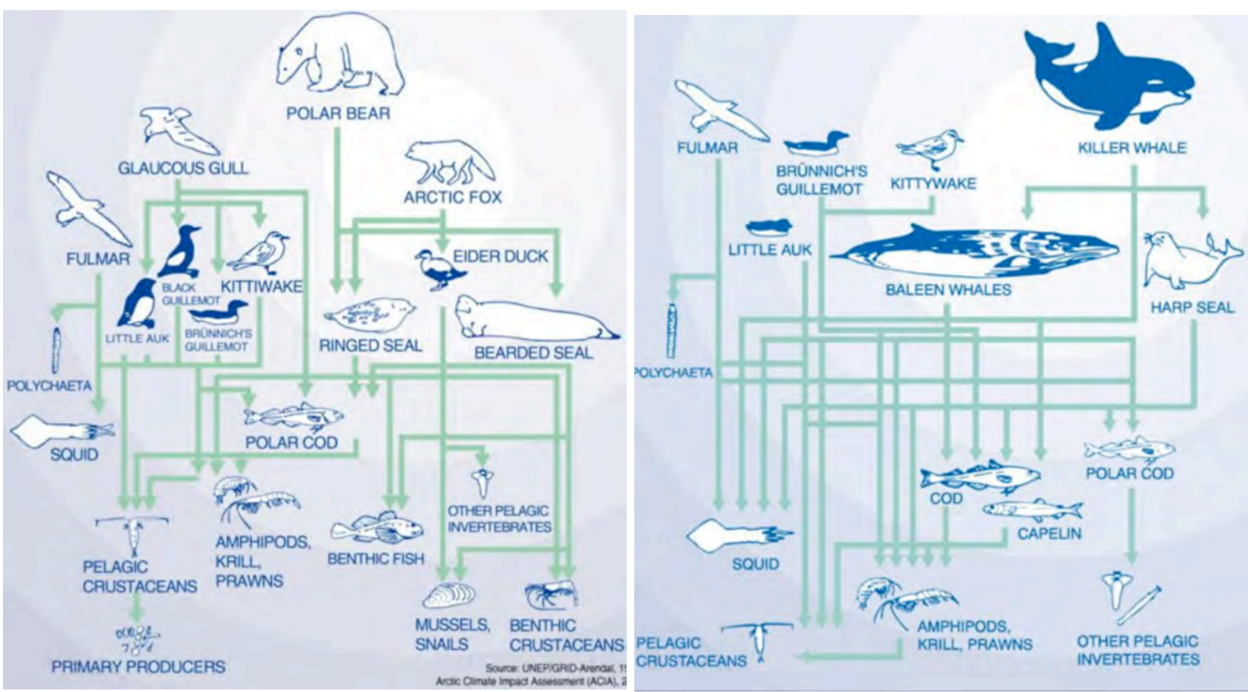

Figure 6. This food web shows two different marine food webs that point out the different tertiary consumers and top predators.
https://beyondpenguins.ehe.osu.edu/issue/polar-oceans/poles-apart-a-tale-of-two-oceans

Terrestrial Food Web:

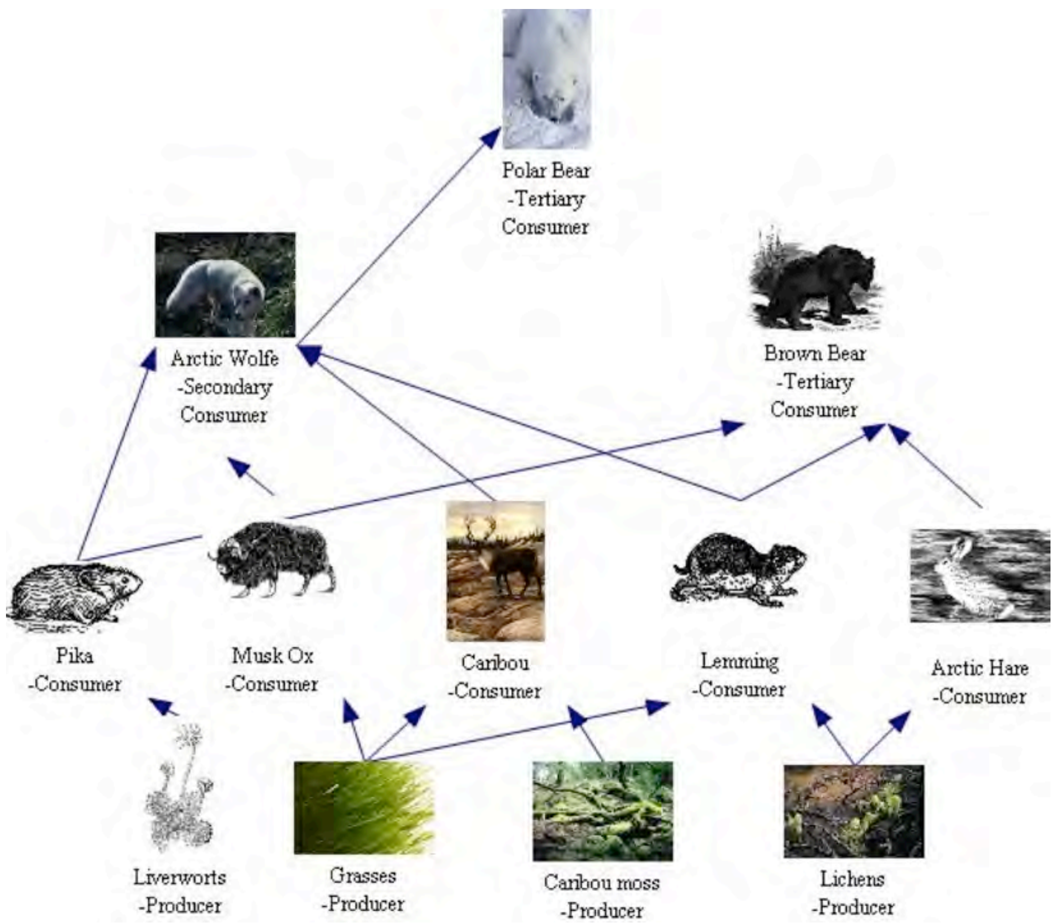

Figure 7. This food web shows the terrestrial organisms that live in the Arctic, from the grasses and lichen to the Polar Bear.
https://s-media-cache-ak0.pinimg.com/736x/99/29/43/99294370a7059a707466560d3ade6e02.jpg

How does climate change play a role in all of this?

In Antarctica, the marine species are among the least capable of responding to environmental changes, even the slightest temperature change is a lot for them to try to respond to. These organisms live in a very harsh environment, but they are perfectly adapted to do so. Because the range in which they live and are dispersed is very restricted, they have evolved to live in that very specific environment. These animals cannot cope with a wide range of environments and have long life histories in this environment. This results in slow adaptations to changes in their environments that may occur. It has been found that even a 2° C increase can be too much for certain benthic organisms to handle, and makes it impossible for them to carry out basic functions (Xavier *et al* 2015).

There has already been evidence that the temperature increase is affecting the krill populations. Like mentioned earlier, krill rely heavily on the sea ice for food and

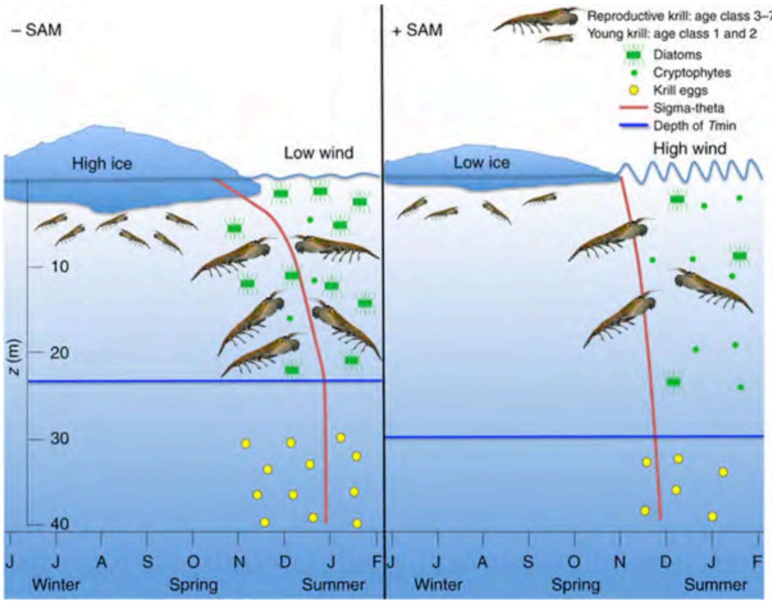

Figure 8. The relationship between the amount of sea ice and the abundance of krill is fragile and important. Krill use these ice packs to feed on ice algae, to spawn, and for protection from predators. The high ice results in more algae whereas the low ice results in less algae that, in turn, results in less krill.
http://www.nature.com/ncomms/2014/140707/ncomms5318/full/ncomms5318.html

protection. But if the sea ice disappears, then the krill are loosing a major food and habitat sources. One study found that there has already been a 50% loss in krill biomass in the Scotia Sea due to ice loss (Figure 8).

In the Arctic, the most talked about issue with climate change is the Polar Bears. The most talked about issue that affects the Polar Bears because of climate change is the ice melting. This creates less space for the bears to hunt, live, and breed on. If there is less ice, there is a higher probability of them drowning, not being able to find food or take care of their young. The fear is that if there are not enough Polar Bears, there might be too many seals and Arctic Wolves, which would disrupt the whole food web. But there is more to climate change than just the ice melting. Polar Bears are also being affected by pollution in the water and land, diseases, overharvesting, and loss of food sources. All of these pose a great threat to the bears and could (and are) affecting their life expectancy, their longevity, and their ability to adapt to the changing climate (Pollution 2016).

Overall, the food webs of the Arctic and Antarctic are diverse and delicate. Each species plays an important role, impacts its environment, and relies on the other organisms around it. But our earth is changing and it effecting the food webs and environments. By looking more closely at these effects on the polar regions, scientists will hopefully be able to better understand the changing world around us.

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Predator and Prey Relationships

By Rebecca Hudak
Edited by Briar Bragdon and Abigail Rhodes

Introduction

An important aspect of a food web is the relationship between predator and prey. There are various types of predator and prey relationships including the classic population model of a predator and how it affects a prey and vice versa. These relationships are not always restricted to a carnivore and an herbivore, but also includes symbiosis relationships. Symbiosis is a relationship between two or more different organisms living in close approximation. There are three main types of symbiosis: mutualism, commensalism, and parasitism. Some examples of these relationships include a barnacle living on a whale; or a remora swimming underneath a shark. Symbiosis occurs in many different ecosystems, but this chapter will focus on those that occur primarily in polar regions.

Mutualism is a relationship in which both of the organisms, the symbiont and the host, benefit from each other. These benefits can include (1) protection from a predator or from the environment (2) dispersal of spores, gametes, larvae, seeds, or other propagules (3) transport away from unsuitable habitats and (4) provision of energy, nutrients, or other substances necessary for growth (Amsler et al. 1999).

During Commensalism one organism benefits in the relationship while the other organisms involved neither benefits nor is harmed. The benefits that the organisms receive come in many forms including food, transportation, shelter, and seed dispersal. Ecologists separate commensalism into four main types: chemical, inquilinism, metabiosis, and phoresy (Sunny Scope 2014). Chemical commensalism is most often observed between two species of bacteria. It involves one bacteria feeding off the chemical waste product of the other bacteria. Inquilinism occurs when one species uses the body or body cavity of another organism as a platform or a living space neither benefiting nor harming the host. An example of this can be found in the relationship between barnacles and whales. Metabiosis occurs when one species is dependent on another for preparation of an environment in which another species can live. An example of this can be found in corals. As the coral grows it builds up a calcium carbonate skeleton that is no longer living. The living coral lives on the surface of the coral leaving the rest of the space for organisms to burrow into and make their home. A phoresy relationship takes place when one organism attaches to another organism specifically for the purpose of gaining transportation.

Toxicity, as a defensive mechanism, is commonly interpreted as alterations in normal cellular physiology, biochemistry, and morphology, leading to cell injury and in the extreme, cell death. Toxicants can destabilize cellular homeostasis through closely related or highly divergent mechanisms, including indirect relationships and cascade effects (Betharia et al. 2014). Organisms produce toxic compounds to prevent being ingested by predators and, in some cases, to weaken prey before ingestion. Toxic compounds can be produced by the organism itself or through the ingestion of certain foods.

Parasitism typically occurs when a parasite lives within or upon a host. There are many types of parasitism including endoparasites, ectoparasites, epiparasites, social parasites and brood parasites. Endoparasites live inside the body of the host, while ectoparasites live on the outside of the host. Epiparasites feed on other parasites. Social parasites do not directly feed on the tissue of their hosts, but rather convince the host to provide food or other benefits. An example of this is when some plants establish a mycorrhiza-like interaction with a fungal symbiont without any benefit. Mycorrhiza is a fungus that takes residence in the roots of a host plant. The plant gives carbon to the fungus and in turn receives better soil interface. In the parasitic relationship, the plant will take carbon from the fungus rather than donating carbon. Brood parasitism tricks a host into raising the parasite's young. For example the cuckoo bird places their egg into the nest of another species of bird. The cuckoo egg usually closely mimics the eggs of the host species. Once hatched, the Cuckoo chick shoves any eggs left in the nest over the edge. Due to the nature of the interaction between a host and a parasite many host populations will develop some form of immunity. This causes either a decline in the parasite population or a genetic mutation in the parasite population allowing it to overcome the immunity. This dynamic tends to form a cycle in the parasite population where there are periods of population increase and periods of population decrease in both species.

The Arctic is home to many kinds of species, but to focus on predator and prey relationships, we will take a closer look at Arctic foxes and lemmings. Arctic fox breeding success and population dynamics are strongly influenced by lemming populations (Angerbjorn et al. 1999). Lemmings, *Lemmus sp.*, prefer wet grasslands and feed mainly on sedges, grasses, and moss. There is an approximate 12 month Siberian lemming population pattern in relation to the Arctic fox. This is primarily attributed to the production rates of lemmings and Arctic foxes. Lemmings produce several litters a year in the winter and summer, while Arctic foxes only produce one litter every year. In a general predator and prey relationship, prey species have a large population size (Figure 1) and a smaller predatory species population. These two populations directly affect each other. If a prey population has many individuals then the predator population will begin to increase. As a result the prey population is put into check and begins to decline, which also shows a decline in the predator population, this trend then repeats.

Another example of a predator and prey relationship, in the context of Antarctica, can be seen in krill (*Euphausia superba)* and baleen whale (*Megaptera novaengliae)* populations. In autumn an extremely high density, 5.1 humpback whales per km^2, feeding on a super-aggregation of Antarctic krill was observed (Nowacek et al. 2011). Recent decreases in the abundance of Antarctic krill have been linked to reductions in sea ice while at the same time baleen whale populations in the Southern Ocean are recovering from past exploitation. This double effect shows an ever decreasing krill population in this area.

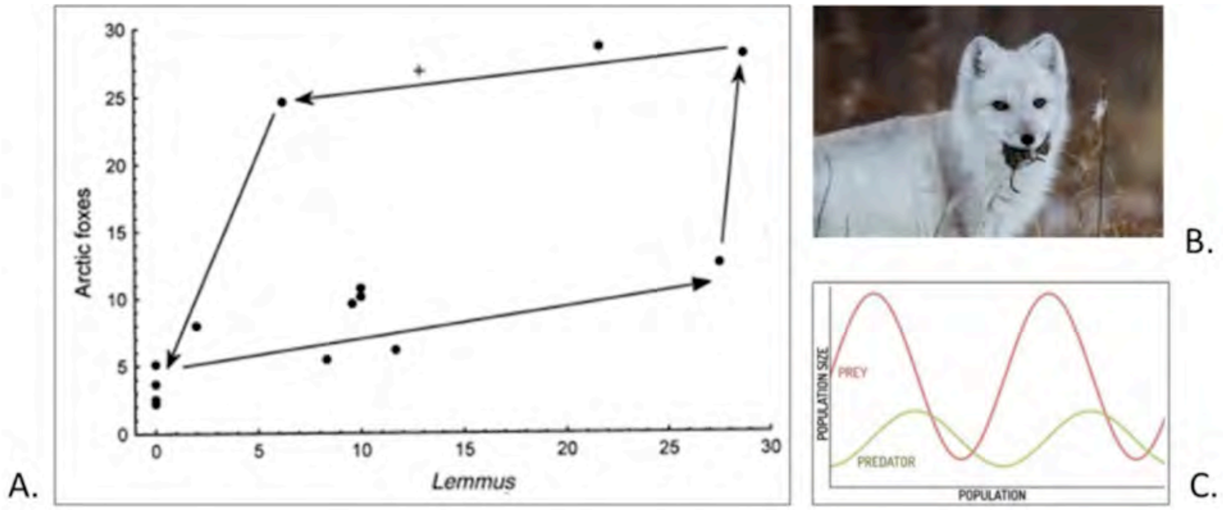

Figure 1. Predator and prey relationship between the Arctic fox and the lemming (A). The arctic fox (B) acts as predator while the lemming acts the part of a prey. A general predator/prey relationship (C) shows high populations of prey with lower populations of predators. Theses populations have a direct relationship, when prey is at its max the predator population increases forcing the prey population to decrease. In turn this decrease gives a decrease in the predator population. (Angerbjorn et al. 1999).

Arctic

The Arctic is known for its inhospitable environment with very little able to live in this area. Although it is a difficult place to live there is still a relatively large biodiversity in this area. The terrestrial ecosystem in the Arctic is dominated by permafrost, an area in which lichen thrives. Lichen is composed of a mutualistic relationship between green algae and fungus. There are many species of lichen because it can involve many different kinds of algae and fungus (Nash 2008). These organisms combine and form a thallus resembling moss or a small plant. The green algae is photosynthetic and turns carbon dioxide into a sugar that the fungus can feed on. In return the fungus can obtain nutrients from the substrate and retain any water. In this way each of the organisms provides what the other is lacking.

As mentioned earlier, the Arctic tundra is covered by a layer of lichen on the permafrost. The lichen is a main food source for caribou. As the caribou scavenge for lichen in the frozen ground they inadvertently reveal small mammals that live under the snow (Sunny Scope). These small mammals are food favored by the Arctic fox and once the caribou continues on its way, the fox digs in the thinner ground searching for the small mammals. As a result the Arctic fox follows the caribou in search of the next meal and falls in to a metabiosis commensalism relationship.

One of the characteristics of the Arctic environment is that it is highly oxygenated. Polar marine water is regarded as a strong pro-oxidant ecosystem due to its high dissolved oxygen levels and intense UV radiation during the summer, while its deep waters are considered refuges against oxidative stress. Pro-oxidant is a substance that accelerates the oxidation of another substance, in contrast to antioxidant, which inhibits oxidation. In these naturally oxygenated environments, toxic reactive oxygen species (ROS) are produced (Betharia et al. 2014). This leads to the development of antioxidant defenses by aerobic organisms to prevent tissue damage. Two arctic amphipods, *Anonyx nugax* and

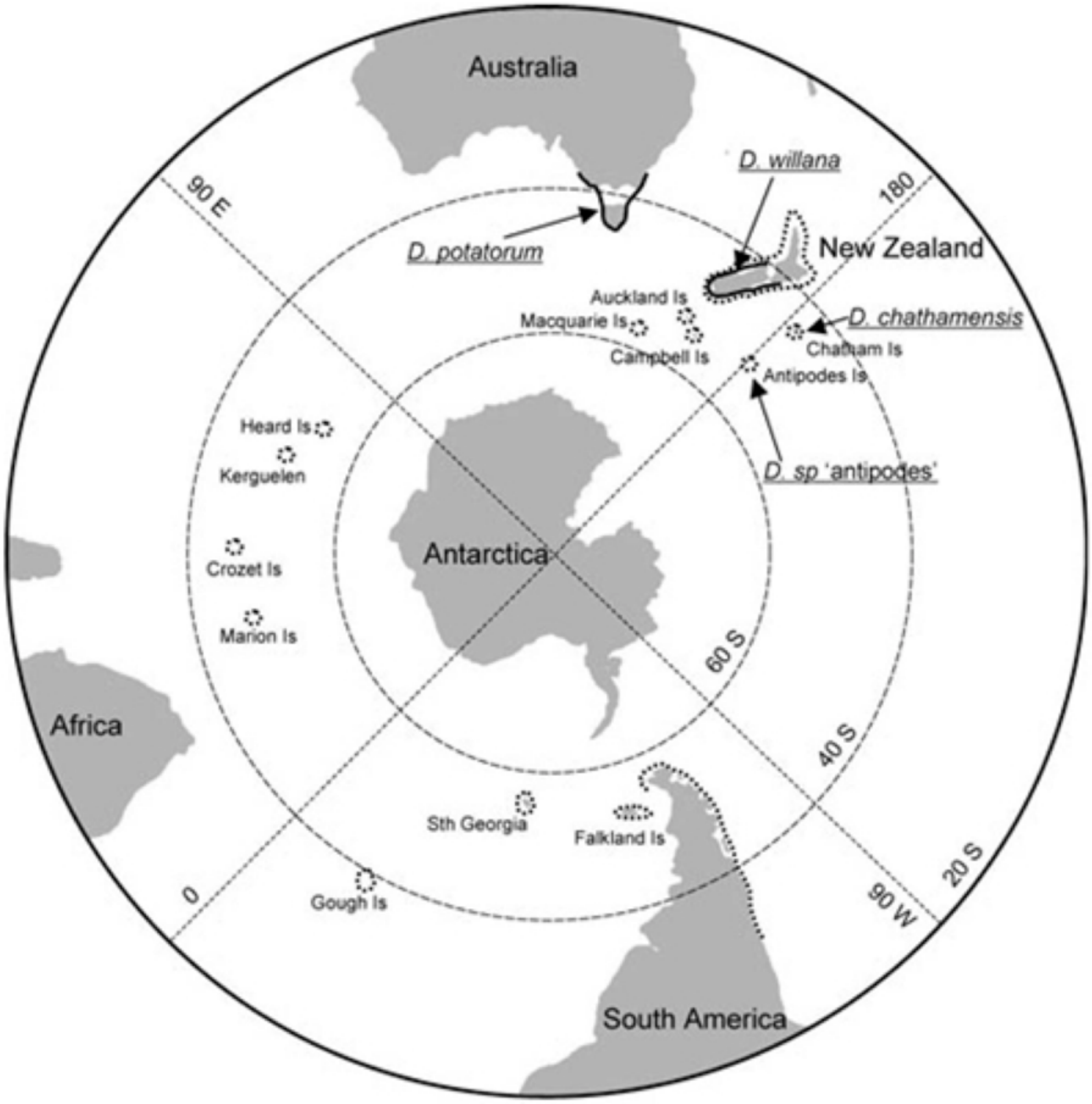

Figure 2. Distribution of buoyant *Durvillaea antarctica* (dotted line) versus non-buoyant *Durvillaea* species (arrows, thick lines). Map clearly shows widely distributed bull kelp, achieved via its' buoyancy. (Waters 2008)

Gammurus wilkitzkii, were tested to determine how they react to ROS. *Anonyx nugax* was found to be highly susceptible to oxidative stress and have not adapted to this kind of situation. *Gammurus wilkitzkii* is an amphipod that can be found in the ice pack and has a mechanism that prevents the diffusion of ROS through the gills and back into the environment (Camus and Gulliksen 2005).

Antarctic

In the Antarctic, there is a feeding triangle between some macroalgae, sea urchins, and sea anemones. The macroalgae and sea urchins have a mutualistic relationship that protects the sea urchin from sea anemones and improve the reproductive ability of the algae (Amsler et al. 1999). The macroalgae (*Phyllophora Antarctica* and

Iridaea cordata) produce a toxic chemical that prevents the sea urchin, *Sterechinus neumayeri,* from consuming it. In turn, the sea urchin does not eat the macroalgae, but uses it as a cover against its major predator, the sea anemone. The algae cover significantly increases the likelihood that the sea urchin will escape from the sea anemone, *Istotealia antarctica.* When the urchin forages for food it sometimes strays into the tentacles of an anemone. The macroalgae acts as a detachable shield against the anemone. The anemone's tentacles adhere to the macroalgae and which then the urchin releases providing ample opportunity to escape. In return, the macroalgae benefits by remaining in the photic zone where they can continue to contribute to the gene pool and thus extend their spatial distribution. Otherwise, once the macroalgae detached from its holdfast it doesn't go directly to waste or food for other organisms.

The Antarctic has a large community of marine organisms surrounding Antarctica. A prominent part of the ecosystem are kelp hold fast communities and example of metabiosis. Kelp has a root-like system called a holdfast that attaches to rocks or boulders to prevent the kelp from floating away. This holdfast provides a habitat for a vast community of species. The primary kelp in this area is bull kelp (*Durvillaea antarctica*) and is known to be so buoyant that they are able to lift large boulders from the bottom of the ocean and drift with the current. While the bull kelp is rooted to the ocean floor it provides a holdfast community, housing many invertebrates and fish. The kelp provides protection from larger prey and a low energy environment. In some cases up to 90 species of invertebrates were identified in these

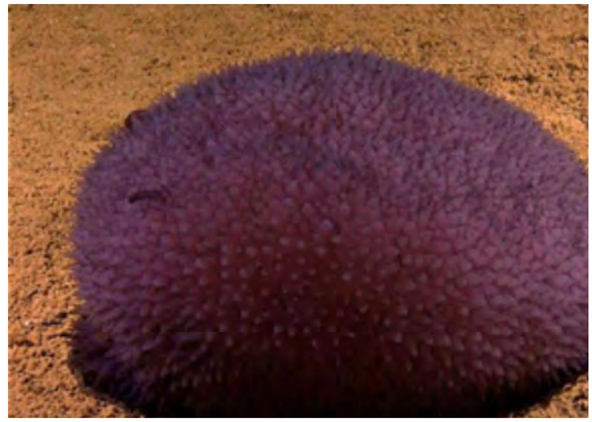

Figure 3. Antarctic nudibranch, *Bathydoris hodesoni,* produces a chemical to deter feeding of sea stars. (Avila et al. 2000)

holdfasts including worms, mollusks, mites, sea-stars, sea-cucumbers, and other crustaceans (Waters 2008). Once afloat, the bull kelp "raft" can carry some of these invertebrates to areas such as New Zealand. **Figure 2** identifies areas in which the bull kelp travels via the Antarctic Convergence Current.

In the Antarctic there are many benthic invertebrates, many of these invertebrates are suspension feeders and ingest small organisms that reside in the ocean current. Specifically in the Weddell Sea, sea stars are the primary predators. In polar regions, gastropods have lost their defensive shell because there are no durophagous (shell crushing) predators. As a result, snails, clams, and brachiopods have unusually thin, delicate shells (McClintock et al. 2015). This loss of the shell prompted gastropods to develop chemical defenses. Chemicals exist in exposed and vulnerable tissue allowing the gastropod to avoid predation by sea stars. Gastropods only release deterrence when disturbed by predators, in this case sea stars (Taboada et al. 2013).

One specific organism in the Antarctic is the *Bathydoris hodesoni*, an Antarctic nudibranch. This organism, depicted in **Figure 3**, produces hodgsonal, an anit-flammatory substance. The hodgsonal is present only in the mantle and external tissue. Studies found that no more than the natural concentrations of hodgsonal deters predation by sea stars (Taboada et al. 2013). This chemical is biosynthesized *de novo* by the nudibranch (Avila et al. 2000). As such, this chemical does not come from dietary sources because it is an omnivorous feeder and no one specific food is needed to produce this chemical.

The following parasites are anisakid nematode parasites believed to be endemic to polar regions (Dzido et al 2009). Anisakid nematodes are a genus of parasitic nematodes that have life cycles involving fish and marine mammals. These parasites are characterized by being limited to a small number of final hosts and indirectly with specific Antarctic or Arctic intermediate hosts. The final hosts are usually limited to one specific species, in this case wolves. Common intermediate hosts in polar regions are invertebrates (euphausiids, squid) and fish. Although Euphausiids (krill) and squid are known to be intermediate hosts of marine nematode parasites worldwide and not limited to polar regions. The Arctic and the Antarctic which have similar environmental conditions, differ with respect to the dominant hosts and parasite taxa. This discrepancy can be explained by possible species divergence and the narrow specificity of parasites living in only one or several hosts. **Figure 4** shows the general life cycle of a nematode parasite and its journey through the digestion of carnivores and herbivores. At the start, parasites are

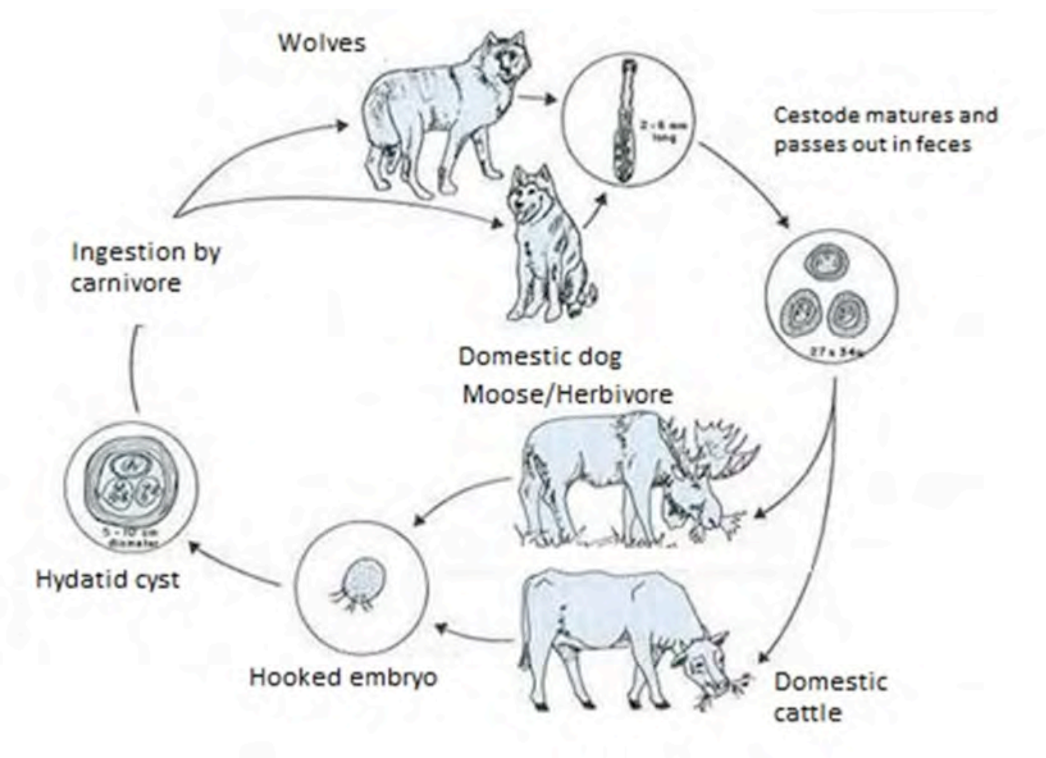

Figure 4. Anaskid nematode parasite life cycle through herbivore and carnivore hosts. (Marquard-Petersen U. 1997)

eggs that can be found on vegetation in which the intermediate host, usually the herbivore, ingests the egg as they consume the vegetation as food. The egg hatches into a hooked embryo which forms cysts in the liver of its host. Sometimes the hydatid cyst develops slowly, taking 1 to 2 years to develop. Cysts are singular and enclosed in a thick laminated capsule. These cysts are then eaten by a carnivore that consumes the infected intermediate host. The cysts release scollces, immature parasite, that attach to the intestinal mucus of the definitive host. The cestode matures into an adult parasite, in the intestine of the definitive host and then releases eggs that are passed out in feces and the cycle repeats. Some species of nematode parasites cause severe malnutrition in their definitive host (Marquard-Peterson 1997). In the Arctic, *Contracaecum osculatum A* and *Pseudoterranova bulbosa* are endemic and can be found in the body cavity of polar cod. In the Antarctic *Contracaecum radiatum, Contracaecum osculatum D & E, Pseudoterranova decipiens E,* and *Contracaecum miroungae* are found to be endemic. These parasites were found in the Southern Elephant Seal, Blackfin ice fish, marbled rock cod, and black rock cod (Dzido et al. 2009).

The relationship between predator and prey is important to the ecosystem as a whole, it defines the relationships between each species. The next chapter will take a look at how migration and behavior affects how these species interact with each other rather than the ecosystem as a whole.

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Migration and Behavior

By Halie Pruitt
Edited by Peter Swan and Gwen Pelletier

Introduction

Generally, animal behavior is a study of different animals and the ways in which they behave with each other, with other organisms, and with the environment they reside in. For example, animals must be able to change their behavior to survive in certain conditions; salamanders, when under threat of drying out or becoming too cold to survive, will move away from that particular area to a more warm and moist environment. Textbooks on the broad topic of animal behavior describe it as being "all observable or otherwise measurable muscular and secretory responses (or lack thereof) and related phenomena in response to changes in an animal's internal or external environment" (Burk and Grier, 1992), or as C.S. Sherrington states it, "movement" or "conduction." While many animals throughout the world may have to face different obstacles in their respective environments, organisms in the Arctic and Antarctic must withstand extreme variables in light, temperature, ice availability, currents, etc. In this chapter we will be outlining some major behavioral aspects of these arctic and antarctic organisms, including reproductive behaviors, social structures, migration, competition, and hibernation.

Behavior Begins at Birth

A logical starting place for understanding animal behavior is at the beginning of the organism's life, and perhaps several steps preceding it.

If behavior is movement, it is important to understand what space the organism is moving in; what environment these animals are born into impacts the reproductive behavior of the parents. Biology follows two natural steps: survive and multiply. Parents of different species will follow different models of population growth, either r-selection or k-selection. R-selection occurs in unpredictable environments where potential death or injury rates of offspring is high-- the parents focus more on getting as many offspring out there that might be able to survive, and thus they retain less responsibility to them. K-selection occurs in stable environments where survival of the offspring is expected to be higher, and there is less predation/disease/etc; parents place more energy in a single offspring or a small group of offspring so that these animals are better equipped to face their respective environments.

One might expect the arctic and antarctic, areas of extreme climate to be host to primarily r-selected species, but in actuality there is a large number of k-selected species

Figure 1: Emperor Penguins as a K-selected species. Emperor penguins breed on the sea-ice in bitterly cold conditions and the eggs have to be kept warm until they hatch. Males are significant carers, as they help the eggs survive the desolate winter by carefully putting them on their feet and covering it with a skin fold. (http://www.arcticphoto.co.uk/Pix/OP/05/FT.0144-00_P.JPG)

in each area. Even invertebrate species of the Antarctic seem to embrace k-selected traits, even in offspring brooding (Duchesne, 1985). Investment in offspring seems necessary in these extreme locations, as offspring, though living in a simple ecosystem, have predators and trials to face. An example of this extreme parental investment can be found in Emperor Penguins. After mating, females start to leave the colony in search of food, leaving the male penguins behind to care for the offspring. The males now have not eaten for two months and must survive another two months without feeding, living in temperatures ranging from freezing to -37 . The question remains: how can these animals and their offspring survive. Physiologically, Emperor penguins are adapted to have lowered heat loss and are able to maintain their body temperature at a constant and high level (Gilbert et al. 2006); this high body temperature provides an environment for the egg of about 35 , yet is difficult to maintain in such an extreme environment. In fact, a male penguin alone would die in this Antarctic winter, were it not for the colony of men banding together. Studies have suggested that the key to their survival is the huddling technique exhibited by this species (Gilbert et al. 2006).

Ancel et al. found that the metabolic rate of huddling birds was reduced by 16% compared with penguins that did not have access to large scale huddling. Effective huddles are densely packed formations that extend for hours, even days, with birds moving slowly inward for warmth. These huddles can be made up of more than hundreds of individuals, reaching recorded ambient temperatures inside huddles at 23-30ºC (Gilbert et al. 2006). Although this huddling is effective for keeping these males alive, they still lose about 40% of their body weight and begin sleeping for extended periods of time to save energy (Gilbert et al. 2006).

Baleen whales will make similar sacrifices for their calves, leaving the Arctic and Antarctic-- where there is a large abundance of krill after the austral spring-- to raise their calves in shallow and warm seas, where low nutrients equate to low plankton and krill counts.

However, before these animals invest/sacrifice their time and bodies, they need to know that their offspring has the greatest potential of survival, and so there exists mating rituals and courtship behaviors. Many birds throughout the world have different courtship behaviors, whether it be the dancing and colorful display of Birds of Paradise, or the swift aerial displays of hummingbirds; the Antarctic and Arctic birds, too, have their own courtship behaviors.

In the Antarctic, we find that Adelie, Chinstrap, and Gentoo penguins all have similar courtship behaviors. Each of these penguins perform an ecstatic display that signals favorable mates (Marks et al. 2010). The ecstatic display is performed by the male to the female, who stretches his neck out and points his bill up. The male penguin then flaps and stretches out his wings while making loud calls. In Adelie penguins, they perform what's called the "Loud Mutual Display" which is when the penguin makes loud calls and whips his neck around in a display (Marks et al. 2006). Emperor Penguins, too, will make loud displays for mate selections, and will have specific calls or songs during mate selection; these calls are what enable the female Emperor penguins to find their mates when they return after winter.

Families of the Arctic and Antarctic

After the chicks, pups, and other critters of these icy lands are born, they become a part of the social structure; many of the charismatic megafauna and the k-selected species will live in large groups with significant social structures, some, however, are solitary animals. We find both in these polar extremes.

The Arctic fox is a small canid found throughout the arctic; the foxes are small bodied with large families, deviating from a trend set by naturalists which states that larger canids have larger litters and parental investment (Geffen et al. 1996). These larger canids are expected to be highly social creatures because non-reproductive family members help provide for the litter as helpers. Research found that the abundance of prey in the arctic led to less necessitation of these helpers, and parental investment remained high. Regardless of the high prey abundance, studies found that the family composition of Arctic fox could consist of monogamous pairs, pairs with additional adults, or 2 reproducing females and 1 male in the same den.

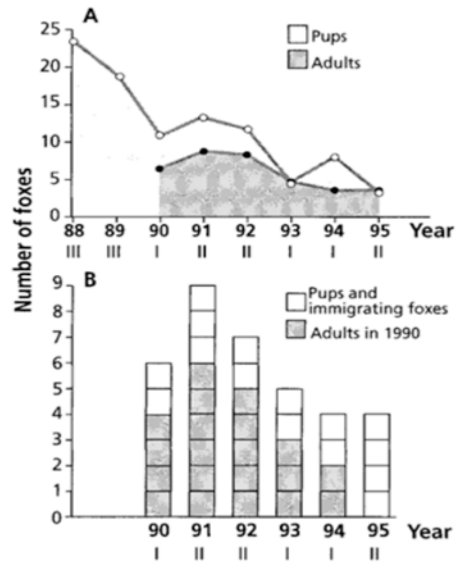

Figure 2: Arctic foxes, while showing less family diversity than other large canids, do experience the growth in adult family size as pups are born. In the first graph, there is a significant and correlational increase of adults with increase of pups between 1990 and 1992. (Geffen et al. 1996)

Orcas, who inhabit both Arctic and Antarctic waters, have high parental investment and significant familial social structures that extend throughout their lifetime. Orcas are known to live in large family groups called pods; each pod is composed of multiple related matrilines, each typically containing 3 or more generations. The pods are led by the Matriarch, the dominant or oldest female in the family. The matriarch has knowledge that she passed on the pod through teaching-- whether it be about parenting, feeding, or navigation of their widespread territory.

Teaching is one of the most studied social characteristics of these large mammals, and we find that different species of orca are taught different things depending on where they live and what they hunt. For example, there are three species of Orcas in the Antarctic based on feeding: type A feeds on Minke whales, type B feeds on seals, and type C feeds on fish. Type B Orca teaching behavior is best documented. The type B Orcas hunt in the pack ice of Fjords and use the ice to their advantage (Pitman et al. 2011). When hunting in open water with little or no ice the orcas swim as a tight group, within two body lengths of each other. In areas of pack ice the pod fans out and travels as individuals or cow/calf pairs (Pitman et al. 2011).

The orcas will use this hunting experience as social play and a learning experience for the young calf. Wave washing, a hunting technique, allows the calves to see a community based hunting technique; the pod of orcas will surround a seal stranded on pack ice and will create waves to wash the seal off the ice. The orcas will not, however, immediately finish the job with one wave, they continue to tip the ice, flip it over, and make more waves as a team. They will play with the seal in these exercises, when they are not actually hunting for a meal. The calves learn skills from this play and build connections with their pod through this hunting/social behavior.

There are, however, animals in the Arctic and Antarctic that are not part of a significant social group; these organisms are considered solitary animals. Solitary animals are often territorial and can become aggressive when another individual of their species enters their territory. The aggression could be competitions for mates or food selectivity. Large cats and bears are often solitary animals, so it comes to no surprise that Polar Bears, too, are solitary. Surprisingly, however, there is a species of seal that is considered solitary.

As a general rule, Seals live in complex social structures that seem unimportant; they live in large groups with several hundred members and form hierarchies. For these seals, traveling in large groups is a primary defense mechanism, as they are highly sought-after prey. Leopard Seals, however, are massive (third only to Walrus and Elephant seals) and dangerous-- threatening to most other animals in the Antarctic, including humans. Generally Leopard seals will hunt alone and hardly ever seen with more than two companions at a time. The only exception to their behavior is for breeding season, from November to March, when several individuals will meet to mate. Not much is known about Leopard seal reproduction. However, a study on Leopard seal vocalizations found that males make territorial or mate selective vocalizations (Rogers et al. 2002). Their vocalizations are trills and hoots, which occur in distinct bouts; the patterns created are indicative of individuals.

http://assets.nydailynews.com/polopoly_fs/1.2049810.1418922400!/img/httpImage/image.jpg_gen/derivatives/gallery_1200/polar-bear-cubs-leave-den.jpg

Hibernation in the Arctic

While bears are seen as these solitary creatures, there are periods in the year when bears must be in social environments: during breeding periods and hibernation. Hibernation is a state of inactivity and metabolic depression in endotherms where these mammals will switch between heterothermy and poikilothermy. Hibernation is physically characterized by low body temperature, slow breathing and heart rate, and low metabolic rate.

Polar Bears, however, are different from other bears in that only females with cubs will hibernate in the winter. Non-reproductive females, juveniles, and all males will roam the Arctic tundra during winter. Pregnant female polar bears will dig a snow den, give birth, and emerge three months later. No different than other bears, during this time, they live off their fat reserves. However, mother polar bears do not enter deep hibernation as they need a higher body temperature in order to meet the demands of pregnancy, birth, and nursing. Studies show that many hibernating animals have reduced muscle and significant bone loss during prolonged immobilisation (hibernation) while wild pregnant polar bears are the first animals to not have significant bone loss after six months of hibernation (Lennox and Goodship, 2008).

Migration of Whales from the Arctic and Antarctic

The Arctic and Antarctic are home to many water-dwelling creatures: Arctic cod, Antarctic Silverfish and toothfish, large invertebrate species, etc.. There are some of these water-dwelling species that only stay for a section of the year-- our charismatic megafauna, Whales.

While most baleen whales are found throughout the world's oceans, these giants still travel extensive distances during migration. The basic migration pattern has baleen whales travelling to winter breeding grounds in low latitude, warm waters and summer feeding areas in high latitude, polar waters. High latitude waters have rich krill supply, along with other planktonic species, where warmer waters are necessary for birthing, as calves only have thin layers of blubber to keep them warm-- they would not survive a polar birth.

Migration is simply another example of high parental investment; when whales migrate, they eat very little for months in warm, but barren seas. The mother lives on fat reserves during the winter so that their offspring may survive, suckling for seven months when the mother is unable to feed for four of those months.

Species	Migration	Times
Southern Right Whale	- Coastal Mating Grounds in Africa/South America/Australia. - Feeding grounds in waters near Antarctica, some at the edge of pack ice.	- Winter and spring in calving grounds - Summer in Antarctic feeding grounds
Blue Whales	- Warm tropical waters for breeding and giving birth - High latitude polar waters for feeding	- Winter in warm tropics - Summer in polar waters
Grey Whales: Western North Pacific (WNP) and Eastern North Pacific (ENP)	- Follows typical Baleen Migration pattern - **WNP**- Korean Peninsula and Japanese Islands for calving, Okhotsk sea for feeding - **ENP**- Alaskan Arctic feeding grounds, Mexican breeding grounds	- **WNP**- Korea and Japan for winter calving, Okhotsk sea for summer. - **ENP**- round trip between their southern breeding grounds and northern feeding grounds - April - November: Arctic feeding grounds - October - February: migrates south - December - April: Mexican breeding grounds - February - July: migrates north
Humpback Whales	- Tropical waters to breed and give birth - High latitude polar waters to feed	- Winter for breeding - Spring, Summer, and Autumn for feeding
Northern Right Whales	- females give birth in the coastal waters of Florida and Georgia - both sexes are found in the Bay of Fundy and in an area on the continental shelf, 50 km south of Nova Scotia	- Winter for breeding females, other males and non-breeding are unknown - Spring for traveling north, whales spotted around cape cod. - During the summer and autumn, Rights are in the colder waters for feeding

Table 1: This details the migration patterns of the primary migratory baleen whales who visit the Arctic and Antarctic

Conclusion

Against all odds-- the extreme temperatures, climate change, lack of food in the winter, etc.-- these creatures of the Arctic and Antarctic have survived. These behaviors of high parental investment and migration, the physiological nature of hibernation, learning opportunities-- these behaviors are what allow life to exist in the polar regions. Without huddling, Emperor penguins would have a significantly smaller, or non-existent, population; without migration, whale calf mortality would skyrocket. These animals not only face their obstacles, but have spent thousands of years adapting their behavior to survive in these harsh and unforgiving polar climates.

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Reproduction and Growth in the Polar Regions

By: Briar Bragdon
Edited by: Emily Johnston and Abby Rhodes

The Polar Regions are some of the harshest places in the world. These areas have extreme temperature differences on land, while in the ocean many places have a constant cold temperature. There are periods of complete darkness and periods of complete light. This doesn't seem like a place where anything would be able to live or survive, but as we have seen there are plenty of life forms found at these regions. Now that we know that organisms do live in the far north and far south of the planet, we should probably ask the question, "how can they grow and reproduce in such a harsh environment?" That is exactly what this chapter will answer. It will explore how different species grow, develop, and reproduce in such cold climates.

Growth

One of the biggest factors that impact the growth of poikilothermic animals in polar regions is the Q10 rule. The Q10 rule is the factor by which the rate of a reaction increases or decreases with every 10 degree change of temperature in Celsius. The equation for the Q10 is as follows: Q10=(R1/R2)^(10/(T2-T1))
R1 and R2 are rate one and rate two. T2 and T1 are the ending temperature and the starting temperature respectively (PhysiologyWeb 2005). If the Q10 value is one then the reaction is not temperature sensitive, then from there as the Q10 value increases the more sensitive to temperature the reaction is (Figure 1).

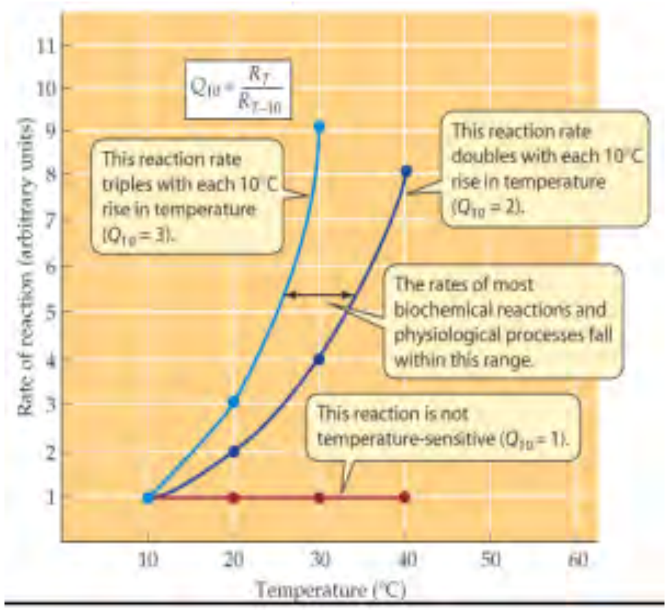

Figure 1: Different Q10 values (calpoly.edu).

Looking at this graph, we see that as the temperature decreases the growth rate also decreases. As a result, many poikilothermic animals have a slower growth rate in the polar regions. Some examples of different organisms that have severely slower growth rates than non-polar organisms are different echinoderm species found in both the Arctic and the Antarctic. These echinoderm species grow 5-10 times slower than echinoderms found in non-polar regions. This can be seen in the graph below (**Figure 2**). Organisms that are greatly affected by the cold climate of the poles are brachiopods. Brachiopods grow 7-100 times slower than brachiopods found in non-polar regions (Arntz 2012).

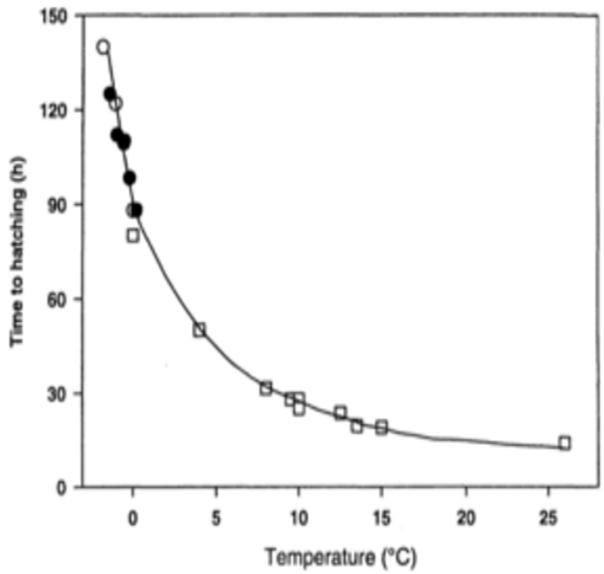

Figure 2: Hatching time of echinoderm species based on temperature (Arntz 2012).

This Q10 rule only holds true when the temperature is constantly cold. This was explored by looking at species found in places that have the same average temperature as the poles, but have a greater variability in temperature from day to night. These organisms had faster growth rates than the organisms that live in the polar regions. Eluding to the fact that the Q10 rule only holds true with constant cold temperatures (Remmert 2012).

Another important concept that affects organisms of polar regions is the idea of critical temperature. Critical temperature is the temperature that the organism begins to shut down and will eventually die. There is the critical temperature one (TcI) that is the cold threshold of an animal. This is the temperature at the cold end that causes the animal to shut down metabollically. Critical temperature two (TcII) is the high temperature threshold that leads to the metabolic shutdown of an animal (Arntz 2012).

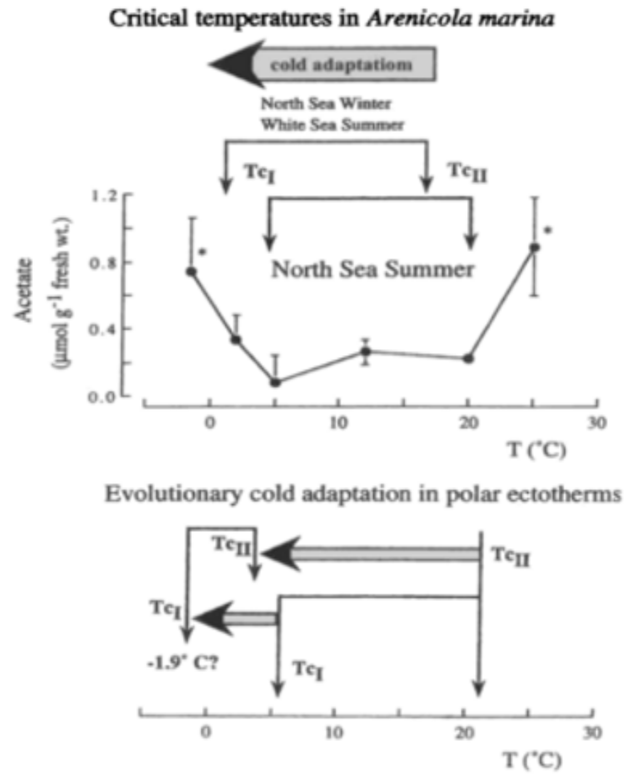

Figure 3: Critical temperatures of the lugworm and cold adaptations (Arntz 2012).

This concept of critical temperature is important for organisms that live in polar regions due to the fact that they are exposed to severely cold temperatures in comparison to other organisms in the world. The impact that living in these cold temperatures has on the critical temperatures can be seen above in Figure 3. Animals that live in the polar regions have critical temperatures that are depressed and closer together. This means that animals in polar regions have a smaller temperature range that they can live in compared to animals in other parts of the world. This is important when taken into consideration the impact that climate change might have on these animals. Since there temperature range is depressed and smaller they have a smaller optimal window of survival than other organisms. As a result if the temperature around them begins to increase due to global warming then the animals may constantly be expose to their critical temperature on a daily basis. If this occurs then the organisms would either die or find a way to adapt to the warmer temperatures (Arntz 2012).

Another interesting factor that organisms of polar regions experience is called Thorson's Rule. Thorson's Rule is highly debated and there are many exceptions to the rule. For this reason many scientists believe that we should abandon Thorson's Rule altogether. Thorson's Rule is most easily explained with Figure 4. This rule is that as the latitude lines increase, the amount of species that have a more direct development, rather than a pelagic development, increases (Colorado.edu).

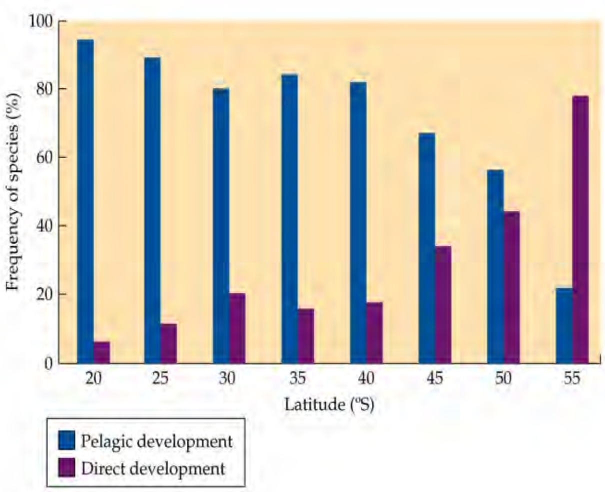

Figure 4: Thorson's Rule for different latitudes (Colorado.edu).

Another strategy that have been observed by animals in polar regions is this idea called Bergmann's rule. Bergmann's rule is that animals that live in higher latitudes grow larger then animals that are found in lower latitudes. This rule is thought to occur because animals that live in these areas that are larger also have a lower surface area to volume ratio, and because of this lower surface area to volume ratio the animals are able keep their body warmer more easily than animals that are smaller and have smaller surface area to volume ratio (Ashton 2000).

It seems that animals found in polar regions have a lot of stressors on them since they live in such an extreme environment on the planet compared to some other places. And as a response to this they have developed many different mechanisms in order to grow and ensure their survival in these specific areas. Next we will explore how these animals also have strategies in order to ensure the survival of their offspring.

Reproduction

The first organisms that will be explored in the polar region for reproduction is terrestrial plants. The polar regions have a very unique area for plants to grow. This is because the temperature in these places are so cold. Also the polar areas have periods of complete sun and complete dark. This is very different than other areas for this reason many plants have developed many different strategies, such as taking two growing seasons in order to flower. Flower production is stimulated by heat, so they will only put energy into making their reproductive flowers when it is warm enough out. Most specie in the polar regions are perennials. The reason why most plant are perennials is because they can put less energy into seed production, and some of these perennials don't reproduce through seeds at all but reproduce through root growth in the ground. This leads to less energy usage in reproduction. Since these areas are also warming because of Global Climate change many plants now have elongated growing seasons and they are also spreading to areas they never were found before.

Also in the polar regions larger animals other than plants must be able to also reproduce in such an extreme environment, and they also have their own mechanisms to reproduce in this environment just like the plants in these areas. One important strategy that most animals do in order to keep warm in these cold areas is by huddling. When animals huddle together they are able to reduce the surface area to volume ratio to make it easier to stay warm in a cold environment. Rodent pups have been observed doing this in order to stay warm. A more famous animal that does this is emperor penguins (Refinetti 2006). This is because emperor penguins reproduce in the most unsuspecting time, in the middle of the Antarctic winter (Australian Government 2008). After the eggs hatched the baby penguins can be seen huddling together in order to stay warm in the harsh Antarctic climate (Figure 5).

Figure 5: Baby Penguins seen huddling in Antarctica (Refinetti 2006).

Another polar animal that has a unique strategy to reproduction in the polar regions is the Arctic Fox. The arctic fox is found throughout the arctic region. One thing that is interesting about the reproduction strategy of the Arctic fox is how variable their littler size is. Most other foxes have a pretty defined average litter size, such as the red fox that has a range of 1-11 pups with an average of 6 pups (Saunders 1988). But the Arctic fox has a bigger range, and even an average range in their litter sizes. This range is greatly dependent on the amount of food that is available to the foxes. The average range of the litter size is 5-8 pups with average amount of food. But there have been litters observed of having 25 pups when there was large abundances of food. This is the largest litter size ever recorded in the carnivores. This leads to the suggestion that this is an adaptation the foxes have made in order to have more surviving offspring in this cooler climate (Angerbjörn 1998).

Another animals the is well known in the polar regions that also has to be able to reproduce in this climate is the polar bear. The polar bear is located throughout the arctic and lives primarily on the snow and ice. The reproduction for a polar bear is slightly different than other bears, but also similar. Female polar bears will overwinter in a den built in the snow when she is going to give birth to her young, this only will occur if the bear has enough fat content to produce enough energy for her and her young, which is the same thing other bears do. The cubs are then born and are dependent on their mother for milk and nutrients. This is where there is a slight difference in the way that polar bears raise their young compared to other bears. Other bears such as the brown bear nurse their young only until the spring (National Geographic). But polar bears have been known to feed their young with their milk from 1.5 -2.5 years after birth. This might be because for polar bears their food sources can be scarce and hard to find, so to make sure that the cub is getting enough nutrients the polar bear feed the cubs longer than other bears do to ensure their survival (Molnar 2010).

The last animals that this chapter will look at for their reproductive strategy in the polar regions is the reproductive strategies of fish within the polar regions. It appears that fish in both the Arctic and Antarctic have similar strategies in their reproductive strategies. The one notable characteristic that is unique to polar fishes is the size and amount of eggs that a fish reproduces. Most fish in other areas produce large amount of small eggs in order to ensure that they have the highest possible amount of offspring possible to pass on their genetic material. But in polar regions this is not so simple. In the polar regions fish may go long periods of time with no food, or abundant food. This variability in food would make it hard for large amount of small fish to be able to survive if they hatched during a time where there was no food present. Scientists think that because of this variable amount of food available caused polar fish to adapt and start to release fewer eggs, but even though there are fewer eggs these eggs are larger and have larger yolks inside of the eggs compared to fish eggs from fish found in lower latitudes. With eggs having larger yolks the fish that hatch have a higher amount of nutrients in their body, and won't need to feed as soon as compared to fish with smaller yolk. Making this a very advantageous way for fish to ensure that some of their offspring will survive in the poles (Christiansen 1998).

As has been discussed in this chapter, animals have amazing adaptations in order to live in such extreme environments. They are able to grow larger, huddle together to keep their body temperature at a livable temperature. They are able to control their litter size, how long they feed their young, and be able to lay larger eggs compared to other animals in other regions of the world. It is truly amazing how animals that are unique to the polar regions are able to survive, grow and reproduce in an area that appears to be impossible to thrive in.

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Anthropogenic Impacts

This section discusses historic, current, and potential future anthropogenic influences on polar regions. Specific examples are drawn to investigate arctic and antarctic exploration, politics, economies, and the effects of climate change.

The Discovery of the Polar Regions

By Emily Johnston
Edited by Bailey Bush, Jennifer Gamble

The Antarctic

Captain James Cook of England was the first explorer to document credible evidence of a frozen southern continent on his second expedition from 1772 to 1775. Although he and his crew did not actually see the continent, they did cross the Antarctic Circle at 67 degrees South Latitude. When they crossed, they saw the icebergs of the frigid Southern Ocean. Cook documented his claim in a journal entry dated February 21, 1775:

> “There may be a continent of large tract of land near the Pole, I will not deny, on the contrary I am of opinion there is, and it is probable that we have seen a part of it. The excessive cold, the many islands and vast floats of ice all tend to prove that there must be land to the South and that this Southern land might lie or extend farthest to the North opposite the Southern Atlantic and Indian Oceans, I have already assigned some reasons to which I may add the greater degree of cold which we have found in these seas, than in the Southern Pacific Ocean under the same parallel of Latitude” (Price, 1961).

The South Shetland Islands and the shore of the Antarctic Peninsula were discovered fifty years later on an expedition led by William Smith, an English mariner. A year later in 1820, Smith returned with James Bransfield, of the British Navy, to explore and map the Shetlands and part of the shore or the Antarctic Peninsula (WHOI: Antarctic Timeline). Captain John Davis, a sealer from Connecticut, led the first expedition that actually succeeded in landing on the continent in 1821. Davis and his crew landed on the continent at Hughes Bay on the Antarctic Peninsula in a search for good seal hunting grounds (WHOI: Antarctic Timeline).

From 1820 to 1840, British, French, and Russian explorers launched some expeditions to the Antarctic, but after 1840 not much work was done in the region. The Norwegians and Scottish explored the area for whaling beginning in 1890, which began a new era of Antarctic exploration.

In 1901, Ernest Shackleton, a master mariner of the British merchant navy, was chosen to go on the Antarctic expedition led by British naval officer Robert Falcon Scott on the ship *Discovery*. Getting closer to the pole than anyone before, they fought through difficult conditions until Shackleton fell ill and could go no further (BBC). Shackleton’s third trip to the Antarctic occurred from 1912 to 1915 on the ship *Endurance*. During the trip, the ship became trapped in ice. The crew was forced to abandon the ship only 97 miles short of the pole. Shackleton and his crew survived being shipwrecked in the ice and were finally rescued after taking a small boat from Elephant Island

Figure 1. The *Endurance* trapped in ice (Wikipedia).

across 1,300 km of rough open ocean on a trip that lasted for sixteen days (BBC).

Through studying Shackleton's attempt at reaching the pole, Roald Amundsen of Norway prepared for his own attempt. He would become known for being the first person to reach the South Pole. Amundsen and his crew set sail in August of 1910. He kept his plans for an expedition to the South Pole a secret, making the world, Norwegian officials, and even his crew believed they were headed north. It was not until they were off the coast of Morocco that he announced they were headed south. On October 11, 1911, Amundsen, his crew, and carefully selected sled dogs left from the Ross Ice Shelf for the pole. On December 14, 1911 they successfully reached the pole, becoming the first ever. Amundsen and his crew returned to their base camp 99 days and 1,860 miles after their departure to the pole (PBS).

Figure 2. Roald Amundsen, 1923 (PBS).

The Arctic

Although the Arctic is much younger than it's opposite pole, it's history of discovery and exploration reaches farther back in time and is much more extensive due to the proximity of the countries that perimeter the Arctic and the accessibility to land. Still, the exploration of the arctic has been an arduous task. Unlike the Antarctic, which is a landmass, the Arctic is composed of drifting sea ice, which has made navigation, and finding and marking the North Pole a difficult task for explorers. The drifting sea ice could impede on navigation as well. "Few critics know what it means to sledge over the rough ice of the Polar Sea…how sledges must be built to withstand the shock of traveling through and over the rough sea ice…how and what kind of clothes must be worn to withstand the bitter temperature of sixty and seventy below zero…" (MacMillan, Kaplan, Lemoine, 2008). The below zero climate and violent winds make breathing painful and therefore any expedition to the Polar Regions a difficult task.

Early Explorations

The first voyages into the Arctic seem to have been made by Europeans searching for whaling grounds in the late 1500s into the 1600s, although the exploration history goes back to 330 BC when Pytheas of Massalia, a Greek merchant, sailed six days north of Scotland to an island he called "Thule." There he was able to describe the midnight sun, the aurora and the ice. Thule has been suggested to refer to Norway, Shetland or the Faroe Islands (Officer & Page, 2012). In 870, Floki Vilgerdarson, a Norwegian Viking discovered Iceland by using three ravens as a navigation system on his ship. The ravens were released when Floki thought he was near land to show the right way to shore. When the ravens were released, one flew forward. When he followed the raven, he found the new land. In 983, Erik the Red explored west after being exiled from Iceland due to a fight. From this exploration, he discovered and settled in Greenland (WHOI: Arctic Timeline).

The Northwest Passage

Starting in the 1500s, the main driver of exploration of the Arctic was in search of the Northwest Passage as an alternate trade route to China by Europeans (Figure 3). Willem Barents, of whom the Barents Sea is named after, made three voyages in attempt to find the Northwest Passage. Never finding the passage, he did discover the island Spitsbergen of the Svalbard archipelago in 1596 (WHOI: Arctic Timeline). On the voyage back, Barents' ship became ice-bound. Barents and his crew then became the first Western Europeans to winter in the high arctic and survive. The crew built a house and wintered on the east coast of Novaya Zemlya for 10 months. When the summer weather melted the ice, the crew embarked on a voyage of 1700 miles before finding Dutch ships to take them back to Holland. Unfortunately, Barents and four others died on the voyage back (WHOI: Arctic Timeline).

Similarly, Henry Hudson, an English explorer, set out on three voyages to find the Northwest Passage. On his final voyage aboard the *Discovery*, he entered what is now called Hudson Bay in northeastern Canada. There, Hudson and his crew explored and mapped the shoreline. When the *Discovery* became trapped in the ice, the crew moved ashore for the winter. When the ice cleared in the spring, Hudson wanted to continue exploring, but his crew wanted to return home. The crew mutinied against Hudson, setting him, his son and some crewman adrift in a small boat without food or water, never to be seen again (WHOI: Arctic Timeline).

During the Great Northern Expeditions of the 1700s, organized by the Russian Admiralty, voyages were set out along the coast of Siberia in search for a Northeast Passage. Mikhail Lomonosov, a physicist and philosopher and for whom the Lomonosov Ridge in the Arctic Ocean is named after, organized explorations on which he did a large amount of scientific work. He was the first to suggest the scheme of currents in the Arctic Ocean as well as classify sea ice types and explain the role of the sun as a heat source in the Arctic (WHOI: Arctic Timeline).

The search for a Northwest Passage continued throughout the 1700s with Captain James Cook of England's third voyage in 1776. Although he was unable to find the passage, as he sailed east from Hawaii he found the present-day west coast of the United States. Following the coast North, he ran into the ice of the Arctic, which he could not pass. He returned south to Hawaii where he was killed in an attempt to recover a boat that was stolen from him (WHOI: Arctic Timeline). Later attempts by explorers to find the Passage would result in the exploration of the North Pole.

Figure 3. The Northwest Passage (Encyclopaedia Britannica).

The North Pole

The first expedition of modern times to the North Pole is considered to be that of William Edward Parry (MacMillan, Kaplan, Lemoine, 2008). Parry was a British Naval officer who set out on three voyages in search of the Northwest Passage. His first voyage in 1819 was the first expedition to enter the Arctic Archipelago. The voyage was cut short at 110 degrees West when ice prevented the ship from going any further and forcing the crew to winter ashore. Parry's second expedition in 1821 continued in the same fashion, being forced to winter ashore. This time they were forced to stay two winters in a row after attempting to continue the expedition after the first winter. On Parry's third and final voyage to the Arctic, his ship the *Fury* became grounded, forcing Parry and his crew to abandon it and return to England on the *Hecla,* a ship that accompanied the *Fury* on the voyage.

Years later in 1831, James Clark Ross, a crewmember aboard Parry's voyages, resumes the search for the Northwest Passage. He also failed to find the passage but became the first to reach the North Magnetic Pole. The magnetic North Pole actually changes every day, moving about 40 meters north each day. It was not until 1903 that Roald Amundsen, a Norwegian explorer, completed the first successful navigation of the Northwest Passage. Amundsen later became a large contributor to the exploration of the Antarctic (WHOI: Antarctic Timeline).

Robert Peary, a 30 year old civil engineer in the U.S. Navy with the rank of lieutenant, made his first Arctic trip, of which he made eight, in 1886 when he attempted to cross the Greenland ice cap with a young Danish man and two Greenlanders. The crew reached about 90 miles inland and 3,000 feet in elevation on foot (Officer and Page, 2012). On his final expedition from 1908-1909, Peary reportedly reached the North Pole. Around fifty men, including his assistant Donald MacMillan, and 246 dogs joined Peary on his expedition. When the crew came within 134 miles from the pole Peary sent everyone back except for four natives and Matthew Henson, an African-American who had accompanied him on previous expeditions. On April 6, 1909l a few days after sending everyone back, Peary and his remaining crew had decided they had reached the pole by use of a sextant. When Peary and his crew returned home, it was discovered that his former colleague, Frederick Cook had already claimed to reach the North Pole (Henderson, 2009).

On Peary's second expedition to North Greenland in 1891, Frederick Cook began his polar career by serving as a volunteer surgeon without pay. Cook turned down the offer to join Peary on his second expedition in 1893 when Peary prohibited any expedition member from publishing anything about the trip before Peary published his account of it, and Cook wanted to publish a study on the Arctic natives (Henderson, 2009). Years after going their separate ways, Cook went on a rescue mission to find Peary in 1901 after turning to Cook for help when Peary's family reported Peary missing. When Peary was found, Cook treated him for scurvy and heart problems (Henderson, 2009).

Figure 4. Robert Peary (Wikipedia).

Cook's own expedition to the North Pole departed from Gloucester, Massachusetts in July of 1907. The schooner was first headed to Northern Greenland. In the native settlement of Annoatok 700 miles from the pole, Cook and his crew wintered over. In February of 1908, Cook and his crew, accompanied by 103 dogs and nine natives, left for the pole from Annoatok. Cook's party traveled 360 miles in 24 days. On this expedition, Cook became the first to describe "a

Figure 5. Indigenous people in the Arctic (Arctic Centre).

frozen polar sea in continuous motion and, at 88 degrees north, an enormous, "flat-topped" ice island, higher and thicker than sea ice" (Henderson, 2009). On April 21, 1908, Cook used a sextant to determine that they were as close to the pole as possible. The crew stayed there for a few days to confirm the position. Fourteen months after they left for the pole, the crew arrived back at Annoatok to find that many people assumed Cook and the crew to be dead and that Robert Peary had departed for his own North Pole expedition eight months earlier in August of 1908.

To this day, there are still questions about who reached the North Pole first, or if either of them even reached it. The opinion of Theodore Roosevelt was expressed in a letter to his sister, Anna Roosevelt Cowels, on Oct 17th 1909: "P.S. That Peary reached the Pole I am sure; whether or not Cook did I can't say, for Cook though a capable man, is a fake."

The Indigenous

Unlike Antarctica, where there are no permanent residents and only a sparse population at various scientific stations, humans have inhabited the Arctic for 20,000 years. The human population above the Arctic Circle (60 degrees North) is over 4 million. Many natives accompanied and assisted the explorers on their expeditions to the North Pole. Now, 10% of the total population of the Arctic is indigenous. The area north of the arctic boundary is home to three-dozen language families, most Indigenous (Fig. 2) (The Circle). Indigenous peoples of the North inhabit areas along the coast of the Arctic and Pacific Oceans.

There are forty groups of indigenous peoples in the North, Siberia and Far East of the Russian Federation alone with a total population of 244,000 people. These groups include the Aleutians, Dolgan, Koryak, Mansi, Nanai, Nenets, Saami, Selkuo, Khanty, Chukchi, Evenks, Inuits and others. The Komi and Yakuts, two larger groups of Indigenous in Russian, make up a population of over 400,000 people. Other groups include the Yupik and Iñupiat in Alaska, the Inuvialuit in Canada, and the Kalaallit in Greenland (Arctic Centre).

The Indigenous residents tend to develop a profound sense of place wherever they live. Their livelihoods range from subsistence or mixed economy hunting, fishing, herding and gathering, to cash-based industries like forestry, mining, tourism, commercial fisheries and hydrocarbon extraction (The Circle). These people have created specific cultures to adapt to the extreme conditions they live in, which cannot suit the requirements of an effective market economy (Arctic Centre).

The Indigenous people encountered on Peary's expeditions have been designated as the Polar Eskimos or the Peary Eskimos. Peary's assistant, Donald MacMillan, described their lifestyle as having no written language of any kind, no schools or government "or conception of the great busy world to the south!" (MacMillan, Kaplan, Lemoine, 2008).

> "Their interests in life are merely primary and essential – food, clothing, shelter, home. Free of the world, they live their life in their own way, untrammeled

> unconventionalized, uncivilized, but they are very far from being savages" (MacMillan, Kaplan, Lemoine, 2008).

The Indigenous peoples of the Arctic are affected greatly by global change, such as dramatic shifts in land use, climate, marine and freshwater systems and wildlife migrations. Arctic peoples, including the Indigenous, are very aware that their environment is changing, but they point out that it has always been very dynamic and they are quite accustomed to adapting to change (The Circle). The Indigenous peoples of the Arctic have already had to adapt to a harsh climate and now are adapting to a changing climate using their traditional knowledge. Their traditional knowledge is an understanding of the environment and ecosystems and ways how to use and manage them (Arctic Centre). An example of this traditional knowledge being used to adapt is the reindeer herders in the Arctic who have been developing unique strategies for protection of their pastures, observation of changes of the environment, and rational use of their natural resources.

Today, the people of the Arctic are living through some of the most dramatic changes the region has seen. Temperatures are reaching record high levels, the sea ice is melting, and countries are competing for access to the untouched resources (The Circle). With the new rapid speed of their changing environment, people of the arctic may begin to have to deal with food contaminants, sea ice retreat, expansion of marine traffic, large scale oil and gas development, thawing permafrost, warmer winters and new introduced species (The Circle). The residents of the Arctic have to adapt to the social, cultural, economic, and environmental stresses that are a result of their rapid changing environment of the polar region.

Figure 6. The demography of indigenous peoples of the Arctic based on linguistic groups. The map presents the original languages of the respective indigenous peoples, even if they do not speak their languages today (Arctic Centre).

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Polar Law

By: Bailey Bush
Edited by: Alex Makucewicz, Halie Pruitt, and Jennifer Gamble

Introduction

Polar Law is a field that has quickly gained global interest in the past decade. Climate change has caught the attention of many countries and created the questions of who will gain access to the newly opened areas and which laws or regulations should be used to govern them. The modern field of polar law was created to describe the legal regimes now in place. Polar law covers all of the international and legal regimes that are applicable to the Arctic or Antarctic; included under this definition are international treaties, conventions, and the domestic laws of the eight arctic states (Loukacheva et al. 2010). The arctic states include Canada, Norway, Denmark, Sweden, Finland, The Russian Federation, Iceland and the United States of America. The field also includes some laws of sub-national arctic jurisdictions, as well as regulations resulting from Antarctic Treaty Consulting Meetings. In summary, polar law is a working term that covers all international and domestic legal regimes that are in effect in the Arctic and Antarctic.

There are two different kinds of law covered by the polar law term. There are hard laws (regulations and legally binding treaties), and soft laws (declarations, resolutions, and cooperation accords) (Loukacheva et al. 2010). Hard laws can be enforced and, if broken, legal action can be taken. Soft laws are not legally binding, but are still useful tools none the less. They are generally issued by forums or councils and then signed by stakeholders to act as an informal agreement between parties. They are important for establishing a legal framework off of which hard laws can be built.

International laws, such as the United Nations Law of the Sea (UNCLOS), are also part of polar law. They are applied only to the areas of the Arctic and Antarctic which are defined as international waters. UNCLOS is especially important to present Arctic law due to article 76; this article states that countries which provide scientific evidence of which areas in the Arctic is on their continental plate will gain access to those areas (Loukacheva et al. 2010). This law will effectively divide all of the newly exposed ocean area between the Arctic states. Presently there have been submissions by Russia, Norway and Denmark with respect to clarifying the limits of their continental shelf in the Artic (Evolution of Artic Territorial Claims and Agreements 2013). The United States have been researching the limits of their continental shelf in the Arctic, but have not yet ratified UNCLOS and therefore would be unable to gain any land under article 76. The possibility of countries gaining the rights to these newly uncovered resource rich sea beds has made UNCLOS highly integrated in recent polar history.

Many different areas of international and domestic law are in effect in the poles. An extensive list covers the branches of: Environmental Law, Human Rights Law, the Law of Sustainable Development, Resources Law, Administrative Law, Criminal Law, Trade Law and Economics, Law of the Sea/ Maritime Law, Transportation Law, Labor Law and Social Securities, Wildlife Law, Constitutional Law, Sports Law, Health Law, the Law of International Organizations, and Entertainment and Internet Law (Loukacheva et al. 2010).

This list highlights that many laws already in place in other regions around the globe can be applied to the polar regions. The biggest difference between law in the poles and law in other regions is which branches are most important. Due to the differences in climate, organisms, resources, shipping routs and sensitivity to pollution, certain branches of law covering environmental protection and economics may be more important than criminal or sports laws.

Polar law is a term covering a wide variety of international and domestic regional regimes that are applicable to either the Arctic or Antarctic. It covers a large range of laws and treaties due to the differences between the Arctic and Antarctic and the ways in which they are governed. The main governing body in the Arctic is the Arctic Council which serves as an intermediary between the Arctic countries. It governs using soft laws and agreements which stakeholders have to willingly uphold. The Antarctic is protected by the Antarctic Treaty System which includes the Antarctic Treaty, a hard law agreement, at its core. These dissimilar legal regimes, as well as geographic differences, are what cause the field of polar law to include so many different legal branches.

Antarctic Treaty System

The Antarctic Treaty System is a collection of arrangements made to regulate the relationships between the Antarctic countries and use of the Antarctic continent (The Scientific Committee on Antarctic Research). At the center of the system is the Antarctic Treaty itself. The treaty was both designed and signed by the 12 nations active in the Antarctic during 1957-58 to ensure that the Antarctic continent would only be used for peaceful purposes. The treaty became active in June of 1961 and applies to everything south of 60˚ South Latitude. It ensures that worlds interests in Antarctica will be used exclusively for peaceful purposes and will not become the scene or object of international conflict or discord (Loukacheva et al. 2010). All territorial claims are held in abeyance and military activity is prohibited. The Treaty is altered by recommendations added at the annual Antarctic Treaty System Consultative Meetings where different protocols and conventions are added. Two conventions, one on the conservation of Antarctic Seals in 1972, and one on the Conservation of Marine Living Resource Activities in 1988 have been adopted thus far. The Protocol on Environmental Protection to the Antarctic was also added in 1991 to deal with shifting environmental issues (The Scientific Committee on Antarctic Research). During each annual Antarctic Treaty Consultative Meeting, the Committee for Environmental Protection also meets to update and implement new environmental protection regulations. Since the implementation of the treaty, 41 more countries have acceded to it. They are allowed to participate in the annual meetings only after they demonstrate an interest in the Antarctic by conducting substantial research activity there.

The Antarctic Treaty System froze all territorial claims by various countries to the Antarctic continent, however there were claims in place before the treaty was agreed upon. The figure below shows the territorial claims made in the Antarctic by seven nations. Other nations

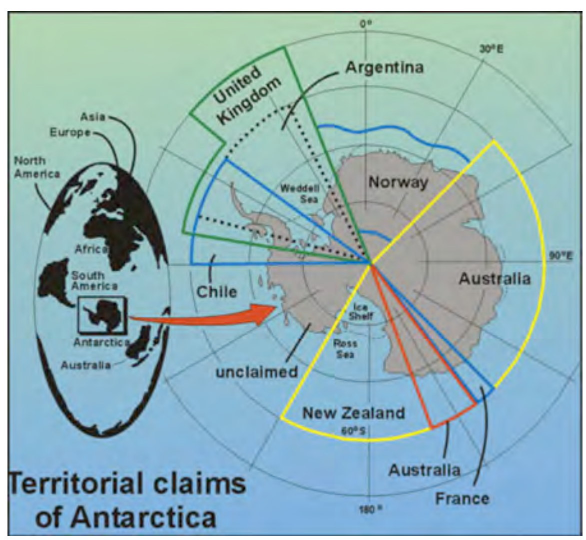

Figure 1
Areas of territorial claims made in the Antarctic. (Braun, 2009)

have reserved the rights to make territorial claims, but have not done so due to the existing treaty.

In recent years, the biggest topic that has been introduced is the rising rates of tourism in the Antarctic. Representatives from New Zealand introduced a new paper to the 2014-2015 meeting which suggested an approach to environmentally managing tourism. The scope of this issue has increased in recent years as the amount of tourism from countries all over the world has increased. The issue is set to be discussed further during future meetings (Secretariat of the Antarctic Treaty 2011). The yearly meetings generally consist of countries sharing their knowledge and assigning working groups for the rest of the year. After every meeting, the Antarctic Treaty Consultative Meeting Secretary posts the final reports on the meetings website for the public to access.

The Antarctic Treaty System is a hard law body which can instate new legally binding regulations and facilitate the use of the Antarctic. It has served to protect the Antarctic from conflict, resource extraction, and pollution by putting laws in place to protect it as a pristine research area.

United Nations Convention on the Law of the Sea

UNCLOS was open for signatures in December of 1982 after 14 years of work by 150 countries from all regions around the world. The first conference was held to create a mutual understanding about the traditional law of the sea for all nations while being able to introduce new legal concepts and address new concerns when needed. The convention is comprised of 320 articles and nine annexes. These touch on the governing of all aspects of ocean management, including: delimitation, environmental control, marine scientific research, economic and commercial activities, the transfer of technology and the settlement of disputes relating to ocean matters (Oceans and Law of the Sea 2013). It also deals with the provisional rights of of the costal states in the five zones of national jurisdiction, the Exclusive Economic Zone, International Waters, Territorial Seas, Continental Shelf, and the Contiguous Zone (Loukacheva et al. 2010).

Since it is in place to regulate the rights of the coastal states, it is much more involved in governing of the Arctic than the Antarctic. The Arctic has coastal states and port cities with a population of over four million (Loukacheva et al. 2010). UNCLOS is used regulate shipping, tourism, traditional hunting and harvesting of marine organisms, the rights of the indigenous peoples of the Arctic and many more issues in the Arctic Region. By comparison, the Antarctic does not have any coastal states or port cities. It also does not have a permanent population, only temporary scientific teams inhabiting scientific research stations.

UNCLOS is especially important at present in the Arctic because of article 76 which would allow countries to gain the rights to areas within the Arctic. Countries which gain access to areas within the Arctic would also gain the right to harvest the resources in those areas. Resources in the Antarctic are protected from extraction by the Antarctic Treaty and article 76 of UNCLOS does not apply.

Arctic Council

The Arctic Council was created in 1996 as part of the Ottawa Declaration (Artic Council Agreements 2015). It is a high level intergovernmental forum which helps cooperation, coordination and interaction between the Arctic states. The council a soft law body and can not pass regulations which are legally binding. This limits the power that it has to protect the Arctic and regulate the Arctic countries. The current members of the Arctic council are Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden and the USA (Loukacheva et al. 2010). The council operates by issuing resolutions, declarations, and cooperation accords which the Arctic countries then need to voluntarily agree to. The council meets every year to make new declarations and recognize other groups and councils being developed to manage the Arctic. During the 2014 meeting, the council discussed improving economic and social conditions and acting on climate change. After discussing these problems, members of the council acknowledged the importance of the indigenous peoples' traditional way of life to their economic well being and decided to increase peoples' awareness of this globally. They also agreed upon urging the parties of the council to follow the Montreal protocol on substances that deplete the ozone layer. In 2015 the council addressed sustaining arctic communities and protecting the unique Arctic environment. These meeting topics raise public awareness of these problems and help by establishing task forces and focus groups to work on them. The council can not pass law or regulations to truly fix the problems that are brought to them. But have helped to negotiate two big agreements between the eight Arctic Countries. In 2009 they facilitated the Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic, dividing all of the Arctic area up into different jurisdictions for each county seen in Figure 2. The second agreement was made at the 2011 meeting. The countries all agreed upon Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic. Both of these agreements became legally binding at future meeting once all eight Arctic Countries had signed onto them (Artic Council Agreements 2015).

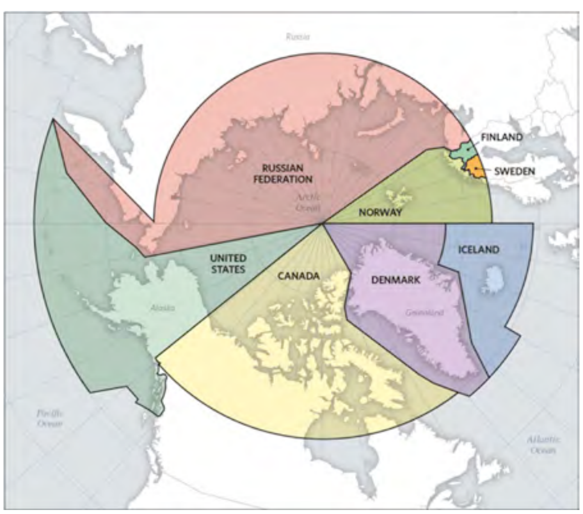

Figure 2
Arctic area divided under the Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic.
(Cooperation in the Arctic … 2014)

Governance of Shipping

The governance of shipping is similar between the poles. Shipping is regulated by many different conventions which have all put forth laws and acts for the safety of shipping in the Poles. All of these regulations are in effect within the area marked out in Figures 3 and 4. Some of the most notable regulations are the Safety of Life at Sea convention and the International Convention for the Prevention of Pollution from Ships (MARPOL) (Loukacheva et al. 2010). The Safety of Life at Sea convention casts a broad net of rules and standards over shipping. It regulates areas such as steering gear requirements, fire detection, and radio communication equipment. MARPOL addresses vessel source pollution and sets detailed pollution and protection standards with six annexes which each deal specifically with a different type of pollutant.

Special guidelines for ships sailing in the Poles have also been set out by the International Maritime Organization (Loukacheva et al. 2010). These guidelines cover enhanced contingency planning for all passenger ships, voyage planning guidance for all ships sailing through the areas shown in Figures 3 and 4, and guidelines for ships operating in icy waters. These regulations were put into place to compensate for the enhanced risk of ships sailing in polar waters, which have extreme weather, ice, and strong currents.

Figure 3
Maximum extent of Arctic waters application (Loukacheva et al. 2010)

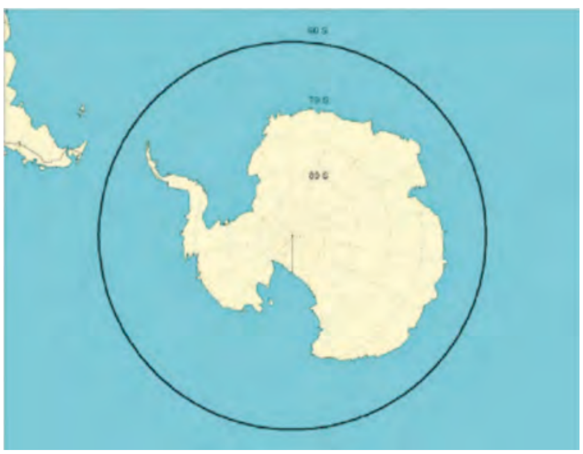

Figure 4
Maximum extent of Antarctic waters application (Loukacheva et al. 2010)

Environmental Protection

The polar ecosystems are very similar. Both of them have very extreme conditions which its organisms have to deal with every day. This leads these organisms to become highly specialized just to survive. They must be able to deal with darkness and extreme cold for half of the year and then bright, quick growing seasons. This ability to deal with extreme environments causes these organisms to be extremely susceptible to changes and pollution. Since these environments are so similar, it would suggest having similar protection strategies for both poles. Presently, there is not specialized environmental protection regulations created specifically for the polar regions (Loukacheva et al. 2010).

Environmental protection in the Arctic is broken up between all of the Arctic countries. All of the lands in the Arctic are claimed by a country. This means that environmental protection on land in the Arctic is dependent on which ever country owns the land. The Arctic ocean area is mostly considered the high seas and falls under International Environmental Law and Multilateral Environmental Agreements. In the Antarctic, environmental protection on the continent is protected by a specialized committee under the Antarctic Treaty System. The environmental protection of the continent is left up to the Committee for Environmental Protection that convenes during the Annual Antarctic Treaty Consultative Meetings. It does not follow International Environmental Law, but rather picks and chooses from different environmental protection regimes to produce the best protection plan specifically for the Antarctic (Loukacheva et al. 2010). The ocean surrounding Antarctica is viewed as the high seas and regulated by International Environmental Law. Of these two management plans, the Antarctic's is much easier to understand mainly because the Antarctic is not claimed by multiple states, each with its own environmental protection plan.

Management of Living Marine Resources

Living marine resources in the poles are managed by two different regimes. In the Arctic, living marine resources are managed on the high seas by regional fishery management organizations, which pass agreements about living resource extraction on all of the high seas. Closer to the coast, the waters inside of 200 nautical miles from shore are managed by the country whose exclusive economic zone they are within. The exclusive economic zone is one of the five zones of national jurisdiction defined by the Law of the Sea.

Living marine resources in the Antarctic are regulated by the Conservation of Antarctic Marine Living Resources Treaty. The treaty regulates marine resources, including fisheries, on the high seas around the Antarctic as seen in Figure 5. It has been developed over the last five years to combine the regulation of fisheries resources with an ecosystem approach. This means studying the effects that fishing will have

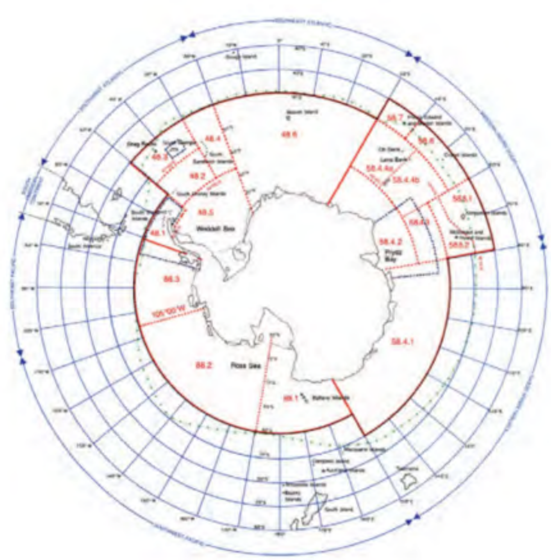

Figure 5
Effective area of the Conservation of Antarctic Marine Living Resources Treaty regulations. (Loukacheva et al, 2010)

on the entire ecosystem, not just each commercially important fish population targeted by the fishing fleets.

These management regimes effect all living marine resources in the areas that they cover. This includes all migratory species as well as permanent residents. The regimes only protect organisms while they are within the regimes specified areas. Any organisms which leave these areas will no longer be protected by the management regimes until they return.

Conclusion

Polar law is still relatively young, evolving field. As global warming progresses, it will continue to gain interest as a professional and academic subject. Many of the laws that govern the polar regions are different between the Arctic and Antarctic. The differences are mostly due to the geography of the two areas. In the Arctic there is not a central land mass or easy way of defining its extent. The Antarctic is its own continent, completely surrounded by ocean with a defined boundary at 60˚ South Latitude (Secretariat of the Antarctic Treaty 2011). While the Antarctic can area be defined as its own region governed by its own laws, all of the land in the Arctic has already been claimed by different countries. The area, therefore, has to be governed by all of the countries together. This causes the law in this area to be much more complex, with no powerful central regulating body. Due to the legal regimes around the poles being so different, the term polar law has to encompass many branches of international and domestic law. The field is a merging of the two very different areas of Arctic Law and Antarctic Law. The differences in these two areas lead to a very small amount of overlap in their legal regimes. Combining them into one field is what causes the term Polar Law to have such a long and complex definition.

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Economy and Resources at World's Ends

By: Abigail Rhodes
Editors: Bailey Bush, Emily Johnston

Introduction

There has been a growing interest in the resources of the Arctic and the Antarctic since the late 1970's. With rising temperatures melting the sea ice, the prospects that the Arctic's and Antarctica's continental margins may contain commercially valuable hydrocarbons in the form of crude oil and gas; that icebergs from Antarctica may be a valuable source of fresh water for dry climates; or the abundance of living resources has led to the growing development of the Poles (Burton 1979).

"Adventurous exploration is history. Scientific investigation is well-established. The era of economic development is dawning." (Burton 1979) While the Antarctic Treaty does help to protect the delicate environment found in Antarctica, it was not designed to govern such activities as resource development. This can lead to conflict between the nations that have an interest in Antarctica's resources if any of them chose to try to develop and extract these resources (Dugger 1978, Burton 1979). Conversely, resources in the north are governed by the Arctic Council, the Law of the Sea Convention (UNCLOS), and the International Maritime Organization (IMO) and, under UNCLOS, the states have the right to extract mineral resources as well as the duty to protect and preserve the marine resources (Bratspies 2009).

Fisheries in the Arctic

Humans are the most significant driver of global change, not only in terms of how we impact the climate, but also how we affect ecosystems through resource extraction and other human activities. However, due to climate change and sea ice loss in the Arctic, boreal fish and their fisheries are moving pole-ward into unexploited parts of the Arctic Ocean. Many marine fish species native to the Arctic region are quite sensitive to large-scale, industrial fishing (Christiansen et al. 2014). Consequently, we need to be very careful about how much of the fish stock we take each year.

The Arctic Ocean and its adjacent seas (AOAS) are home to 59 commercially harvested species of fish which include capelin, halibut, Greenland halibut, squid, crabs, shrimp, scallops, polar cod, pacific cod, sablefish, perch, salmon, sole, Pollock, flatfish, and turbot, with most of these fisheries being located in sub-Arctic seas (Christiansen et al. 2014, Hassan 2009). In addition to these commercially harvested

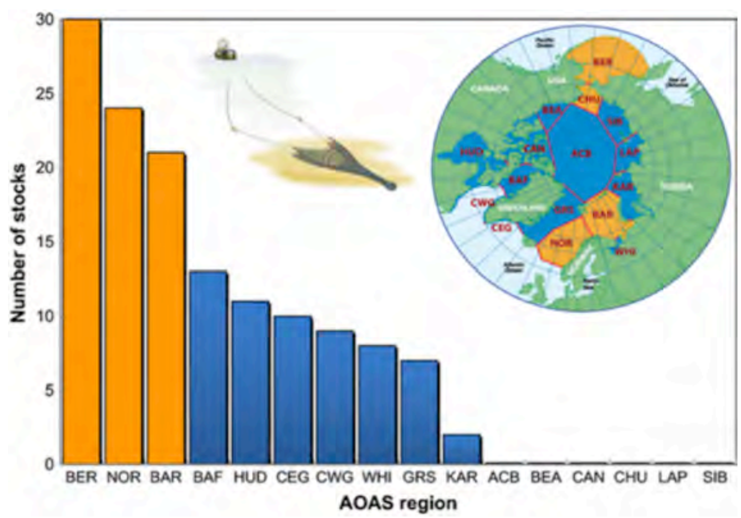

Figure 1. The number of marine fish species ('stocks') currently harvested by industrial fisheries in the Arctic Ocean and adjacent seas (AOAS). The Arctic gateways are shown in orange and the Arctic seas in deep blue. Note that the same species may be harvested in more than one region. The regional codes are as follows: ACB, Arctic Central Basin; BAF, Baffin Bay; BAR, Barents Sea; BEA, Beaufort Sea; BER, Bering Sea; CAN, Canadian Arctic Archipelago; CEG, Coastal East Greenland; CWG, Coastal West Greenland; CHU, Chukchi Sea; GRS, Greenland Sea; HUD, Hudson Bay Complex; KAR, Kara Sea; LAP, Laptev Sea; NOR, Norwegian Sea; SIB, East Siberian Sea; WHI, White Sea. (from Christiansen et al. 2014)

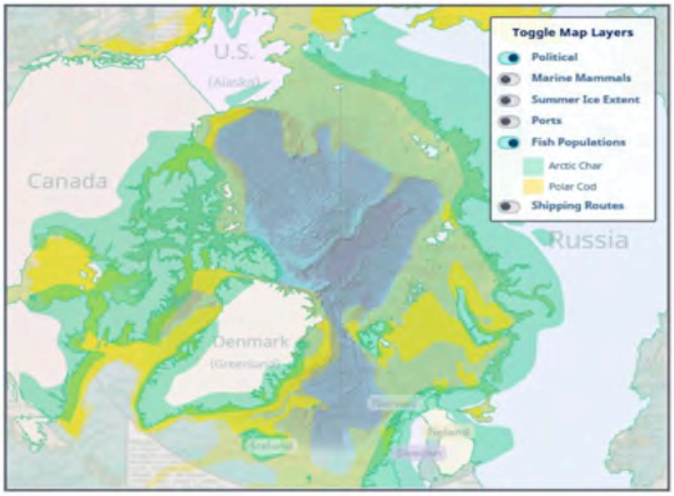

Figure 2. Fish populations from the Arctic (Arctic char and polar cod) are being displayed. (from NOEP 2015)

species there is a substantial amount of Chondricthyes bycatch. In 2011 alone, there were 7.5 million tonnes (metric tons) of fish taken from the northeast Atlantic and 15.8 million tonnes taken from the northwest Pacific. The largest commercial fisheries are found in the Bering Sea, which has 30 marine fish species or fish stocks; the Atlantic Arctic gateway, which has 21-24 stocks; and in Baffin Bay and Greenland Sea which have 9-13 stocks (Fig. 1) (Christiansen et al. 2014). Additionally, small-scale subsistence fisheries exist among the indigenous people of the Arctic. From 1950 to 2006, they harvested an average 950,000 tonnes of fish (Kofinas 1993; Christiansen et al. 2014).

Fisheries in the Antarctic

In the Southern Ocean, whaling and sealing is managed by the International Whaling Commission and the Convention for the Conservation of Antarctic Seals (Burton 1979). It is unfortunate that other the fisheries, such as those for krill, squid and fish, are not regulated under these or any international laws (Burton 1979). Because of this lack of regulation, most fisheries in the Antarctic have a rather long history of being commercially over-exploited. This led to the establishment of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) in 1982, which helps to regulate living resources extracted south of the Antarctic Polar Front (Burton 1979, Constable et al 2000).

Commercially valuable fish species in the Southern Ocean are estimated to be so abundant that the protein production from the world's oceans could double if we had the technological, economic, political, legal, and environmental means to recover these living resources sustainably (Burton 1979). The top four fisheries in the Antarctic are the Antarctic toothfish, Patagonian toothfish (both of which are often sold as Chilean sea bass), mackerel icefish, and the Antarctic krill (CCAMLR 2015b, Australian Government 2015).

Krill is one of the most abundant and valued fisheries in this region with an estimated biomass of 379 million tonnes (CCAMLR 2015a). However, as it is a key species in Antarctica's marine food web and over-exploiting them would be detrimental to the entire ecosystem, this fishery has been managed in a very precautionary manner (Burton 1979, CCAMLR 2015a). In an effort to minimize the impact to the ecosystem, rather than maximizing the size of the fishery, the krill fishery is only as big as the population can sustain over an extended time-period (CCAMLR 2015a).

Unfortunately, the finfish fisheries have not fared so well given our history of over-exploiting Antarctica's living resources. By the time many of these exploited fisheries were closed, many of the species being extracted had populations numbering less than 20% of their original stocks (UAF

Figure 3. Patagonian toothfish. (from ASOC 2014)

2013). As a result of this and their high marketability, several fish species have been commercially exploited to the point of near extinction since the 1970's in both the Arctic and the Antarctic (Burton 1979, UAF 2013). Fortunately many of these species are recovering quite nicely 30 years after closing their fisheries, which has led to a desire by many to reopen these fisheries. However, even after 30 years, some of these populations still have yet to recover to a point where it would be safe to reopen the fisheries, partially due to the fact that these species are still being extracted from the environment, either in illegal fisheries or as bycatch in destructive commercial fishing methods (UAF 2013).

Table 1. List of species that have been and are currently being commercially harvested from the Southern Ocean. Also listed are the years their fisheries opened and closed, the percentage of stock that remains of the closed fisheries, and the annual harvest limit of currently open fisheries. (from UAF 2013)

Fishery	Date fishery opened	Date fishery closed	Current Tonnage limit	Stock remaining (%) For closed fisheries
South Georgia & vicinity (48.3)				
Champsocephalus gunnari	1970		3072	
Dissostichus eleginoides	1976		2600	
Gobionotothen gibberifrons				
Pseudochaenicthys georgianus				
Chaenocephalus aceratus	1975	1999		25-40
Notothenia rossii	1969	1985		<5
Patagonotothen guntheri	1978	1990		~20
Antarctic Peninsula & South Shetland Islands (48.1)				
C. gunnari	1978	1980		<5
Chaenodraco wilsoni	1978	1990		?
N. rossii	1978	1990		<10
South Orkney Islands (48.2)				
C. gunnari	1977	1990		<5
G. gibberifrons	1977	1990		40
N. rossii	1979	1990		<10
Kerguelen Islands (58.5.1)				
C. gunnari	1970			~30
D. eleginoides	1977		5100*	~15
Lepidonotothen squamifrons	1971	1989		<5
N. rossii	1970			<10
Heard Island (58.5.2)				
C. gunnari	1971	1989		~15
D. eleginoides	1995		2730	?
Ross Sea (88.1 & 88.2)				
Dissostichus sp.	1996		3812	

Mineral Resources in the Arctic

The Arctic has an abundance of mineral resources, mostly in the form of oil and gas (Borgerson 2008). The US Geological Survey (USGS) completed a geologically-based assessment of the area north of the Arctic Circle in order to determine the oil and gas resource potential. The survey considered only areas of recoverable hydrocarbon volumes greater than 50 million barrels of oil, or 300 billion cubic feet of natural gas, and excluded smaller accumulations of coal bed methane, gas hydrates, oil shales, heavy oil, and tar sands. They found that one third of the Arctic is above sea level, one third consists of continental shelves under less than 500 m of water, and the rest is in the Arctic's deep oceanic basin, which has been historically covered by sea ice. The USGS found that the deep oceanic basins have relatively low potential for petroleum, while the continental shelves contain one of the world's largest remaining prospective areas for oil and gas.

According to the USGS, the Arctic holds 13% of the world's undiscovered oil resources (90 billion barrels) and 30% of the world's undiscovered natural gas resources (1.67 trillion cubic feet) (Conley et al 2013). However, many of these areas remain unexplored and undeveloped because of the current low oil prices, remoteness of the sites and corresponding technical difficulty. Development of the Arctic would depend on market conditions, technological innovation, and the actual sizes of these estimated areas (Gautier et al. 2009). The estimated volume of undiscovered oil ranges from about 22 billion barrels of oil (BBO) to 256 BBO, with a mean estimate that indicates that there is more than double the previously estimated amount of undiscovered oil in the Arctic. It is estimated that the Arctic may contain almost 4% of the world's remaining recoverable oil resources

Figure 4. Map showing the potential undiscovered oil resources of the Arctic estimated by the USGS survey. Only areas north of the Arctic Circle were included in the assessment. (from Gautier et al. 2009)

with the Alaska Platform containing more than 31% of the Arctic's mean undiscovered oil (27.9 BBO) (Gautier et al. 2009). However, this abundance of oil and natural gas in the Arctic is not sufficient enough to shift the world's oil balance from Saudi Arabia to the Arctic, especially as the oil mined from the Arctic would only be added to already existing reserves (Gautier et al. 2009).

Natural gas is typically measured in trillion cubic feet (TCF), except when looked at on an energy-equivalent basis with oil. Then it is measured as billion barrels of oil equivalent (BBOE). The Arctic is estimated to contain more than three times the amount of natural gas as oil on an energy-equivalent basis, with the largest gas accumulation being almost eight times the size of an energy-equivalent oil accumulation (22.5 BBOE vs.

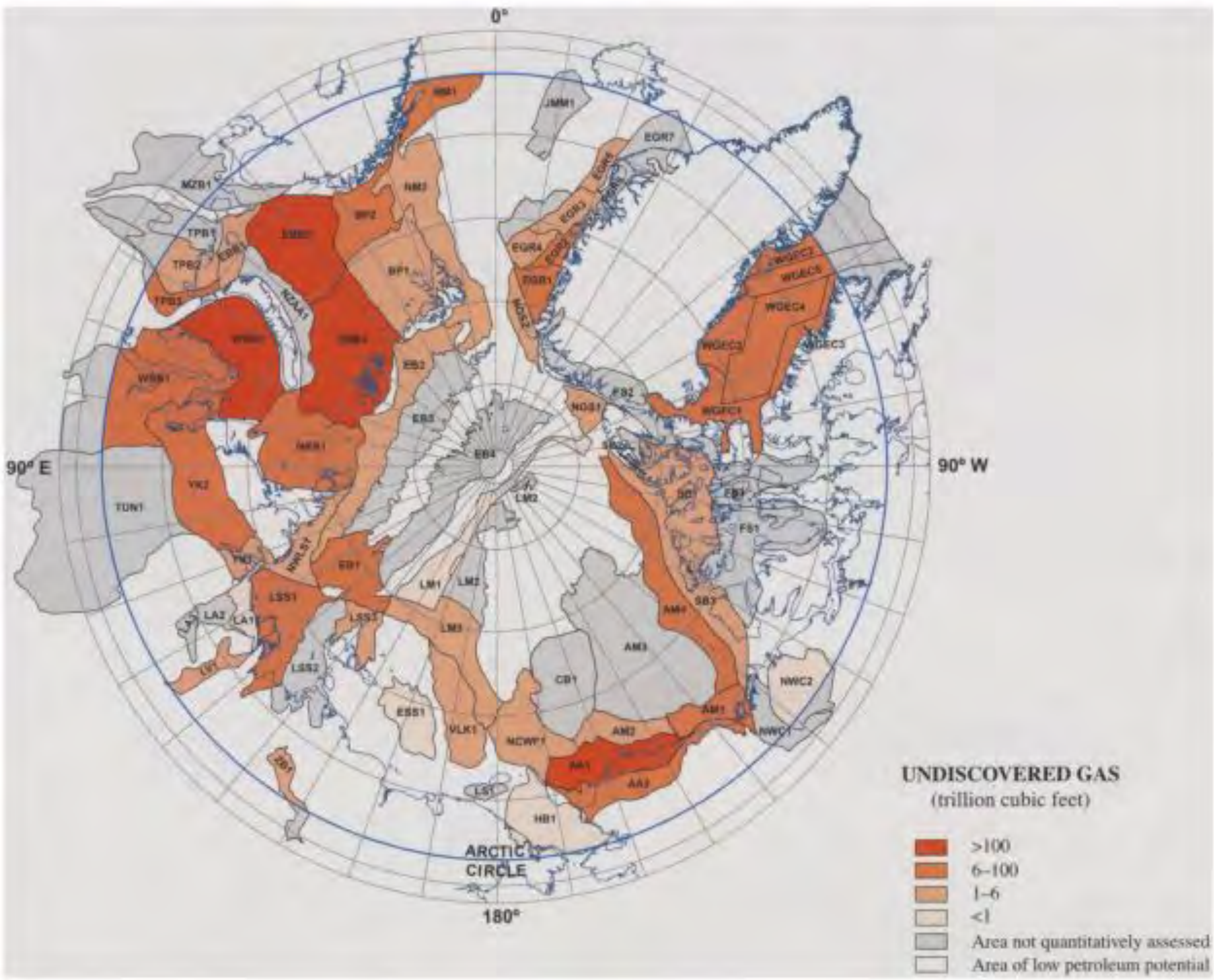

Figure 5. Map showing the potential undiscovered natural gas resources of the Arctic estimated by the USGS survey. Only areas north of the Arctic Circle were included in the assessment. (from Gautier et al. 2009)

2.9 BBO). There is believed to be more than 770 TCF of natural gas north of the Arctic Circle, representing more than the global undiscovered gas resources (Gautier et al. 2009). The greatest concentrations of undiscovered gas in the Arctic are found in Russia, with substantial amounts also being found in Alaska, Canada, and Greenland. By 2007, more than 400 oil and gas fields, containing 40 BBO, 8 billion barrels of natural gas liquids and 1136 TCF had been developed north of the Arctic Circle (approximately 66˚ N) in West Siberian Basin, Russia and North Slope, Alaska. (Gautier et al. 2009).

Mineral Resources in the Antarctic

Despite geological structures on the continental margin suggesting the presence of a significant amount of oil and gas, Antarctica does not have as much potential attainable mineral resources as the Arctic. Most of the mineral resources that are present here are more abundant and could be more easily extracted elsewhere in the world (Dugger 2008, Burton 1979). Thus, mineral resources are less attainable in the Antarctic due to the harsh climatic and environmental conditions of the region. With air temperatures that can drop as low as -100˚C and winds that can reach up to 200 miles per hour and can rise up without warning, it can be very difficult to extract resources from the continent (Burton 1979). Current knowledge suggests that significant quantities of oil and gas may be present in the continental margin. However, environmental, political, economic, and technical difficulties prevent anyone from exploiting this resource. Offshore drilling is not done either because it is inhibited by severe storms and huge ice bergs (Burton 1979, Dugger 2008).

Shipping in the Arctic

Shipping lanes through the Arctic could decrease the transportation time of large cargo ships by as much as 40% (10-13 days) once the ice melts, which in turn would reduce carbon output and emissions. Transits through the Northern Routes have been increasing drastically lately. In 2011-2012, the Northern Sea Route has seen a 53% increase in use, transporting 33 cargo ships and 850,000 tons of cargo (CFR 2014, NOEP 2015a). In 2013, that Northern Sea Route transported 71 vessels. This is a dramatic increase from the amount of traffic these routes saw in 2009 (5 vessels) (CFR 2014). Given these numbers, it is not too inconceivable to believe that cargo ships will be shipping through the Northern passages very soon. This increases the urgency of settling any disputes about who owns the Northern trade routes, which there is a lot of, as quickly as possible. Canada claims the Northwest Passage as theirs, but other nations claim it as international waters and Russia claims the Northern Sea Route above Siberia as theirs. The US says that only part of it actually belongs to Russia (Borgerson 2008, NOEP 2015a).

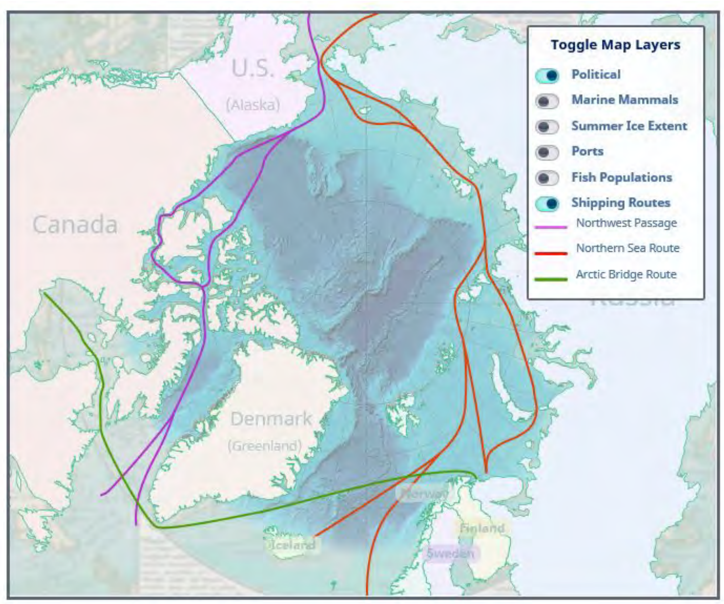

Figure 6. The shipping routes in the Arctic are displayed. Once the ice completely melts, ships will be able to travel through the center of the Arctic as well. (from NOEP 2015b)

Figure 7. M/V American Tern being led into McMurdo Station, Antarctica, by the Russian Icebreaker Krasin during Operation Deepfreeze 2006. (from: https://upload.wikimedia.org/wikipedia/commons/c/ce/Operation_Deep_Freeze_2006,_MV_American_Tern,_Krasin_200601.jpg)

Economy in the Arctic

Traditionally the Arctic and sub-Arctic communities are supported by a mixture of cash income and traditional subsistence farming and hunting. They hunt animals like moose, caribou, whales, ducks, and fish. What they get from subsistence hunting consists of more than 50% of their diet. It is not uncommon in this region for hunting to be one's occupation and communities that specialize in the hunting of one species or in farming will trade with other communities for different items. For example, one community may trade fish for caribou from another community (Kofinas 1993).

Tourism in the Arctic is an important and increasingly valuable economic activity with cruises to the Arctic ranging from $3,895 to $10,995, or as much as $35,000 for an icebreaker cruise. In Alaska, cruise ships to the North Pole generate $2 billion annually with 400 ships traversing the Bering Strait in 2011 (Conley et al 2013). Today, there are more tourists to the Arctic than there are Natives Peoples (UNEP 2007). However, cruises to the North Pole are not the only forms of tourism in the Arctic. Ecotourism is also playing an increasingly important role in Arctic economic activity. In Alaska, wilderness parks have been increasing in tourism as well. The Gates of the Arctic National Park and Preserve have had a steady 11,000 visitors each year (Conley et al. 2013).

Economy in the Antarctic

Economy in Antarctica is virtually non-existent, outside of tourism and fisheries activities on account of the fact that the continent is, at present, primarily used for scientific research and because there is no permanent population (CIA 2013, Burton 1979). However, tourism seems to be increasingly popular in recent years with more than 100 companies from 16 countries bringing ships full of tourists to the continent and its islands (BAS 2015). Tours of the research facilities and visiting monuments, historic sites, and the graves of scientists who died there are among the more popular destinations (BAS 2015). With a growing number of tourists each year (there were over 27,000 tourists from 2005 to 2006), tourism in the Antarctic has become such a valuable economic activity that the Antarctic Treaty now recognizes it as a legitimate activity (IPCC 2007). Tourists travel to Antarctica via ship frequently seeking adventure and to see the rigid, dramatic beauty of the continent. However, access is only possible for roughly three months during the austral summer, with air travel available for an additional two months in the spring (Burton SJ 1979).

Conclusion

For the first time in millennia the Northern Passage is opening which is reducing costs and time of shipping. With this melting of the sea ice and technological advances, we are also gaining greater access to the mineral and biological resources in these previously inaccessible areas. Furthermore, economy in the Arctic and Antarctic is growing at an unprecedented rate. One might think that all of this melting ice is a good thing. In Greenland farming is booming as fields that were once barren and too frozen for agriculture, now yield crops such as broccoli, hay, and potatoes (Borgerson 2008). However, all of this is now possible because of climate change.

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UV Radiation and the Ozone Hole

By: Gwendolyn Pelletier, Abigail Rhodes
Editors: Bailey Bush, Kaitlyn Kennedy

Ozone

Ozone is a molecule made up of three bound oxygen atoms, taking the molecular form of O_3. It is found in low doses throughout the atmosphere, and is toxic in large quantities. However, it is also an essential molecule that allows life to exist on the earth's surface. Earth's atmosphere is made up of several different layers, including the troposphere, where all of the earth's weather takes place, as well as the stratosphere, the layer above that (Solomon 1999, Lindsey 2014). Up in the stratosphere, there is a very high density of ozone molecules, called the ozone layer, which is essential to life on earth. Ozone molecules in the stratosphere absorb wavelengths of UV-B radiation, preventing rays from reaching the earth's surface and damaging molecules in animals and plants that are essential for life. (Solomon 1999, Newman 2016). There are three main types of UV radiation, UV-A, UV-B, and UV-C, which are classified based on wavelength. UV-C radiation has the shortest wavelength and is the most dangerous, but never reaches the surface of the earth. UV-B is the next most dangerous, and UV-A has the longest wavelength and is the least dangerous, although all types can be damaging (World Health Organization 2016). Figure 1 shows how UV-B radiation is absorbed by the ozone layer, preventing the majority of these damaging rays from reaching the earth's surface.

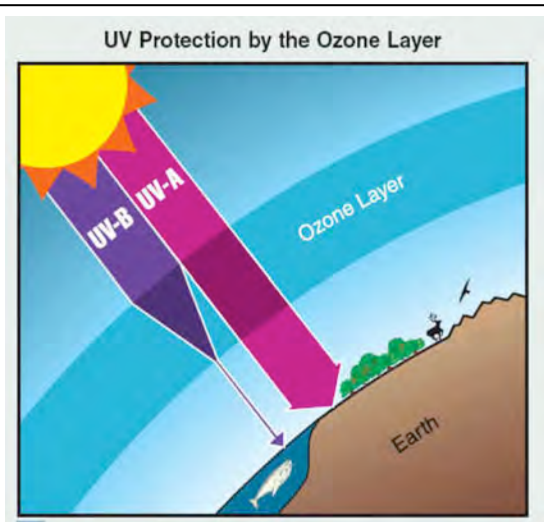

Figure 1: UV-B radiation is absorbed by ozone molecules in the stratosphere. (ozonehole.com)

Ozone Chemistry

Ozone molecules are in chemical equilibrium with molecular oxygen (O_2) in the atmosphere. Ultraviolet radiation cause ozone to break apart into molecular oxygen and oxygen radicals. Oxygen radicals consist of a single oxygen atom with only six electrons in their outer shell, instead of the full eight, which makes a complete octet. Because the oxygen radical has an incomplete octet, this makes it more reactive, as it tries to fill the octet. The oxygen radical will bump into an oxygen molecule and react, regenerating the ozone molecule (Solomon 1999).

This reaction can take place in minutes, and the concentrations of ozone can change based on the environmental conditions. However, the overall concentration of ozone plus oxygen radicals remains more or less constant. Occasionally, two oxygen radicals can combine to form an oxygen molecule, taking the radicals out of the ozone equation, and resulting in the transformation of two ozone molecules into three oxygen molecules. However, this reaction does not take place very frequently, and the overall concentration of ozone does not change much. When certain other compounds are introduced into the stratosphere, the equilibrium can change. Hydroxyl, nitric oxide, chlorine, and bromine radicals can all catalyze the breakdown of ozone into molecular oxygen. In this reaction, the radicals are not used up, so small increases of these radicals in the atmosphere can cause the breakdown of a lot of ozone molecules (Solomon 1999).

Chlorofluorocarbons and Ozone

Chlorofluorocarbons, or CFCs, are gases that were commonly used in many different applications, including refrigerants and aerosol sprays. They are incredibly stable compounds and do not break down easily. However, when they are released into the atmosphere and travel into the stratosphere, UV radiation can break down CFCs, releasing carbon radicals. CFCs are insoluble in water, so once they are in the atmosphere, they cannot be removed by precipitation. Additionally, these compounds have very long residence times in the atmosphere, between 50 and 500 years, meaning they will not be removed from the atmosphere easily. The release of chlorine radicals from the breakdown of CFCs causes the breakdown of ozone molecules into molecular oxygen in the stratosphere. This lets more UV radiation penetrate the ozone layer and reach the earth's surface (Newman 2016, Solomon 1999).

Polar Stratospheric Clouds

At the poles, the ozone layer is particularly susceptible to breakdown because of the low temperatures. Polar stratospheric, or nacreous clouds, form in the stratosphere only when temperatures are -78°C or below. This happens more frequently in the colder polar regions because of the decreased temperatures. In polar stratospheric clouds, CFCs are broken down much more readily, meaning that ozone is generally broken down at a faster pace at the poles (Lindsey 2014).

Ozone Seasonality

The relatively fast reaction rates of ozone chemistry means that the concentration of ozone in the stratosphere can change readily to reflect changing environmental conditions. Ozone concentrations show seasonal cycles as well as yearly variation that reflect this. Figure 2 shows an example of how ozone concentrations can change from year to year. However, there is also a decreasing trend in the ozone concentrations in both the Arctic and the Antarctic, while mid-

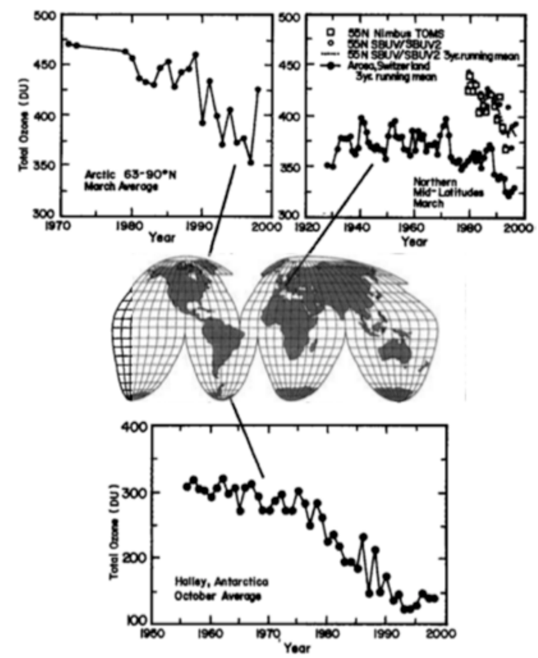

Figure 2: Stratospheric ozone concentrations in the Arctic, mid-latitudes (Switzerland) and the Antarctic, showing yearly variation in all locations, and a decreasing trend in polar areas (Solomon 1999).

latitudinal concentrations remain constant (Solomon 1999). These trends reflect the cold chemistry required in the polar stratospheric clouds to break down ozone into molecular oxygen (Lindsey 2014).

The Antarctic Ozone Hole

In 1985, a seasonal winter ozone hole over Antarctica was discovered and linked to the use of CFCs and other ozone

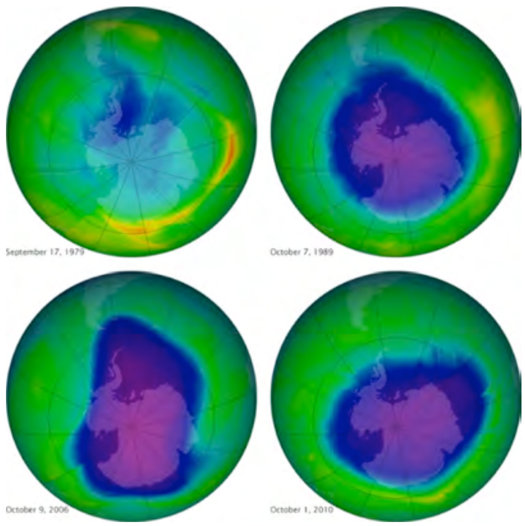

Figure 3: The extent of the seasonal Antarctic ozone hole in 1979, 1989, 2006, and 2010 (Ichoku).

depleting compounds (Newman 2013). It continued to grow in size for several years after discovery, and the minimum concentration of ozone over Antarctica occurred in 1994, and the maximum extent of the ozone hole occurred in 2006, with an area of nearly 30 million square kilometers, more than twice the size of Antarctica (Newman 2016).

Effects of UV radiation on flora and fauna

UV radiation is a high energy radiation that affects many organisms at the molecular level by damaging tissue and pigments, and denaturing proteins and DNA which can cause transcription and replication errors (Agusti 2008, Obermuller et al. 2005). UV-B radiation has also been found to destroy the cell membranes and inhibit nutrient uptake and photosynthesis in autotrophic organisms. UV radiation has even been reported to affect the mobility and navigation systems of some marine organisms, as well as increase the toxicity of some chemical, marine pollutants such as the petroleum-derived aromatic polycyclic hydrocarbons. Furthermore, UV radiation strongly reacts with the nitrates and other compounds that are present in polar waters, forming the hydroxyl radical (OH^-) and hydrogen peroxide (H_2O_2), also referred to as reactive oxygen species (ROS). Reactive oxygen species are highly toxic because they modify and destroy an organism's biomolecules and can even form in the water inside the cells of many organisms (Agusti 2008).

Ways of dealing with UV radiation

Over the course of their evolution, polar species frequently exposed to UV radiation have had to develop mechanisms that minimize its harmful effects. One of the mechanisms developed by organisms frequently exposed to UV radiation is avoidance. Some organisms, like zooplankton, make daily vertical migrations through the water column and are thus able to escape the harmful effects of the UV radiation. In the evening, they rise to the surface when UV exposure will not occur and sink to depths below the penetration range of the UV photons during the day. Other forms of avoidance can be seen in organisms that have adapted to living under the sea ice and in those that grow at a depth where they are not affected by UV radiation (Agusti 2008).

Another mechanism of dealing with UV radiation is the building of a protective barrier to block UV radiation's negative effects. Organisms belonging to the phyla mollusca, arthropoda, and brachiopoda produce protective shells against the damaging effects inflicted by UV radiation. However, these shells do not completely shield them under long-term exposure. Further, larvae often lack these protective structures and are therefore very vulnerable to UV radiation (Agusti 2008). Some microalgae, like *Phaeocystis pouchetii*, secrete mucus which acts as a barrier that prevents the ultraviolet radiation from penetrating into their colonies. Other phytoplankton build crystals on the outside of their cell walls to reflect the UV radiation, thus preventing penetration into the cell (Agusti 2008).

Organisms that cannot build protective shells or escape the harmful effects of UV radiation have developed a different strategy for dealing with intense UV radiation. They developed a protection and repair system which is believed to be activated by UV-A radiation, a low energy form of UV radiation that is less damaging to cells in low doses (Roos and Vincent 1998). Polar autotrophs, which have adapted to thrive in low light conditions, endure the harmful effects of intense amounts of UV radiation in order to photosynthesize. As they are bombarded with the UV photons, the UV-A radiation activates their molecular repair systems which begins to heal them quickly. However, as a result of climate change, the intensity of UV radiation is increasing and these repair systems are not able to keep pace with the damage being done to the cells. This increased stress on polar autotrophs can reduce their photosynthetic activity. If this occurs across all species of phytoplankton it can reduce the ability of the ocean to absorb CO_2 (Agusti 2008).

Case Studies

The following case studies show how the loss of ozone over Antarctica causes more damaging UV radiation to reach the surface of the earth and harm both plants and animals in Antarctica and worldwide.

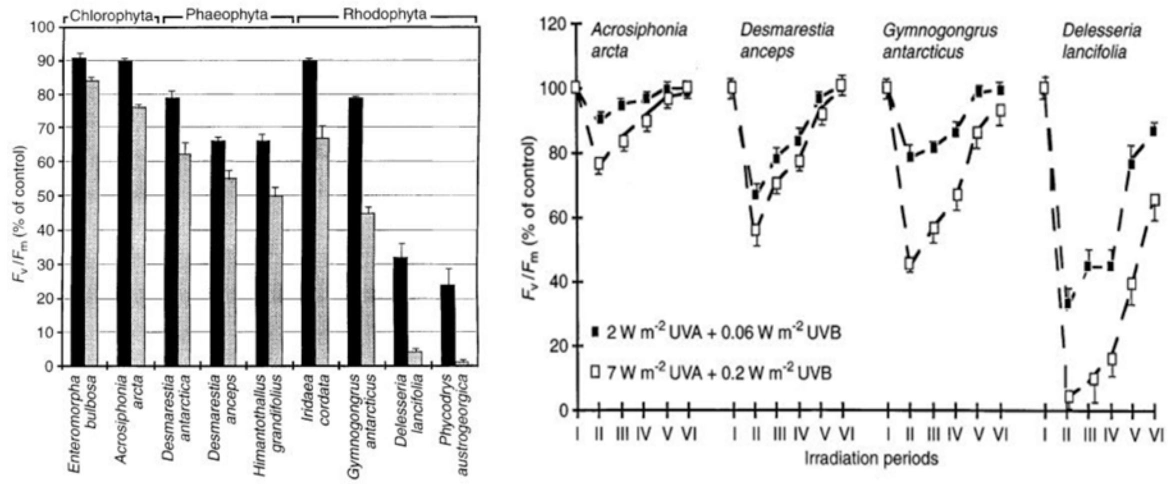

Figure 4: Nine species of macroalgae were irradiated with a high dose of UV radiation (7 W/m^2 of UV-A, plus 0.2 W/m^2 of UV-B) (shaded bars) for 1 hr and a low dose of UV radiation (2 W/m^2 UV-A, plus 0.06 W/m^2 UV-B) for 1 hr. The figure on left displays the degree of photosynthesis occurring, while the figure on right displays how the macroalgae reacted during the irradiation period (negatively sloped) and the recovery period (positively sloped). (Bischof et. al. 1998)

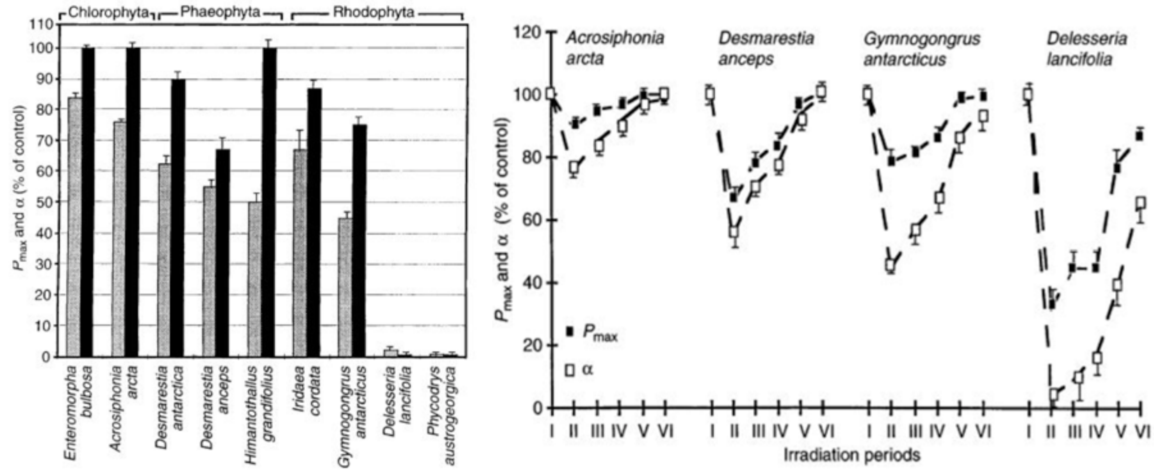

Figure 5: Nine species of macroalgae were irradiated with a high dose of UV radiation (7 W/m^2 of UV-A, plus 0.2 W/m^2 of UV-B) (shaded bars) for 5 hrs and a low dose of UV radiation (2 W/m^2 UV-A, plus 0.06 W/m^2 UV-B) for 5 hrs. The figure on left displays the degree of photosynthesis occurring, while the figure on right displays how the macroalgae reacted during the irradiation period (negatively sloped) and the recovery period (positively sloped) (Bischof et. al. 1998).

Bischof et al. examined the UV-sensitivity of photosynthesis in nine species of Antarctic macroalgae under laboratory conditions. Samples were exposed to artificial UV-A and UV-B radiations for one and five hours at a time. After a 48hr recovery period, their photosynthetic activity was measured to determine how well each species of macroalgae recovered (Bischof et. al. 1998).

The study found that Chlorophyta (green algae) handled the increase in UV radiation better than Rhodophyta (red algae) after one hour of irradiation (Fig 4). The same held true for the samples that were irradiated for five hours (Fig 5). Results indicated that UV radiation has the potential to impact the vertical zonation pattern of Antarctic macroalgae (Bischof et. al. 1998). This is important for determining the upper distribution limit of individual macroalgae species in Antarctica.

This study in 2003 by Hughes et al. looked at the how five species of Antarctic fungi were impacted by UV radiation. Specimens from five species of fungi were collected from Adelaide Island in the Antarctic Peninsula during the austral summer and grown in petri dishes for 28 to 35 days. They found that after exposure to solar and artificial radiation greater than 287 nanometers (nm), the growth of the hyphal extensions (the filamentous tips) in all five species was inhibited. Furthermore, they found that growth was most inhibited with the lower wavelengths, like UV-B radiation. Fungi mineralize nutrients from the organic matter in soil, making them important to terrestrial ecosystems, thus exposure to

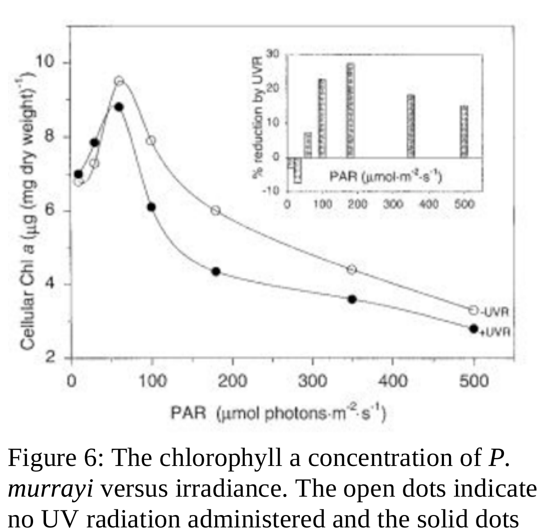

Figure 6: The chlorophyll a concentration of *P. murrayi* versus irradiance. The open dots indicate no UV radiation administered and the solid dots indicate that UV radiation was present. (Roos and Vincent 1998).

increased UV radiation is likely to affect the biogeochemical cycles of the Antarctic

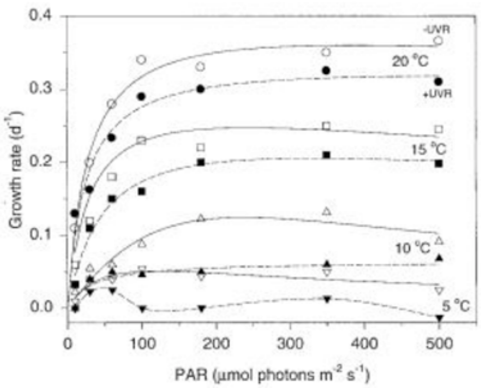

Figure 7: The growth rate of *P. murrayi* versus the irradiance at four temperatures. The open dots indicate no UV radiation was present, while the closed dots indicate UV radiation was present (Roos and Vincent 1998).

ecosystem. The growth of fungi is limited by other abiotic factors such as temperature, water and nutrient availability, and as

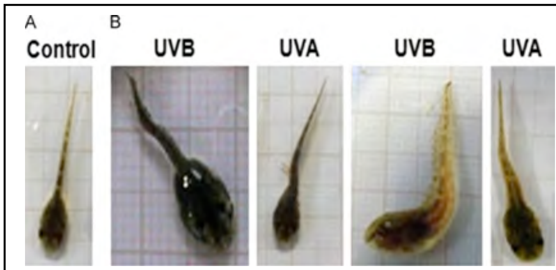

Figure 8: Representative examples of normal *H. pulchellus* tadpole (A) and tadpole with spinal curvature induced after UVB and UVA treatments (B). (Schuch et.al. 2015).

similar studies have also indicated, by UV radiation (Hughes et al. 2003).

In 1998, Roos and Vincent conducted a study on freshwater cyanobacterium from Antarctica with the aim to better understand the physiological responses of cyanobacteria to UV radiation in a warming climate. Cyanobacteria of the family Oscillatoriaceae can be found throughout the marine and freshwater environs of the Arctic and the Antarctic. Other studies have linked photoinhibition in higher plants to very low temperatures which increases the damage to the cells by decreasing the rate at which the chloroplast D1 protein can repair them. Roos and Vincent examined the relationship between temperature and chloroplast D1 protein degradation in a mat-forming, freshwater species from Antarctica. *Phormidium murrayi* was collected from an ice-shelf pond in Antarctica and grown in a unialgal culture for five days. They found that the pigmentation of *P. murrayi* was significantly influenced by photosynthetically active radiation (PAR) and UV radiation during the five day growth period (Fig. 6). However, their results did not indicate any significant impacts to photosynthesis in cyanobacteria, although they did conclude that growth is inhibited (Roos and Vincent 1998).

A depletion in the ozone hole can also affect animal populations. Populations of amphibians have been declining globally, and this study by Schuch et.al. aimed to see if an increase in UV-B radiation was contributing to the mortality of Brazilian tree frogs (*Hypsiboas pulchelus*) during their developmental stages. The Antarctic ozone hole can affect nearby ozone concentrations as well, and a decrease in the ozone layer over Antarctica corresponds to a decrease in ozone over Southern Brazil. This study found that UV-B radiation causes more deformations in tadpoles (Figure 8) and higher mortality than UV-A radiation, and that population declines correlated to an increase in the Antarctic ozone hole. This means that ozone depletion events can have a significant impact on the population of tree frogs and other animals around the world, and not just in Antarctica (Schuch et.al. 2015).

The Montreal Protocol

In September of 1987, twenty-four countries met in Montreal and signed the Montreal Protocol on Substances that Deplete the Ozone Layer, which detailed the phasing out of CFCs and other ozone depleting compounds from common use. Figure 9 shows Chlorine concentrations in the atmosphere and the ozone layer's response following the Montreal Protocol. The ozone layer began recovery in 1997, and is expected to make a full recovery by 2065 (Newman 2016).

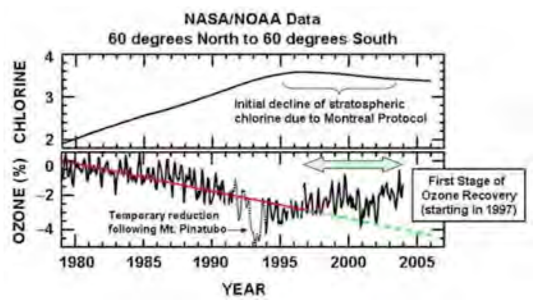

Figure 9: Atmospheric concentration of chlorine correlated with ozone concentrations. The Montreal Protocol in 1987 began to show effects around 1995, with a corresponding increase in stratospheric ozone concentrations starting around 1995 (Welch).

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Climate Change in Polar Regions

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Editors: Gwen Pelletier and Sharlene Maynard

Introduction

Naturally, Earth cycles through periods of glacial and interglacial periods, marked by respective periods of global cooling and warming. These fluctuations are attributed to several factors, the primary causation lying in alterations in the orbital geometry of the planet (Hays et al. 1976). These fluctuations are linked to Milankovitch cycles, which describe the patterns in the Earth's position and orientation in the solar system. Milankovitch describes how changes in the eccentricity (how elliptical the orbit), obliquity (tilt affects magnitude of seasonal change), and precession (direction of the axis with respect to the Sun) of the Earth may affect global climate patterns (Milankovitch 1920). In positive correlation with these warming and cooling cycles, global atmospheric carbon dioxide (CO_2) concentrations have fluctuated from 190-290 parts per million (ppm) throughout the late Pleistocene and Holocene (Fig. 1) (Liggett et al. 2015). Global warming skeptics argue that the current changes are able to be explained by these natural fluctuations, and that the Earth will eventually shift back towards cooler temperatures. However, current CO_2 levels have exceeded 400ppm with a strong increasing trend over the past 50 years (Fig. 1) (NOAA: Earth… 2016).

While climate change is a global phenomenon affected by both natural and anthropogenic influences, in this chapter we will discuss how climate change affects the polar regions of this planet specifically. Overall, the Arctic is warming at twice the global rate, with decreasing ice and snow mass. In addition, the arctic summer sea ice minimum decreased by 9.4-13.6% per decade from 1979 to 2012 (Fig. 2). Conversely, during the same time period, antarctic sea ice increased at 1.2-1.8% per decade (IPCC 2013). However, the rate at which Antarctica is losing its ice shelves is increasing rapidly, particularly on the peninsula. This chapter will focus on the primary causes of climate change, the non-linear systems it creates, and some of its consequences for polar regions.

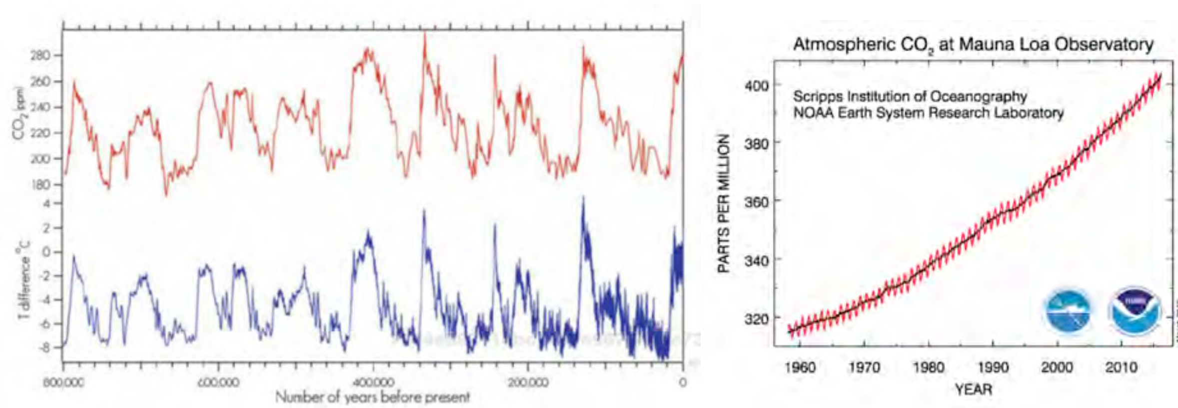

Figure 1. Global atmospheric CO_2 levels in ppm and temperature in degrees Celsius are displayed over the past 800,000 years (Left) (Liggett et al. 2015), and the atmospheric CO_2 levels in ppm at the Mauna Loa Observatory, HI, are displayed since 1960 (Right) (NOAA: Earth… 2016).

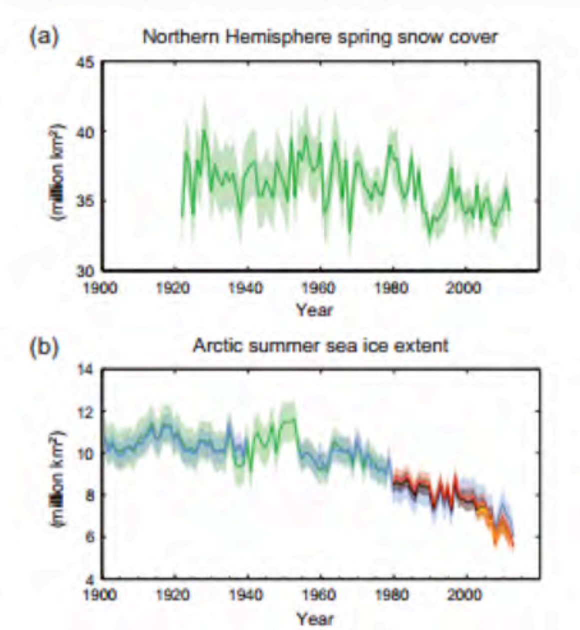

Figure 2. (a) Northern Hemisphere spring snow cover in millions of km^2 is displayed from 1920 to present. (b) Arctic summer sea ice extent in millions of km^2 is displayed from 1900 to present (IPCC 2013).

Probable Causes

The primary drivers of global climate change are anthropogenic greenhouse gas (GHG) emissions and deforestation. These GHGs restrict the amount of solar energy that can be radiated off of Earth into space, effectively retaining heat on the planet. Specifically, when monitoring arctic climate change, it is critical to consider the arctic oscillation (AO) phase, which is controlled by counterclockwise circumpolar winds, ultimately impacting weather patterns (Fig. 3) (NOAA: National… 2016). When in positive AO phase, strong circulating winds retain colder air in the Arctic. In contrast, negative AO phase is marked by a greater southerly penetration of cold arctic temperatures and increased frequency and severity of northern hemisphere storms (Fig. 3). Furthermore, the effects of El Niño must be considered when comparing climate changes from year to year (Holthaus 2016).

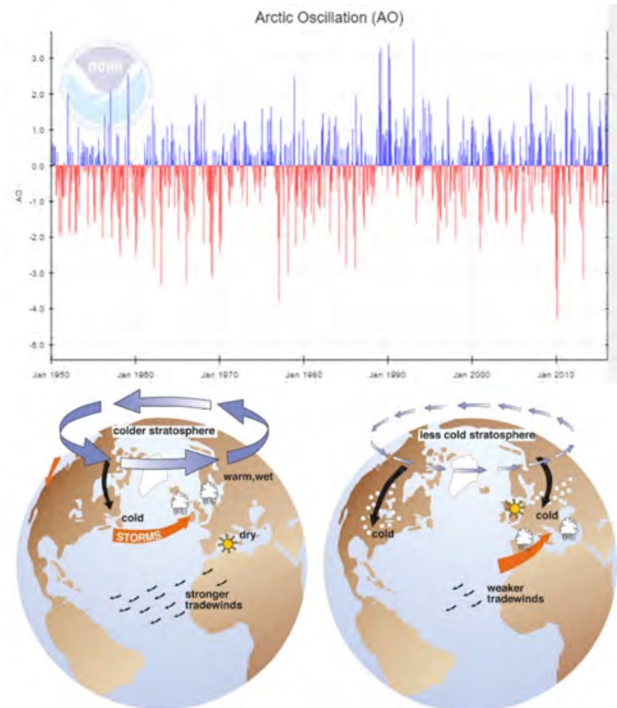

Figure 3. The arctic oscillation (AO) phases are displayed from 1950 to present (Upper). Blue bars represent positive AO (Lower left) and red bars represent negative AO (Lower right) (NOAA: National… 2016).

Over a 45-year span, annual precipitation intensity in northern Eurasia has been increasing at a rate of 1-3% per each degree Celsius of air temperature increase, with decreasing precipitation frequency. This may be due to a greater atmospheric water vapor holding capacity linked to the warmer temperatures (Ye et al. 2016). This general trend of warming and increased precipitation is also observed in parts of the Antarctic, which, coupled with warming temperatures, aids in lubricating the bottom of ice shelves. This water-induced sliding has resulted in the loss of eight peninsular ice shelves over the past 50 years (McClintock et al. 2008).

In contrast, some areas of Antarctica are actually cooling, as a possible result of a low-pressure system directing warm air over the peninsula and cold air over the Ross Sea. These wind patterns may be influenced by the hole in the ozone layer (NASA 2014), which continued to grow through the end of the twentieth century and now fluctuates at a relatively stable level (NASA 2016). Ozone depletion has been linked to chlorofluorocarbons (CFCs) and the creation of polar stratospheric clouds (PSCs). PSCs form in the winters, trapping chemicals like chlorine and bromine, which, through springtime photolysis, destroy ozone molecules (Liggett et al., 2015). To combat this depletion, the Montreal Protocol banned the use of CFCs in 1989, causing industries to switch to other harmful GHGs.

In addition, it has been proposed that mixed phase clouds over the continent, made of super cooled water and ice crystals, may influence the spread of these cooler temperatures (Lawson and Gettelman 2014). Conversely, expanding sea ice may result from a greater amount of freshwater at the surface associated with glacial melting. Furthermore, upwelling of colder water near the peninsula may aid in ice expansion (NASA 2014). The general pattern of antarctic cooling through arctic warming was observed during the last glacial maximum (21,500 years ago) and has been characterized as a bipolar see-saw mechanism (Xiao et al. 2016). Thus, while the primary cause of climate change is anthropogenic in nature, there are several global processes which must be considered when analyzing trends.

Non-linear systems

One of the greatest concerns with polar climate change are the non-linear systems that are created, where warming encourages further warming. In particular, this phenomenon can be modeled with the positive feedback system associated with receding arctic sea ice. Snow and ice have high albedo, or solar reflectance, compared to the ocean's surface. The melting of sea ice in this region lowers albedo, which in turn increases the amount of absorbed sunlight. This accelerates warming and encourages further melting of sea ice, in a process known as snow-ice albedo feedback (Fig. 4) (Houghton et al. 1990).

The role of clouds in climate change is more complex and generally less understood. This is because clouds have the capability to participate in both negative and positive feedback systems. Through warming arctic atmospheric and sea surface temperatures, there is increased evaporation and cloud formation (Cronin and Tziperman 2015; Ye et al. 2016; and Seo et al. 2015). Similar to ice, clouds have a relatively high albedo, reflecting infrared radiation back into the atmosphere, in effect cooling the planet through a negative feedback system (Fig. 4) (Houghton et al. 1990). Having a shortwave cloud effect, the negative feedback system may be inducing a poleward expansion of tropospheric circulation systems including Hadley cells and storms (Ceppi and Hartmann 2016). In contrast, the increase in cloud cover may be associated with a positive feedback system, where solar energy being reflected off the surface of the Earth is trapped, causing a relative warming of the planet (Fig. 4) (Houghton et al. 1990). Positive cloud feedback is amplified by low, optically thick clouds over the Arctic, where continental surface air may increase by two degrees for each degree increase of sea surface air temperature (Cronin and Tziperman 2015).

Increased precipitation and cloud feedback have been predicted in the Antarctic (Liggett et al. 2015; McClintock et al. 2008). Furthermore, these systems behave differently in polar regions compared to lower latitudes due to limited sunlight. In the Arctic, the insulating properties of the clouds associated with positive feedback outweigh albedo effects. As a result, the relative cloud effect, which typically decreases with increasing humidity, cannot be accurately determined

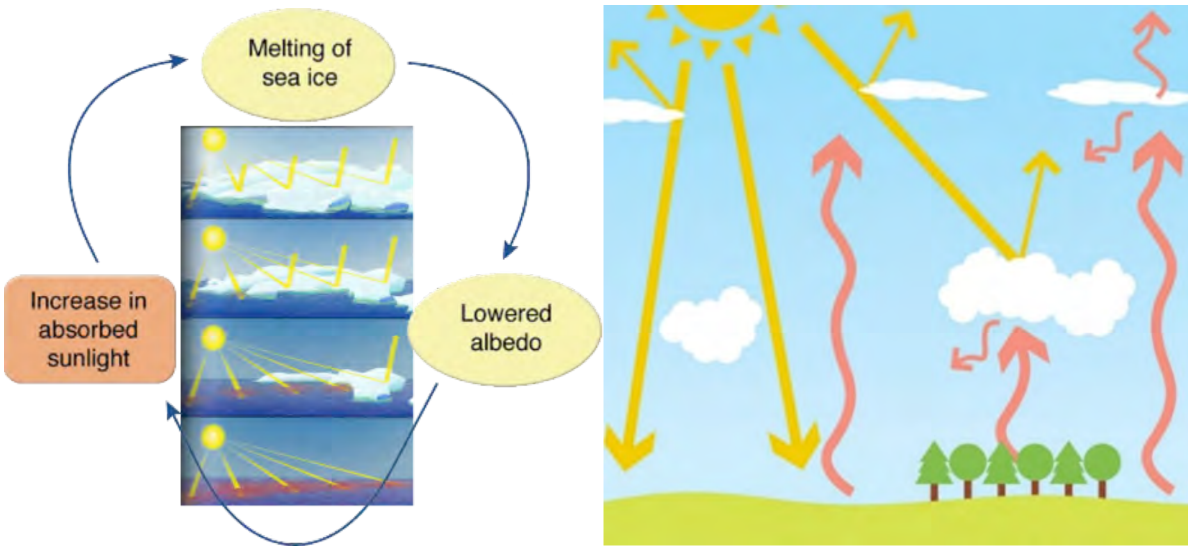

Figure 4. The snow-ice albedo positive feedback loop is depicted (Left) (Only-one-solution.org). Both the negative feedback (Yellow arrows) and the positive feedback (Pink arrows) systems of clouds are depicted (Right) (Booth 2013).

(Cox et al. 2015).

Increased precipitation and cloud feedback have been predicted in the Antarctic (Liggett et al. 2015; McClintock et al. 2008). Furthermore, these systems behave differently in polar regions compared to lower latitudes due to limited sunlight. In the Arctic, the insulating properties of the clouds associated with positive feedback outweigh albedo effects. As a result, the relative cloud effect, which typically decreases with increasing humidity, cannot be accurately determined (Cox et al. 2015).

The warming temperatures associated with these systems has induced the melting of permafrost in many arctic tundra landscapes, when defining this region by the tree line. The warming may cause drought stress on plants, and, coupled with increased precipitation, may increase phenol oxidase activity within the soil, leading to the release of stored carbon molecules within the permafrost (Seo et al. 2015). However, other studies have shown that increased warming also induces greater primary productivity and respiration rates (Becker et al. 2016), transforming the landscape from a carbon sink to a source by the end of this century (Fig. 5). Researchers also calculate that methane (CH_4) emissions from these regions are expected to increase from 34 to 41-70 teragrams per year (Koven et al. 2011).

This increase in the amount of CO_2 and CH_4 being emitted into the atmosphere only enhances the greenhouse effect, inducing further warming, leading to increased permafrost thawing. The increased levels of CO_2 in the atmosphere may result in greater deposition into both the Arctic and Southern Oceans. This additional CO_2 reacts with water molecules to create carbonic acid and bicarbonate ions, releasing hydrogen ions, effectively lowering the pH of the water in a process known as ocean acidification (NOAA: Pacific… 2016). The carbon cycle has two types of feedback mechanisms associated with climate change. First, both the warming atmospheric and sea surface temperatures and higher oceanic carbon content may reduce its uptake ability, encouraging further atmospheric warming. Conversely, warming temperatures and greater arctic open water may allow for increased primary production and greater uptake of CO_2, whereby warming accelerates the already occurring ocean acidification. (Manthis et al. 2015).

Consequences

In areas where ocean acidification lowers the pH significantly, the calcium carbonate shells of some organisms, particularly mollusks, begin to dissolve and thin (NOAA: Pacific… 2016). This has potentially disastrous effects on ecosystems, making these organisms more susceptible to predation. In the Northern Pacific and Arctic Oceans, this process may be exacerbated by sea ice melt and riverine inputs, reducing the amount of aragonite, an organic carbonate compound (Manthis et al. 2015). In Antarctica, dissolving shells encourages the expansion of crab distributions towards the continental shelves and favors gelatinous organisms such as salps (McClintock). From 1998-2014 there was a 4% reduction in summer calcification rates in the Southern Ocean associated with the acidification of the area (Fig 6) (Freeman and Lovenduski 2015).

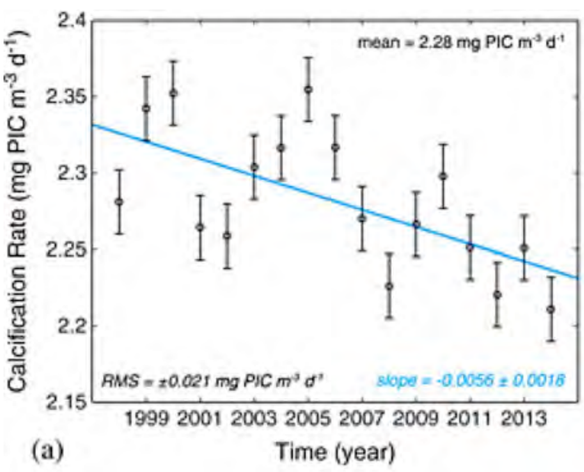

Figure 6. The calcification rate in milligrams (mg) of particulate inorganic carbon (PIC) m^{-3} d^{-1} is displayed over the past twenty years (Freeman and Lovenduski 2015).

Increasing polar temperatures associated with climate change may also alter thermohaline circulation (THC), influencing the global conveyor belt which circulates water throughout all five oceans. During the last glacial cycle, there was great variability in the Atlantic meridional overturning circulation (AMOC), which controls the heat transport from low to high latitudes. In effect, large shifts in THC are influenced by the sea surface temperature and ice extent (Böhm et al. 2015). In the Arctic, there is often an estuarine system of Atlantic water mixed with freshwater from runoff and melting ice at the surface above colder arctic water. As this water cools, it sinks and outflows into the Atlantic Ocean, providing the main source of freshwater (Eldevik and Nilsen 2013).

The reduction of arctic sea ice threatens to stop the current THC system through the expansion of the freshwater surface layer, especially in the waters surrounding Greenland (Fig. 7). This reduction in density may slow AMOC, in turn reducing the flow of the Gulf Steam and the transport of warmer water to the North. Already, the Labrador Sea Water formation has decreased, representing a weakening AMOC (Yang et al. 2016).

The influx of freshwater from melting polar glaciers, sea ice, and ice sheets inevitably raises local and global sea levels. When factoring in current GHG emissions and the melting of both Greenland and Antarctic ice sheets, sea levels may rise by nearly two meters by 2100 (Dennis and Moody 2016). This will have devastating implications for coastal geography, ecological communities, and development across the planet.

Melting sea ice in the Arctic is also associated with habitat loss for charismatic megafauna like polar bears and harp seals. Indeed, widespread reductions in population connectivity and genetic variability have

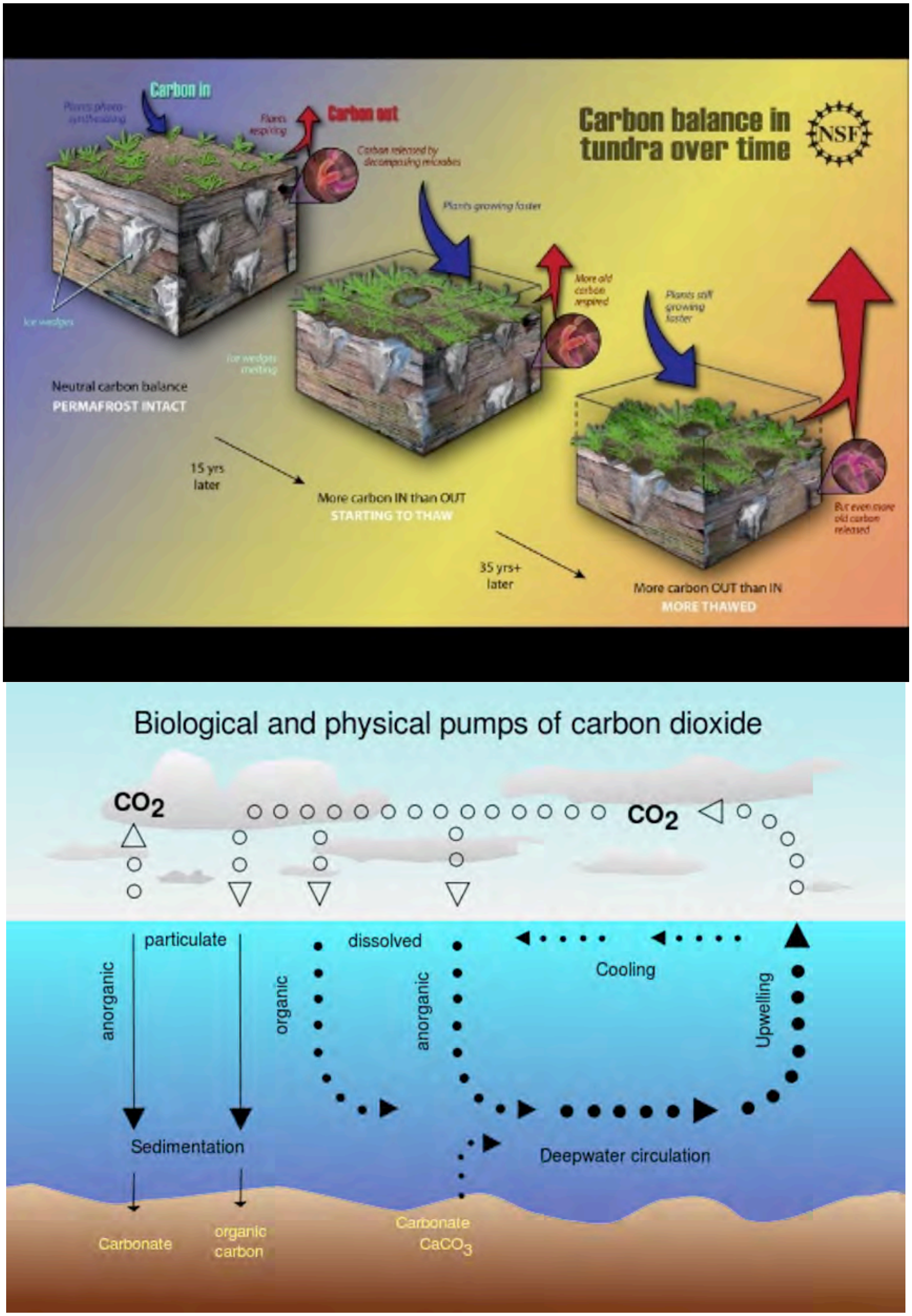

Figure 5. The progression of melting permafrost associated with warming temperatures and subsequent release of carbon into the atmosphere is depicted (Left) (Science20.com). A general model for a balanced carbon cycle in an ocean environment is depicted (Right) (Grobe 2006).

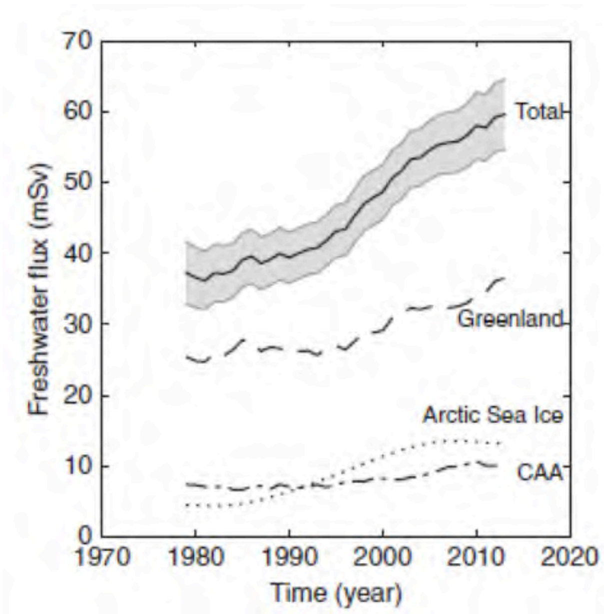

Figure 7. The flux of freshwater in milisieverts (mSv) in the North Atlantic from Greenland, Arctic sea ice, and the Canadian Arctic Archipelago (CAA) are displayed from 1979-2013 (Yang et al. 2016).

been observed and are predicted to increase (Kutschera et al. 2015). This habitat loss also reduces the distribution ranges of endemic species, generating new inter- and intraspecific interactions, including predator-prey relationships (Glig et al. 2012). In particular, a study on polar bear distribution found earlier, increased duration on land as a possible resilience to sea ice loss (Rode et al. 2015). Furthermore, the loss of the ice itself reduces the habitat availability of ice algae and initiate phytoplankton blooms that were previously restricted by the ice cover (Meler et al. 2014). Similarly, antarctic species like the Adélie penguins and krill lose habitat to the receding peninsular sea ice (McClintock et al. 2008). In contrast, the reduction of arctic sea ice cover can be seen as a habitat gain for Atlantic species of fish, such as Atlantic Cod and Haddock, that may be migrating away from warming temperatures and anthropogenic harvesting

In the warming tundra regions of the Arctic, there are current and predicted changes in ecosystem type, with endemic species with narrow habitat ranges most susceptible to local extinction. In particular, a 67% reduction of the current shrubbery coupled with a projected doubling expansion of black spruce forests associated with melting permafrost (Marcot et al. 2015). In addition, recession of permafrost regions creates thermokarst, which is comparatively a diverse wetland area that supports a greater diversity of plant species. This habitat transformation initiates community restructuring and may encourage increased primary productivity (Becker et al. 2016). However, this contributes to the increased emission of CO_2 and CH_4 discussed earlier, amplifying the positive feedback systems (Fig. 5).

Conclusions

While climate change affects polar regions differently than lower latitudes, several factors distinguish the Arctic from the Antarctic. Changes in these regions are accelerated in comparison to temperate regions, and greatly impact the changes occurring globally. Specifically, there are a number of interconnected non-linear systems that are amplified and perpetuated by anthropogenic influences. The observed snowball effects and associated habitat alteration can be devastating for local endemic species, yet may provide migratory expansion for species typically found at lower latitudes.

Polar regions host a unique array of geological, oceanic, and biological features and adaptations, unlike those found in more temperate regions. Humans have long utilized these environments for various socio-economic purposes. Global climate change threatens to alter many of these systems in the imminent future, pushing life to the extremes.

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