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A Comparative Analysis of the Andes and the Himalayas: How Climate Change Effects the Health of Glaciers and the Social Impacts This Has on Surrounding Communities

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A Comparative Analysis of the Andes and the Himalayas: How Climate Change Effects the Health of Glaciers and the Social Impacts this has on Surrounding Communities

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Senior Honors Thesis: Environmental Studies

A Comparative Analysis of the Andes and the Himalayas: How Climate Change Effects the Health of Glaciers and the Social Impacts this has on Surrounding Communities

Jacqueline Mountford (2022)

I. Abstract:

The glacial ice in both the Andean and Himalayan Mountain ranges act as water towers for the billions of people that live within their watersheds. Throughout the year, these communities rely on the glacial meltwater to increase the flow of rivers, but this meltwater is the most impactful during the dry season when there is less precipitation. Communities in both the Andes and Himalayas use this glacial meltwater for human and animal consumption, agricultural purposes, and harnessing hydroelectric power as a clean energy source. One of the biggest worries for scientists and people around the world is how climate change affects the ablation rate of these glaciers. The glacial dynamic and water budget are changing in both the Andes and Himalayas and we are losing glacial mass at an alarming rate. In the coming years, some scientists predict that by 2100 or sooner, we will reach a peak melting rate, and the glaciers will be past the point of no return and will melt away completely. Both Andean and Himalayan communities have a strong reliance on glacial meltwater, which is a quickly depleting source of freshwater. There are 1.4 billion people that live within the Himalayan river basins, so about 20 percent of our world's population will be affected. There are millions of farmers within the Himalayan river basins that grow enough food for the billions of people that live within Himalayan the region as a whole. Although drinking water can be shipped in and alternative sources of energy can be used over hydropower, there is no replacement option for the vast amount of water that agriculture needs. For this reason, our society should be most worried about creating plans to help the Himalayan farmers prepare to lose their biggest water source.

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I have received a tremendous amount of support throughout the entire process of completing my Senior Integrative Project.

I would first like to thank my advisor, Doug Thompson for his endless support throughout the entire process of both writing this thesis and supporting me during my time at Connecticut College. Doug has shaped how I've grown as an individual over my four years at Connecticut College. He has not only pushed me to excel as a student, but more importantly as a person and I will be eternally grateful for his guidance as a mentor.

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1.0 Introduction

Glaciers hold more than 70 percent of our freshwater and land based glaciers are one of the most important sources of freshwater for thousands of communities around the world. Due to climate change, most glaciers are in a fragile state with extremely high ablation rates that are starting to make scientists and glacial meltwater dependent communities begin to worry. Humans around the world use glacial meltwater for a variety of activities including for direct human and animal consumption, for agricultural purposes, and for the production of hydroelectric power. Given the rapid changes that we are seeing in glacial dynamics, there are predicted to be extremely negative impacts on humans. Changing glacial dynamics include the increased ablation and accumulation rates that are being caused by climate change.

There are two main regions in which scientists are very worried there will be a variety of negative human impacts from the changing glacial dynamics. The Andes Mountain Range and the Himalayan Mountain Range are considered to be water towers for downstream communities because they house a huge amount of glacial ice. There are over 1.4 billion people in the Himalayas and 260 million people in the Andes that rely on glacial meltwater to keep their streams and rivers flowing (Immerzeel et al, 2010). These communities are even more dependent on the glacial meltwater in their dry seasons when there is even less precipitation to keep their streams and rivers flowing. Both the Andean and Himalayan communities have a strong reliance on glacial meltwater for agricultural purposes and drinking water, but the Andean communities also have a very strong reliance on glacial meltwater for aesthetic and recreational purposes to bring in income from river tourism. Although glaciers in the Andes and Himalayas are both facing a decrease in glacial mass balance due to climate change, we should be the most concerned about the impact on the Himalayan farming industry because these farmers grow food for the 1.4 billion people that live within their river basins, and finding an alternative source of water to sustain a sufficient amount of agriculture within the Himalayan river basins seems to be nearly impossible.

2.0 Glacial Background

Glaciers are a very important resource for humans and the environment. Ten percent of the world's surface is covered by glaciers and ice caps, mostly in places like Antarctica and Greenland. Scientists estimate that about 69 percent of all freshwater on Earth is stored in these glaciers and ice caps. If all this ice melted, the ocean would rise an estimated 230 feet or 70 meters, drowning many cities and coastlines that are highly populated (Water Science School, 2018). In the face of climate change, glaciers can be a threat to humans, but they are also an important water source that many people depend on. People around the world rely on glaciers to provide them with clean water that can be used for household purposes and hygiene, but also for crop irrigation and hydropower. Engineers are also starting to dam glacial meltwater to harness hydroelectric power for the communities nearby (NSIDC, 2020). In order to more effectively understand glaciers in a way that can be used to protect and provide for humans, it is important to take a deeper look into the science behind glaciers.

2.1 Importance of Glaciers

Glacial ecosystems are important because they can regulate hydrological processes, store carbon, and can help to improve water quality (Rojas, 2021). Glaciers act as a frozen reservoir of freshwater, so when they melt, they provide water to the downstream processes that need it. This can include feeding rivers and streams that are important habitats for animals and refilling and replenishing water aquifers and the groundwater systems. Fresh running water from glaciers prevents stationary water that can grow bacteria and have led to harmful diseases in humans and animals (Chevallier et al., 2010). Aside from the hydrological processes that are regulated by glaciers, glaciers also store carbon dioxide. It has been found that glaciers act as passive carbon sinks by storing the carbon in the soil and organisms that they advanced over many years ago (Wadham et al., 2019). Furthermore, the surface acts as a sink for anthropogenic sources of carbon. This surface carbon, mostly arising from the use of aerosols, is found to be easily trapped and stored in the snow on the top layer of glaciers. This carbon is trapped in snow, so scientists have found that these carbons are transported mostly unchanged when they runoff in glacial meltwater (Stubbins et al., 2012). Glaciers also act as active sinks because the aquatic environments within and on top of the glaciers are inhabited by a wide variety of microorganisms that store carbon themselves and are great places for biogeochemical weathering to take place. These processes participate in the global carbon cycle, whether that be for better or for worse (Wadham et al., 2019).

2.2 Glacial Ice Formation and Movement

Glaciers are created through snowfall that amasses to form a large sheet of ice. When the amount of snow that falls is far greater than the amount of melting that occurs over the course of many years, the snowfall compresses to form a mass of ice. When these masses of ice are formed in a valley or on a hill, the ice mass slowly moves downhill by sliding and internal deformation, smoothing the landscape below (Water Science School, 2018). The two main processes through which glaciers move are sliding and deformation. (Davies, 2020). The gravity, and therefore weight, behind the glacier helps to move the mass across the landscape (Water Science School, 2018). The ice within glaciers can be kilometers thick in some locations and can cover an entire landscape with ice. The massive weight of glaciers can drastically alter the landscape. For example, much of the northern United States was carved by glaciers to create the valleys, hills, and glacial deposits that we often see (Water Science School, 2018).

In order to form glaciers, there needs to be snowfall for a long period of time. Glaciers are ice, but that ice one day started out as snow. When snow accumulates on top of a moving glacier and doesn't melt all year long, for multiple years, the snow is able to turn into ice through compaction. Firn is the substance created in the process of forming glaciers; it is a half snow, half ice mixture. Firn is more commonly defined as particles that have lasted one year, or one melt season, without turning into glacial ice. From a numerical standpoint, firn is 400-830 kg/m^3 and the density of glacial ice is 830 kg/m^3. There are many different classifications of snow that range from 50-400 kg/m^3, but two common forms of snow are new snow (50-70 kg/m^3) and settled snow (200-300 kg/m^3) (Davies, 2020). As more snow keeps getting piled on, the snow below compacts and condenses as the air gets squeezed out. The longer the snow sits and gets compacted, and the more snow that falls on top, the easier it is for the snow to continue to form ice and add to the increase of the mass balance of the glacier. When the air spaces decrease, the snow becomes more dense and ultimately forms the ice of glaciers (NSIDC, 2020).

There are two main temperature regimes of glaciers, temperate and polar glaciers. Polar glaciers are those that are frozen to the rock below the ice, all the way to the base. Temperate glaciers have a layer of water below them that act as a lubricant to allow the ice to slide more easily over the rock. Temperate glaciers create a positive feedback loop because as the glacier moves, it creates more friction, which increases the melting below the glacier. When the melting increases, there is more water between the ice and the rock, allowing the glacier to move even faster across the landscape (Davies, 2020). Temperate glaciers move much more quickly than polar glaciers because of the layer of water between the glacier and rock, and this increase in water can lead to more avalanches and other land and rock slides.

One important glacial process is the movement of the ice and the flow of a glacier. Two processes that allow for movement of the ice are plastic and brittle deformation, which happen more commonly in glaciers that are frozen to the ground, polar glaciers. Deformation is a microscopic process in which each ice crystal breaks and moves downhill, then forms a new ice crystal slightly downhill. Through this process, the ice slowly moves down hill, but it can also lead to cracks and crevases being created in glaciers. Brittle deformation is mostly limited to the upper portion of glaciers because the pressure is lower (NPS, 2018). Aside from deformation, glaciers also experience a sliding movement at the bed of the glacier from water, most commonly in temperate glaciers. Water can flow under glaciers from meltwater, friction, and heat from the Earth. This water can collect in air pockets at the base of the glacier and then act as a lubricant as the ice easily slides over the bedrock below (NPS, 2018). Another way that glaciers move is through regelation, or pressure melting. Regelation occurs in large glaciers when the weight of the glacier increases the pressure at the bottom of the glacier. This increase in pressure lowers the melting point of the ice, leading to an increase in melting of the ice. The melting of the glacial ice at the bottom lubricates the surface below and leads to movement and advancement of the ice (Verma, 2011).

2.3 Glacial Mass Balances: Ablation and Accumulation

The mass balance of a glacier, also known as the mass budget, is the change in mass of the glacier over some defined period of time, usually a year or a season. The mass balance of a glacier is determined by balancing the amounts of accumulation and ablation. Ablation is defined as any process that leads to the reduction in the mass of a glacier. Opposingly, accumulation is defined as any process that adds to the mass of the glacier. This can include many processes, the most common and important being snowfall. Another common process is the deposition of hoar, which is when the water vapor in the air space of glaciers turns directly into ice. This is essentially like the formation of frost, but it is on a glacier instead and adds to the accumulation. Another way that accumulation occurs is through the windborne blowing or drifting of snow, which can be very important for the survival of smaller glaciers. Rainfall does not add to the accumulation of glaciers unless it freezes, nor does the rocky debris that is left behind from mass movements (Hock, 2010).

There are many factors that affect the snow rates and accumulation rates of a glacier. The first process that affects the accumulation rate of a glacier is the actual volume of snow that is delivered. If there is a particularly harsh winter with a lot of precipitation, the overall volume and mass of the snow added will most likely positively affect the accumulation rate for that season. Another factor that affects the accumulation rate of a glacier is the length of the winter. If the cold period of winter is longer in a particular year, then the snow will have longer to accumulate, compact, and turn to ice, which would allow for a higher accumulation rate of the snow. In a shorter winter, the snow has less time to accumulate and compact, so there might be a lower accumulation rate that particular year. The more snow that can survive the warm season, the more snow that is ready to be compacted during the next snowfall season, allowing for more accumulation (Davies, 2022d). Both the length and temperature of the summers affect the amount of ablation that occurs. When there is a longer, hotter summer, more melting occurs, whereas a cooler, shorter summer promotes a net increase in the mass balance. The same thing goes for winters; a longer, colder winter with more precipitation allows for a net increase in mass balance. A shorter, warmer winter with less precipitation, combined with a longer, hotter summer will lead to a net decrease in the mass balance of the glacier. Along with the seasons, precipitation levels are a major factor in the accumulation and ablation rates (Davies, 2022d). The accumulation and ablation rates are dependent on so many different factors that it is easy for either rate to be affected by climate change.

Two other important factors that can affect accumulation rates are the latitude and elevation of a glacier. Higher latitudes and altitudes are colder, so it is more likely for snow to last for a long time. This creates a line for snow to occur that can vary by latitude; higher elevations are required for snow to occur at lower latitudes. On a similar note, 50 degrees latitude to 60 degrees latitude are high precipitation areas because of the convergence of the Polar Cells and Ferrel Cells. Within these high precipitation zones, from around 50 to 60 degrees latitude, there are a lot more glaciers because the higher precipitation rates allow for there to be more accumulation of snow on glaciers. The increase in snow on glaciers and fewer total sunny days also makes these areas more capable of surviving glacial ablation.

The most important process for ablation of land-based glaciers is melting. However, if a glacier melts and then refreezes onto another part of the same glacier, it is not included in ablation. Another process that aids in ablation is calving. This is when ice chunks fall off the glacier and discharge into a sea or lake below; it is a fast way to lose a lot of mass. Two other common processes are the loss of mass from windborne blowing snow, drifting snow, and avalanching from the glacier. The final ablation process that commonly occurs to reduce the mass of glaciers is sublimation. This is the chemical process when a solid turns directly into a gas, skipping over the liquid phase. This is particularly common at high altitudes or low latitudes, such as tropical glaciers, and in the dry climates of Antarctica (Hock, 2010).

Ablation rates can be increased by multiple factors, including climate change, warmer summers, and sea level rise. Overall global warming is not evenly distributed, so warmer summers with more rain storms and fewer snow storms can occur. Although this doesn't seem like a big deal, this affects both accumulation and ablation rates, as there is more melting in the summer and less precipitation to add in the winter. Glaciers can melt a lot faster than they accumulate, so warmer summers can be very detrimental to the mass balance of glaciers. Sea level rise is another big factor that can affect ablation rates for tide water glaciers. As sea level rises, the tide water glacier starts to float, so it is advancing while losing mass on the front. As the glacier moves forward, it starts calving into the ocean and the mass balance quickly decreases.

Two other factors that affect ablation rates are surface albedo and sediment. Surface albedo is the amount of reflected sunlight from the glacier. A large white glacier reflects a lot of the sunlight, helping to slow down melting. Nonetheless, glaciers still experience melting, and as they do, sediment collects up on top of the glacier as ice melts. The collected sediment, of which there can be multiple meters in depth, increases the solar absorption which may or may not promote melting. Although it can help increase melting, when there is a lot of extra sediment, it can actually help to insulate the glacier. One study found that when there is 2 centimeters of sediment on top of glacial ice, the melting rate of the glacier falls exponentially. This amount of sediment prevents sunlight from penetrating the glacial ice and therefore slows the ablation process down (Bendle, 2020).

The mass balance of a glacier is found by looking at the amount of accumulation and ablation over a specific period of time (Figure 1.). The mass balance is measured by looking at the average ablation rate and accumulation rate over the course of the year and it is expressed in units per area; for example, kg/m^2. If there is a negative mass balance it implies that the glacier is shrinking, whereas a positive mass balance implies the glacier is growing. Mass balances can often exhibit seasonal variation, where there are distinct periods of accumulation and ablation (Hock, 2010). Glaciers are more likely to exhibit this when they are at mid-latitudes and in a location with distinct seasons. Glaciers in the tropical region don’t usually display the same seasonal pattern because the accumulation and ablation happen at the same time (Hock, 2010).

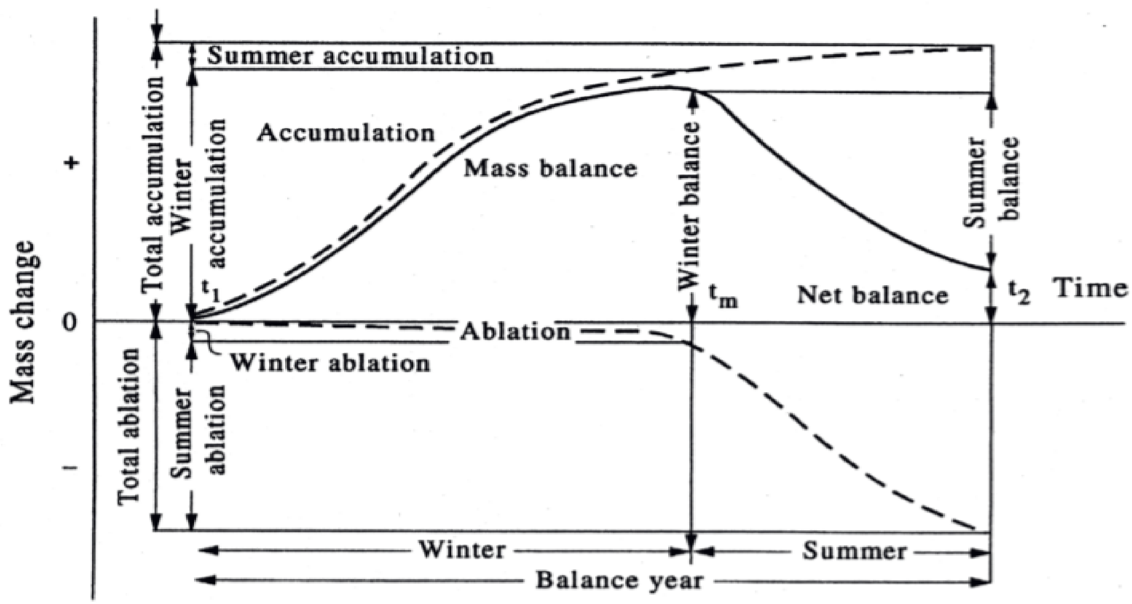

Figure 1. The mass balance of a glacier and the distinct accumulation and ablation that occurs within a year. Figure courtesy of Hock (2010).

The accumulation line is a strictly scientific, imaginary line that goes across alpine glaciers that separates the ablation zone from the accumulation zone. This climatically determined line has already been affected severely by climate change on many glaciers. As the climate warms, the equilibrium line will increase in elevation, so the accumulation area will decrease in area and the ablation zone will increase in area. When the equilibrium line moves up in elevation, it can get to a point that is higher in elevation than the top of the glacier and the land surface itself. When this happens, there is no more accumulation zone, so it will be impossible for the glacier to grow in size unless the equilibrium line moves back down in elevation. This will ultimately lead to the complete melting and disappearance of the glacier because glaciers can't persist without an accumulation zone (Davies, 2020).

2.4 Global Circulation and Glaciers

The circulation cells, primarily the Hadley, Ferrel and Polar cells, greatly influence the precipitation patterns around the globe, ultimately affecting the location of glaciers. As seen in Figure 2, the Hadley Cell moves from the intertropical convergence zone, around 5 degrees north and south of the equator, to about 30 degrees north and south latitude. The cell is driven by the heat from solar radiation that builds up in the intertropical convergence zone because of the direct sunlight and solar radiation. The Hadley Cell is a convection cell where the warm air rises at the equator and then sinks around 30 degrees north and south latitude. As the warm air rises at the equator, the air cools adiabatically leading to an increase in the relative humidity levels while the volume of water in the atmosphere stays the same. Then, this change in humidity will lead to a decrease in water vapor and the creation of condensation and precipitation. This increase in precipitation leads to wet zones in the latitudes where the air is rising. When the air sinks around 30 degrees, the climate is more dry because descending air heats up and increases the atmosphere's ability to hold water vapor, so there are often desert-like climates at the latitudes in which air is descending. This movement creates a convection cell in which the high altitude air moves towards the poles and the lower altitude air moves towards the equator. Although similar to the Hadley Cell, the air in the Ferrel Cell, also known as the Mid-Latitude Cell, moves towards the equator at higher altitudes and towards the poles at lower altitudes. At 30 degrees north and south latitude, the air descends and starts moving back towards the poles. The northernmost cell is called the Polar Cell, which is also depicted in Figure 2. This cell is similar to the Hadley Cell because the warmer air rises around 60 degrees latitude and then descends at the poles. The circulation patterns lead to a desert climate at the poles because there is very little precipitation at these latitudes. Given the small amount of precipitation that the poles get, as climate change worsens and the Arctic and Antarctic glaciers continue to melt more rapidly, it will be very difficult for these areas to recover (Zurita-Gotor and Alverez-Zapatero, 2018).

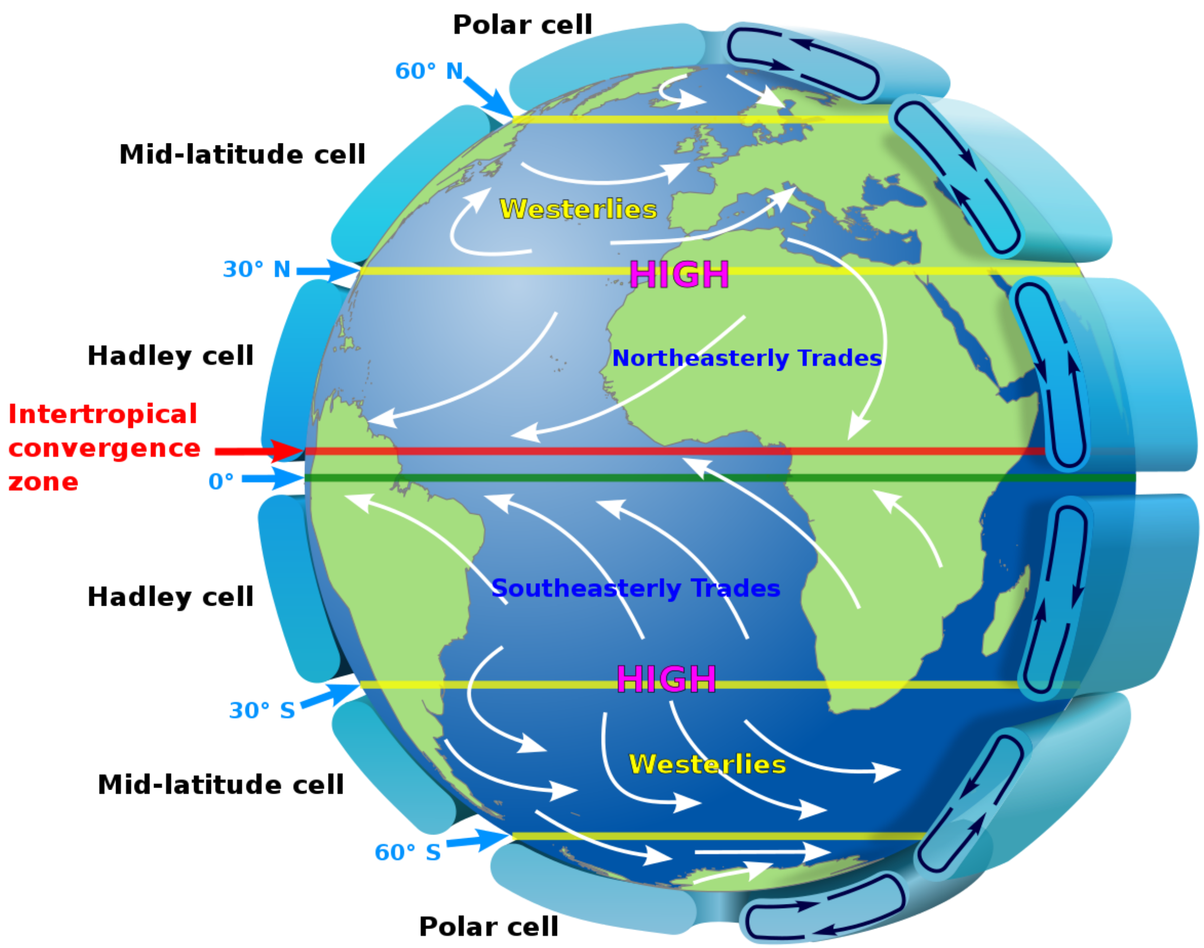

Figure 2. This figure shows the latitudes at which the Polar, Mid-latitude Cell and the Hadley Cells take place on the Earth, and the directions the winds blow in those cells. The Trade Winds and Westerlies are also shown in this figure as they play a role in the Hadley and Mid-latitude Cells. Figure courtesy of Wikipedia (https://en.wikipedia.org/wiki/Atmospheric_circulation#/media/File:Earth_Global_Circulation_-_en.svg).

2.5 Climatic Circulation Patterns: The Trade Winds and The Westerlies

Working alongside the circulation cells, the Hadley Cells, Ferrel Cells, and Polar Cells, mentioned above, one major idea that plays a role in affecting the health and size of glaciers, no matter where they are, are global surface wind patterns. These consist of the Trade Winds and the Westerlies, which are present in both the northern and southern hemispheres. These wind patterns are driven by the same low pressure and high pressure circulation patterns that are shown in Figure 2. The Trade Winds blow from the Intertropical Convergence Zone, a low pressure zone, to 30 degrees north and south of the equator, where there are high pressure zones (NOAA, 2021). The Intertropical Convergence Zone is the area 5 degrees north and 5 degrees south of the equator (NOAA, 2013). These Trade Winds blow from east to west around the intertropical convergence zone. The Trade Winds are diverted by the Coriolis effect, which is the Earth's rotation causing the air to move westward in this zone; combined with the high pressure zone at the equator, the factors allow the creation of the Trade Winds (NOAA, 2021).

Above the Trade Winds, from 30 degrees north and south, areas of low pressure zones, to 60 degrees north and south, areas of high pressure zones, the Westerlies are formed. The Westerlies blow from the west to the east. These winds are stronger during the winter because the pressure over the poles is at its lowest, and they are weaker during the summer while the pressure over the poles is higher (National Geographic Society, 2012). Similar to the Trade Winds, the Westerlies are also diverted by the Coriolis effect. The Trade Winds and Westerlies play a crucial role in where glaciers tend to form because they change temperatures and precipitation levels, both of which affect the creation of glaciers.

2.6 Orographic Precipitation and The Rain Shadow Effect

One phenomenon that greatly affects the health and size of glaciers is called the rainshadow effect related to orographic precipitation. Orographic precipitation is the idea that large mountain ranges can alter weather patterns and create dry and moist areas (Roe, 2005). Although they don't have to be coastal, large coastal mountains can alter the weather patterns. The mountains can create the rainshadow effect, where one one side of the mountain, the weather is wet and colder and the other side of the mountain is warmer and more dry. As seen in Figure 3, when the winds move across an ocean and then run into a mountain range, the air masses are forced upward from a lower altitude to a higher altitude. This movement of the air masses allows the air to cool, which causes condensation and the creation of clouds. As the air moves higher in altitude, the clouds drop rain and snow, before moving over the peak of the mountain. On the other side, the air masses move back down in altitude and warm adiabatically. This decreases the relative humidity and the climate becomes more warm and dry (National Geographic, 2012).

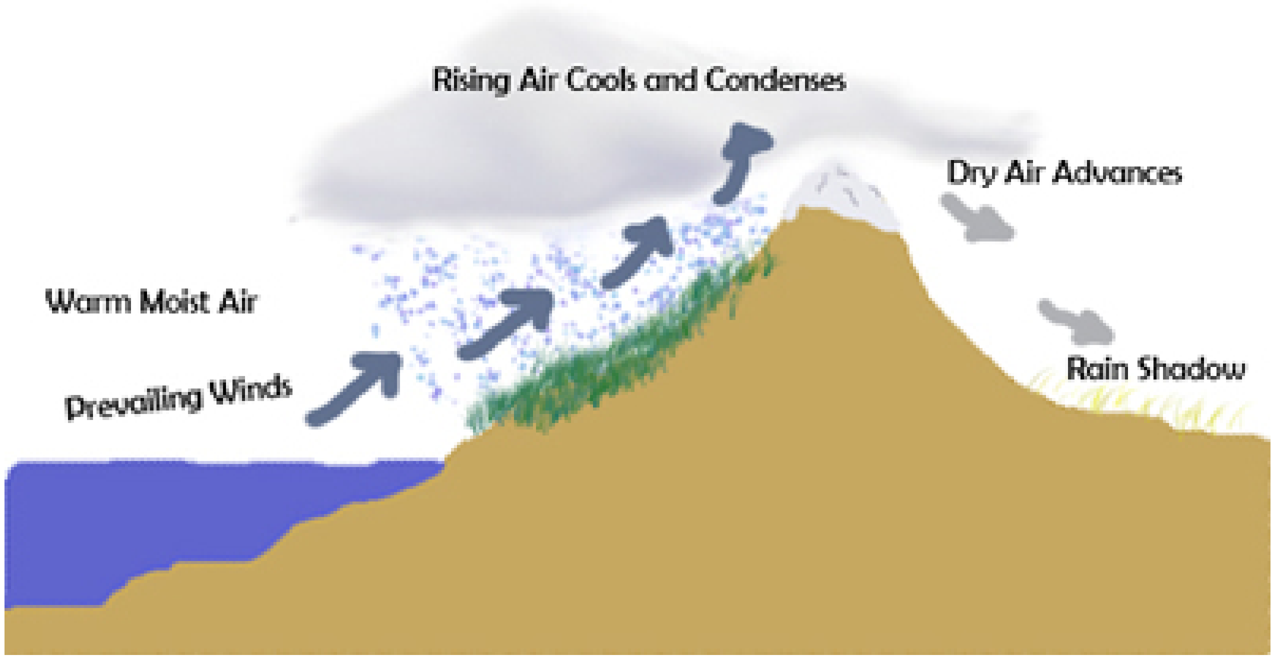

Figure 3. The rain shadow effect is created when strong winds move over high mountain tops and lead to the windy side having more precipitation and the less windy side having a drier climate. Figure courtesy of Windows to the Universe (https://www.windows2universe.org/earth/Atmosphere/precipitation/rain_shadow.html).

The Trade Winds and Westerlies play such a large role in the creation of glaciers because it leads to a difference in the snowfall on either side of the mountain. The side of the mountain where the wind is coming from has an increased amount of precipitation, and a higher likelihood of glaciers. As shown in Figure 4, the Westerlies and Trade Winds are blocked by the Andes Mountain range that extends down the continent. For the Westerlies, the tall mountains of Chile block the winds coming from the west and lead to a wet zone on the western side of the mountain range; in Figure 4, the wet side of the mountain is where the glaciers would form. In the vicinity of Bolivia and northwards, the tall mountains block the wind coming from the east and create a wet area on the eastern side of the mountain range, also contributing to the Amazon Rainforest. The southwest Trade Winds bring moisture rich air from the Atlantic Ocean across the Amazon Rainforest and then are blocked by the Andes Mountain Range (National Geographic Society, 2012).

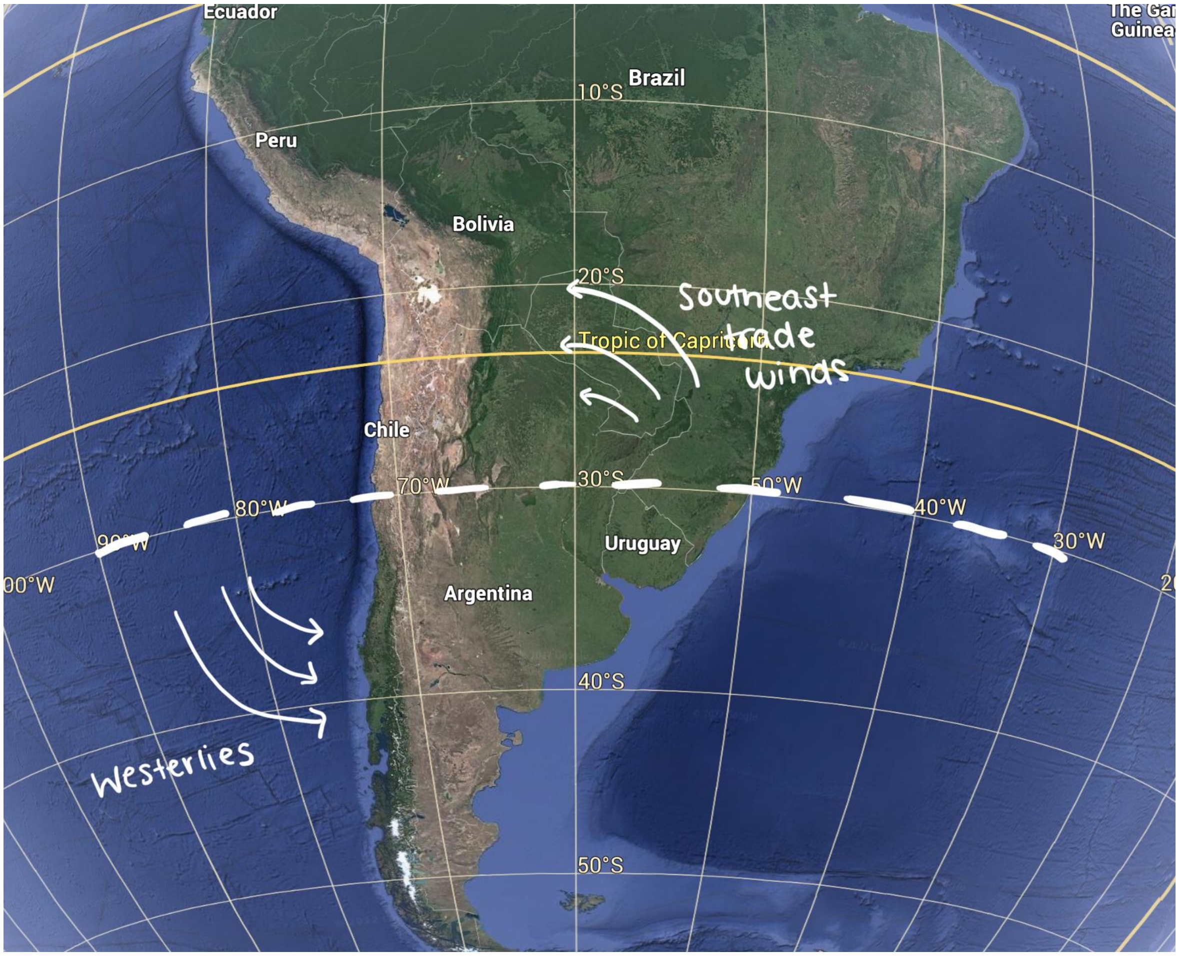

Figure 4. This map shows the Southeast Trade Winds and the Westerlies over the Andes Mountain Range. You can see how the Westerlies make a wet zone on the western side of the mountain range, while the Trade Winds make a wet zone on the eastern side of the mountain range. Photo courtesy of Google Earth with annotations created in this study.

Although the Himalayan glaciers are dominated by the monsoons, as seen in Figure 5, the Trade Winds and Westerlies also play a role in the creation of glaciers. Similarly, glacial runoff will differ on the east and west sides of the mountains depending on the latitude. Runoff coming from the east and west sides will differ because the ice is sitting on one side of the mountain or the other, so when it melts, the water will runoff to the side of the mountain that it is sitting on. This means that depending on the latitude, the direction and amount of glacial runoff will differ.

Figure 5. This map shows the Southeast Trade Winds and the Westerlies over the Himalayan Mountain Range. The white dashed line is the 30 degree latitude line, which is an important marker between the Hadley and the Ferrel Cells. Photo courtesy of Google Earth with annotations created in this study.

2.7 Comparative Interactions Between Climate and Glaciers

Two examples that work to show the difference between the effects of latitude, altitude, and precipitation are Greenland vs. Antarctica and Mount Rainier National Park vs. Glacier National Park. Antarctica has glaciers because it is so cold that snow doesn't melt, but it is actually a desert. Antarctica has been sitting on the south pole for much longer than Greenland has been where it is now, so these large glaciers exist despite the conditions that don't favor glacial accumulation. The glaciers there must be older than those in most other locations on Earth because there isn't much modern snowfall and accumulation. Greenland, however, is at a lower latitude that gets more precipitation; it is a high precipitation zone, even though it is a warmer climate. In Antarctica, there is a lot less ablation because of the colder temperatures, whereas in Greenland, there is more ablation, but the higher precipitation rates make up for the melting. This difference in latitude works with the Polar and Ferrel atmospheric cells discussed above because these atmospheric cells affect where there are high and low precipitation areas.

Mount Rainier National Park and Glacier National Park are both at the same latitude, but Rainier reaches about 14,400 feet or 4390 meters in elevation while Glacier National Park peaks at about 10,500 feet or 3,200 meters in elevation. Mountain peaks in Glacier National Park are in a drier and warmer climate compared to Mount Rainier. Both places have similar temperatures regionally, however, Washington gets a lot more precipitation compared to Montana. When this happens, it allows the glaciers on Mount Rainier to continue to exist and accumulate snow, whereas the glaciers in Glacier National Park in Montana are almost completely gone. Montana gets a lot less accumulation of snow because the climate has less precipitation. Along with the amount of precipitation, the elevation greatly affects the length of the winter and summer seasons. At higher elevations, like where Mount Rainier is situated, the length of winter is extended because it stays colder for more months of the year. This allows these higher elevation places to have more time to accumulate snow and more time for that snow to turn into ice and add to the mass of the glacier. At the lower elevations, where Glacier National Park is situated, the winters tend to be shorter because these areas warm up more quickly, so less snow and glacial mass is able to accumulate. This process is resulting in the rapid disappearance of glaciers in this area.

On a similar note, Mount Rainier National Park can be compared to Rocky Mountain National Park in Colorado. Both of these places are very similar in elevation, at about 14,000 feet of 4,270 meters, but Mount Rainier is at a much higher latitude. Even though they have similar elevations, Rocky Mountain National Park recently lost its active glaciers because it is now too low in latitude for snow to accumulate and stay frozen for long enough to accumulate glacial ice. In this case, there is pure ablation because the accumulation zone is too high in elevation for new ice to form; despite the pure ablation, it will take a while for the glacier to fully disappear because the ablation process takes a long time. Rocky Mountain National Park gets much less precipitation because it is farther away in latitude to the Mid-latitude and Polar Cells convergence zone compared to Mount Rainier. Mount Rainier is closer to the Mid-latitude and Polar Cell convergence zone, which is at 50 degrees latitude, so there is more precipitation. Rocky Mountain National Park, closer to 40 degrees latitude, is just low enough in latitude and elevation that it doesn't get as much precipitation and there is an increasing ablation rate, so there are no active glaciers in the park.

3.0 The Andes Mountain Range and The Himalayan Mountain Range

Alpine glaciers in both the Andes and the Himalayas have life histories that show how they have changed over the last thousands of years. Alpine glaciers are those in mountain ranges and are much smaller compared to continental scale glaciers, which are those that cover an entire continent. The life history of a glacier can be extremely helpful in looking at how these glaciers have responded to the altering conditions of climate change. Not only can we use the life history of glaciers to see how glaciers have already reacted to climate change, but we can also use this information to predict how glaciers might react to climate change in the future. This can be really important when the social impacts that melting glaciers have as a water supply source for nearby communities are examined.

3.1 The Himalayan Mountain Range

The Himalayan Mountain range is located in the south central portion of Asia, extending through India, Pakistan, Afghanistan, China, Bhutan, and Nepal. The mountain range is approximately 1,500 miles, or 2,400 kilometers in length and consists of three parallel ranges known as the Greater Himalayas, the Lesser Himalayas, and the Outer Himalayas. These ranges are directly next to each other and they take on an elongated 'U' shape (PBS, 2021). The Himalayan Mountain range extends between latitudes 26 degrees and 35 degrees North and between longitudes 74 degrees and 95 degrees East. The highest peak in the Himalayan Mountain range is Mount Everest at 29,032 feet of 8,850 meters above sea level (PBS, 2021).

Scientists believe that the glaciers in the eastern and central Himalayas are retreating, whereas those in the western Himalayas are stable or advancing (National Research Council, 2012). This growth of glaciers in the western Himalayas appears to be partially affected by the mid-latitude Westerlies in the winter, whereas glaciers in the eastern Himalayas appear to be more strongly influenced by the summer monsoons (National Research Council, 2012). As seen in Figure 5, the mid-latitude Westerlies come from the west and bring lots of moisture from the Indian Ocean with them. When these winds and the moisture meet the large Himalayan Mountain range, the moisture is squeezed out, causing a wet zone, and leading to more growth in the glaciers. The Westerlies can lead to an increase in precipitation and more accumulation at higher altitudes, leading to more glacier growth, most specifically in the western Himalayas, where the Westerlies play a bigger role (Rowan, 2016).

On the other hand, the eastern Himalayas are more strongly influenced by monsoons than the Westerlies, compared to the western Himalayas. The monsoons mostly occur in the warmer summer months, so there is less of a chance of snow and a higher chance of rain from these storms. The winds and weather patterns created by the monsoons have a greater impact on the eastern Himalayas because the winds lose strength before they get to the western Himalayas, allowing the western Himalayas to be dominated by the strength of the Westerlies. The rain shadow effect is created by the monsoon winds and rain, leading to a lot of precipitation and glacier formation in the eastern Himalayas. After the winds move over the eastern Himalayas and the precipitation is squeezed out, the wind continues on, but without the same amount of precipitation. For this reason, the Westerlies play a larger role in glacier creation in the western Himalayas, whereas the summer monsoon winds are the driving factor in creating glaciers in the eastern Himalayas (Fugger et al., 2021).

These weather patterns in the Himalayas often bring dust and debris that accelerates the melting of glaciers. Scientists have recently been noticing an increase in dust and debris from anthropogenic sources. This incorporates things like the pollution, including harmful outputs of industrial processes, the burning of wood, animal, and garbage, and the pollution from the increase in automobile use. Alongside climate change increasing the average global temperatures and increasing the glacial melting rates of the Himalayas, the increase in these anthropogenic pollutants has exacerbated the acceleration of melting glaciers (Prasad et al., 2011).

Using spy satellite data from 1975, one scientist recently studied how over 650 glaciers across the Himalayas changed from then until 2016 (Maurer, Rupper, and Schaefer, 2016). The satellite data and computer modeling confirmed that the overall changes in mass balances are caused by temperature and climate change, and not as much caused by other factors, including pollution and rainfall. The scientists used a computer model and were able to conclude that temperature is the biggest culprit in aiding the melting process. They input the data from 1975 into the model to predict what the ice should look like now, based on the temperature changes measured over the last few decades. The model predictions were very consistent with the changes observed in the mass balance of the glaciers in the Himalayas, so the scientists in charge of this study were able to confirm that temperature is the largest and most important factor in aiding the ice melting and that the other factors, like pollution and rainfall are much less important (Maurer, Rupper, and Schaefer, 2016). Although this study does make sense, it contradicts the observations that parts of the Himalayas are stable because of the increase in precipitation. This study found that rainfall on glaciers is not as important in aiding in the ablation process, but it doesn’t address the fact that snowfall precipitation is actually helping to stabilize other glaciers in the Himalayas

A similar study looking at the Hindukush-Karakoram-Himalayan (HKH) region found that most of the Himalayan glaciers are retreating. This study used satellite data and remote sensing starting in 1950 to look at snout fluctuations of 285 glaciers in the HKH region. The scientists found that most of these glaciers have retreated and the rate of retreat has accelerated over the past few decades (Kulkarni et al., 2021). It has been found that the average length change in the entire region is -14.9 (+/-) 15.1 meters per year, with a range from 60 to -88 meters per year (Kulkarni et al., 2021). This implies that glaciers are retreating on average 14.9 meters per year, with some glaciers retreating 15.1 meters more or less than this. Although some glaciers are actually advancing each year, the overall trend is still a reduction in glacial mass (Kulkarni et al., 2021).

3.2 The Andes Mountain Range

The Andes Mountain range is located in the west coast of South America, extending through Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile, and Argentina. The mountain range is about 4,500 miles or 7,242 kilometers long, and about 500 miles or 800 kilometers wide (Zimmermann, 2013). The Andes Mountain range extends between 10 degrees north and 57 degrees south latitudes and 70 degrees to 80 degrees west longitude (Zimmermann, 2013). Compared to the Himalayas, the Andes are much longer and more straight, extending north to south on a map, instead of east to west. Therefore, the Andes displays more variation with changes in latitude. The highest peak in the Andes Mountain range is Mount Aconcagua in Argentina at 22,841 feet or about 6,962 meters above sea level (Zimmermann, 2013).

The Andes are home to 95 percent of the world's tropical glaciers, so it is important to try to mitigate the effects of climate change in order to prevent nearby residents from being negatively affected (Davies, 2020). Melting of glaciers in the Andes is being exacerbated by an increase in volcanic activity and wildfires, most specifically the central Andes, between Chile and Argentina. When dark ash and rock fragments get deposited on glacial ice, the dark color attracts sunlight to make the ice melt away faster. This process is increasing the ablation rate of glaciers across the Andes, which is negatively impacting thousands of nearby communities (Davies, 2020).

Tropical glaciers play a crucial role in moderating the flow of mountain rivers and making sure there is a steady supply of freshwater for communities that live downstream. Tropical and subtropical regions are more at risk for increased vulnerability from receding glaciers due to climate change compared to glaciers closer to the pole. Two big risks seen in the Andes from receding glaciers are the melting ice leaving behind exposed hillsides and natural dams that are unstable and lead to avalanches, landslides, and dams that break and lead to floods. Receding glaciers are also creating more glacial lakes and putting more sediment in the water that compromises the meltwater quality in downstream communities. The dams that create the glacial lakes can overtop and lead to glacial outburst floods that can be dangerous to downstream communities (Rojas, 2021).

Not only do glaciers in the Andes play a major role in feeding water supply resources, but the mountains also provide a home for thousands of endemic species (Rojas, 2021). It is also one of the most biodiverse and endangered ecosystems in the world. Scientists believe that this area became isolated during the Andean uplift, between six to ten million years ago, which led to speciation and an explosion of endemic species - plants, mammals, birds and other animals - in this area. The glaciers in the Andes play a major role in water supply to the entire Andes region, which helps to support the habitats and lives of these endemic species (Swenson et al., 2012). Scientists have noticed that, as glaciers melt, delicate endemic alpine flower species are thriving in this newly exposed space for plants to grow. Although these plants are thriving in the short term, in the long term more aggressive species begin to take over the endemic alpine flowers.

Scientists are worried that these aggressive species will threaten the biodiversity of these areas as the endemic species will become extinct. (Weston, 2021).

One study from 2014 of the Tapado Glacier in the Andes, located in the Elqui River Basin in Northern Chile, found that the daily and monthly weather conditions are highly correlated to the water output from the glacier (Pourrier et al., 2014). Most specifically, this study focuses on solar radiation and temperature. The scientists used ground penetrating radar to analyze the groundwater in the glacial foreland. This glacial foreland is the space between the glacier's last retreat, where a moraine was left, and the foot of the glacier in its current position. The scientists found that this glacial foreland acted as a large groundwater reservoir, storing water from large weather events or periods of greater melting, and then supplying water to interconnected downstream groundwater reservoirs when there was less melting and fewer weather events. By analyzing the glacial foreland, scientists were able to determine that the water output from the glacier directly correlates with the weather conditions and patterns, but the glacial foreland is able to store water for low melting periods, to allow the system to continue to supply water during the summer months (Pourrier et al., 2014).

Another study concluded that the glaciers in the Tropical Andes have shrunk from 30 to 50 percent over the last 30 years (IRD, 2013). Not only have they lost a lot of mass, but some of the smaller glaciers are predicted to completely melt away in the next 10 to 15 years. Given that this research was completed nine years ago, there is likely even more change occurring today (IRD, 2013). Similarly, another study of glaciers in Bolivia and Ecuador found that the mass balances of four different glaciers all decreased, so there is more ablation than accumulation, since the data collection started around 1990. The authors concluded that there appears to be an overall negative trend in the mass balances of glaciers in the tropical Andes. As seen in Figure 6, the Chacaltaya glacier has seen the biggest loss in mass balance since 1962, but there does still appear to be an overall negative trend in the mass balances of the glaciers looked at in this study (Mishra and Verbist, 2017).

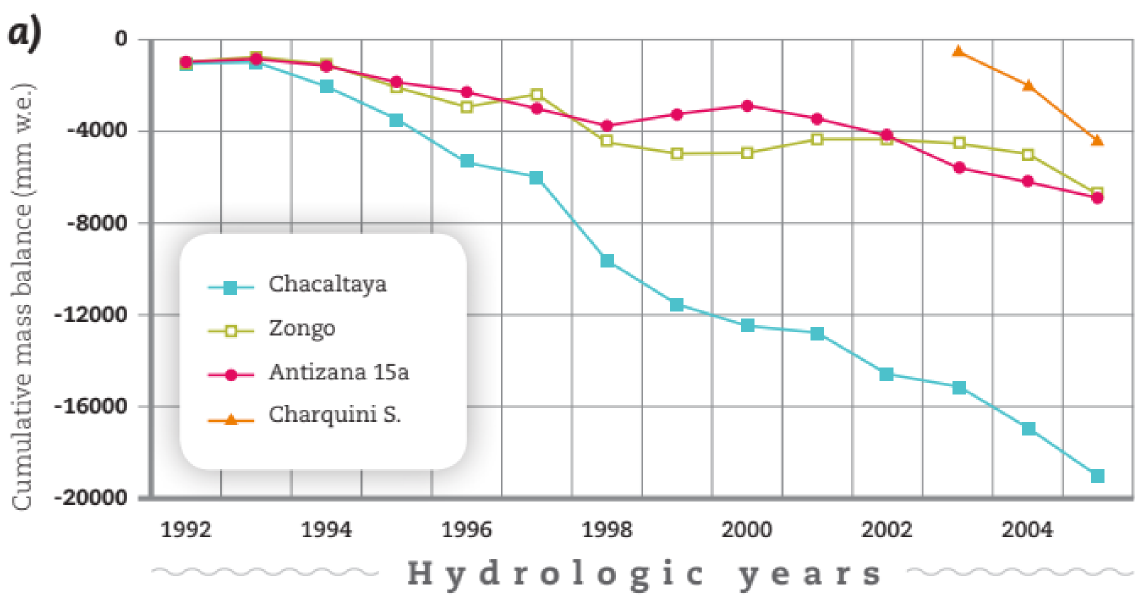

Figure 6. The cumulative mass balance of four different tropical glaciers in Bolivia and Ecuador. A negative mass balance means the glacier is losing mass each year. The steeper the line, the more mass the glacier is losing each hydrologic year. Figure courtesy of Mishra and Verbist (2017).

This negative trend in mass balance is not only caused by the rapid worsening of climate change, but it is also caused by the increased intensity and occurrence of El Nino years. (Seehaus et al., 2019) An El Nino year occurs when the surface water of the Pacific Ocean is warmer around the equator and the eastward blowing winds are weaker than normal. This leads to warmer winters with less precipitation and oftentimes more natural hazards like glacial lake outburst floods and hurricanes. In terms of the Andean glaciers, El Nino years lead to less precipitation, less accumulation and more ablation, and therefore a significant decrease in the mass balance of the glaciers (Morizawa et al., 2013). As global temperatures continue to rise due to climate change, El Ninos are intensifying and becoming more frequent because the surface of the Pacific Ocean is able to heat up much faster than normal (Freedman, 2019). The opposite of an El Nino event is a La Nina event, which is where the Pacific Ocean surface water temperature is colder and the winds are blowing faster. This event leads to an increase in precipitation and can lead to the expansion of glaciers in the Andes (Morizawa et al., 2013). A recent study completed by Morizawa et al (2013), found that the annual patterns of glacial advance and retreat coincide with the La Nina and El Nino years respectively. Although La Nina years lead to the expansion of the glaciers in the Andes, the El Nino years have more greatly affected the contraction of the glaciers, so there is an overall net decrease in the mass balances of the Andean glaciers (Morizawa et al., 2013).

4.0 Human Dependence on Glacial Meltwater

There are a few main ways in which glacial meltwater is used by humans, including hydropower, agriculture, and direct consumption by people and animals. As climate change is greatly affecting the rates at which glaciers are melting, the amount of water supplied by the glaciers for these human activities is also changing. Although glaciers are melting more quickly now and these communities might actually have more than enough water supply right now, as the glaciers become smaller and smaller in the coming years, there will be an increasingly smaller amount of water left for human use and consumption. This is predicted to greatly affect the humans and communities nearby that currently rely on glacial meltwater as their main water source. At this point, the melting that will arise from climate change is inevitable and irreversible, so it is important for scientists to study the role that glaciers play as a water supply source so that communities can start making plans to have alternative sources of water supply to replace glaciers.

4.1 Glaciers as a Water Supply

Scientists estimate that glaciers store 75 percent of all freshwater on Earth, so they are the largest reservoir of freshwater on the planet and the second largest reservoir of water (USGS, 2021). Glaciers are such a huge source of freshwater, so it is very important to study glaciers and look at what will happen when this freshwater source is depleted (USGS, 2021). Meltwater can have a variety of impacts on human lives, but mostly this meltwater is an important water supply source for communities nearby. Glacial meltwater is higher during certain times of the year, mostly during the warmer summer months. Although there can be seasonal variations in the melting periods, glaciers act as massive reservoirs that store frozen freshwater. Glaciers experience the highest melting periods during the times of hot, dry weather, and the least during cool, wet weather. Many other other sources of water such as rain and precipitation are much higher during the cool, wet periods and lower during the hot, dry periods. This allows the glacial melt period to compensate for the lack of other water sources during the hot, dry periods. As seen in Figure 7., peak discharge of glacially fed streams is about a month later than the non-glacially fed and mixed streams. This period of peak discharge in glacially fed streams often relates to the period in time with the highest need for irrigated crops, so it is of the utmost importance to utilize this increase in discharge.

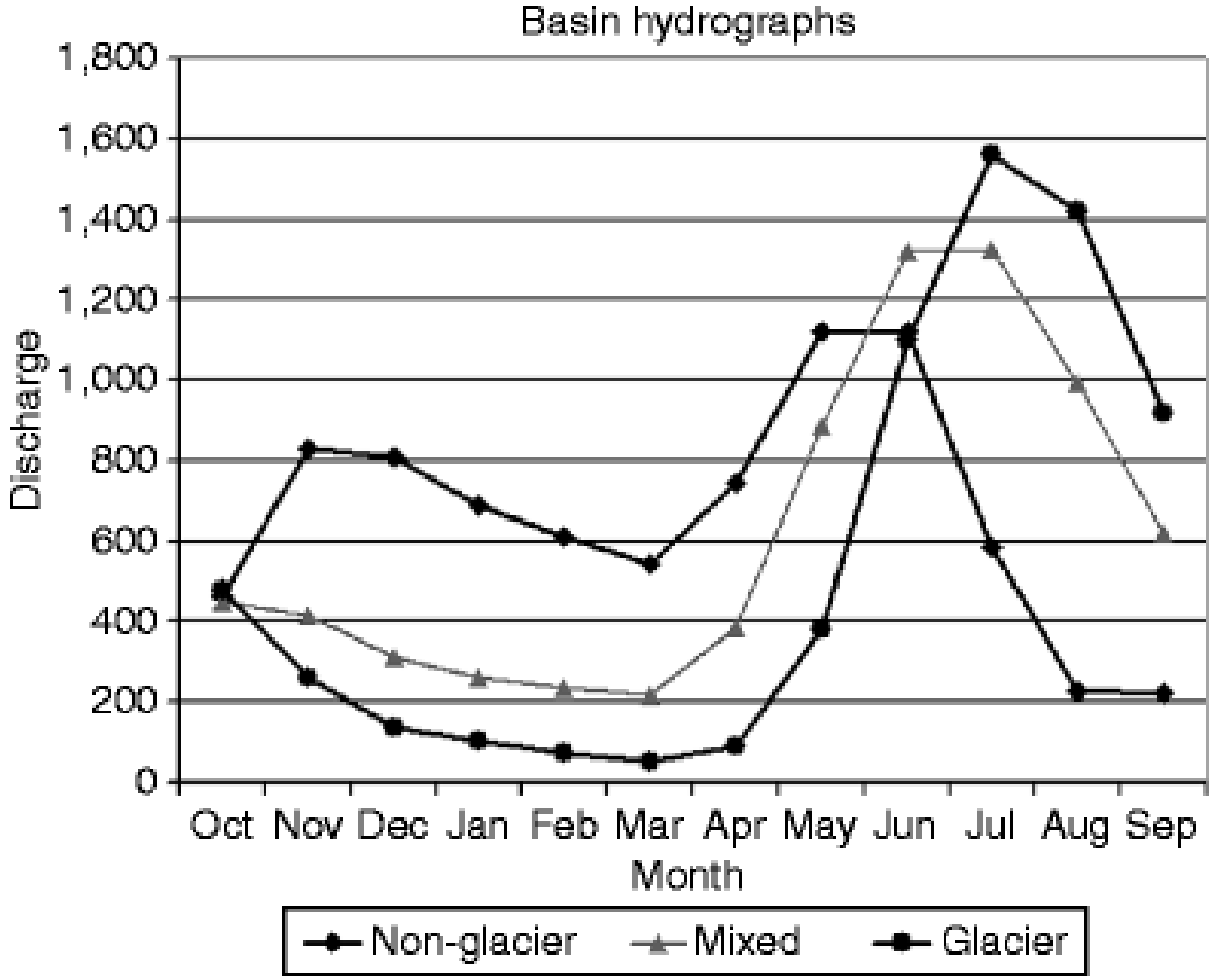

Figure 7. This hydrograph shows the timing of discharge from glacial streams, non-glacial streams and mixed streams (both glacial and non-glacial) in the Northern Hemisphere. As seen in the hydrograph, the discharge of the glacial streams peaks in July and August, while in the mixed and non-glacial streams the discharge peaks in May and June. Figure courtesy of Pelto (2014).

4.2 Hydropower

One important human use of glaciers as a water supply source is the production of electricity by hydropower facilities. Hydropower facilities and reservoirs can be placed on glacially fed or mixed streams to extend the flowing season of glacial meltwater. Mixed streams are those fed by glacial sources and other sources including groundwater or other lakes and ponds. This approach allows humans to create and run hydropower systems on rivers downstream that can be run all year round. Not only can glacial meltwater be used during the high melting periods, but it can also be dammed up, if needed, in order to release the water for hydropower later on (Pelto, 2014). Glaciers can affect the timing of runoff depending on when the glaciers are melting the most which can lengthen the hydropower season; having a reservoir that gets built up behind hydropower dams lessens the impact and importance of the timing of this runoff. However, with the addition of glacial meltwater, there is an overall increase in annual water volume that can be stored in the reservoir and used for hydropower, so the addition of glacial meltwater for harnessing hydropower is still important.

The amount of runoff from a glacier is directly related to the ablation rate of that glacier. The timing of the peak of discharge can be very important in running hydropower facilities because it extends the time that hydropower can be harnessed. As seen in Figure 7., the discharge of mixed rivers and glacial rivers is one or two months later in the year, respectively, compared to the non-glacial rivers. This difference allows for water to be stored in basins and reservoirs and used during the drier months of the year that have less precipitation and glacial melting. This allows for communities to extend the timing of their electricity production every year (Pelto, 2014).

One study found that hydropower from glacial runoff supplies much of the region's electricity (Pelto, 2014). It found that 81 percent of Peru’s electricity, 73 percent of Columbia’s electricity, 72 percent of Ecuador’s and 50 percent of Bolivia’s electricity come from glacially related hydropower systems. This same study found that in the Himalayas, 50 percent of the region's hydropower comes from glacial melt systems (Pelto, 2014). As these glaciated mountain belts lose ice mass due to climate change, the communities will need to rely on alternative sources of energy production, whether it is green energy or not, to make up for the loss.

There are a few main ways that glacially fed rivers can be used to harness hydropower and create electricity for surrounding communities. The most common way to harness hydropower is by creating dams in a valley or stream and using the hydrostatic head to turn turbines. Hydropower dams can open gates to release water and harness the electricity when it is needed. These work the same way as normal hydropower dams placed on non-glacially fed rivers. Another most common way that glaciers are used to harness hydropower is by capturing the glacially fed rivers and streams in one valley and diverting the water to an adjacent valley. This process affects an increase in productivity of the adjacent valley and is oftentimes a more productive use of resources because fewer total dams are built, whereas the same amount of energy is harnessed. In order for water diversions to occur, dams must still be built, but they are often much lower and smaller than the massive hydropower dams because they don't need the height to harness energy. Lastly, glaciers can be used to harness hydropower electricity by abstracting the water from a glacially fed river and transporting it through a series of pipes to a higher altitude and then using it at a dam downstream. Although it results in a use of electricity to partake in this process, there is more energy that is harnessed instead of used, so it is still worth it for communities to harness this type of hydropower. This process allows the water to build a higher hydraulic head, so it builds more potential energy to create more electricity (Gabbud and Lane, 2016).

One of the biggest challenges with hydroelectric power generation on glacially fed rivers is the amount of sediment that is present in glacial meltwater and the disruption to the natural transfer and use of sediment downstream. Glacial meltwater is really high in many different types of sediment including sand and silt. This sediment can become built up behind dams, which, over time, can decrease the productivity of the dams because it reduces the amount of water that can be stored behind the dam. One main issue with sediment build up behind dams is that it can affect the ecology and channel morphology downstream. Sediment plays a major role in creating healthy habitats for plants and animals downstream and is an important factor in shaping what the river looks like (Gabbud and Lane, 2016). Sediment can also frequently damage the water turbines and hydropower systems when they get clogged (Butz, 1989). Glacially fed rivers have a very high sediment load in the water because of the glacial silt that running off the landscape; given this high sediment load, hydroelectric power in glacially fed systems is not always the most productive and can lead to a huge decrease in sediment load further downstream.

As climate change becomes a more prevalent issue and increasingly raises the melting rate of glaciers, the communities that rely on glacially fed rivers to create their hydropower will need to adapt and find new sources of electricity. Some scientists have predicted that the peak for glacial melting will occur within the upcoming decades, potentially by the end of the 21st century (Huss and Hock, 2018; Valentin, Hogue, and Hay, 2018). Leading up to this time, glacially fed hydropower systems will see an increase in productivity and be a valuable source of energy and electricity for local communities. People may have a false sense of hope and security when they see the increase in electricity production if they don’t know that this resource is quickly depleting. After we reach this peak flow, hydroelectric power generation on glacially fed rivers will become increasingly less productive and less cost effective. When this happens, these communities will need to replace this valuable energy source with other electricity sources, whether those be sustainable or not. Depending on the location of communities affected, some possible clean sources of energy that could replace the hydropower might be solar power, wind power, or geothermal power and some dirty sources of energy could be coal, gas, oil, or nuclear power (Musselman, 2021).

4.3 Agriculture

Another important way that humans can use glacial meltwater is as a water source for agricultural purposes. In many places around the world, glacial meltwater can be diverted and stored in a basin or reservoir and then be used for crop irrigation in downstream areas. Glacial meltwater can be extremely important when it comes to supplying farmers with water during times of drought or during the dry season. In many of these areas the farmers grow food for themselves and to sell commercially, so it won't only affect the farmers ability to eat, but it will also affect the lives of millions of people around the world that rely on these areas to grow certain crops, such as rice, wheat and barley (LSE, 2019).

The water supply for downstream communities is modulated by glacial meltwater production and is used to irrigate crops. During the drier months, glacial melting, snow melt, and groundwater flow are the biggest producers of stream water, whereas during the wet months monsoons or large rain events play a bigger role as a stream water source. Monsoons mostly occur around 10 and 15 degrees latitudes, so they only act as a water source for glaciers in the areas that they occur. These different water sources are used together in order to balance the growing seasons for agriculture in communities downstream of glaciers. The scientists from one study believe that climate change will severely weaken this modulating effect and that farmers and communities will need to adapt to these changing conditions (Biemans et al., 2019). As seen in Figure 7, glacially fed streams' peak discharge is a month or two later than the peak discharge of mixed streams or non-glacially fed streams respectively. This modulated water supply for agriculture allows farmers to expand their growing season while sustainably using water and increasing their overall productivity (Biemans et al., 2019).

Scientists and professionals are worried that there will be negative economic impacts when the decrease in water supply affects the agriculture industry (The Third Pole, 2022). One major economic concern is that millions of farmers will lose their jobs because crops will no longer be able to grow in these areas when the water runs out. Not only that, but they will lose their main source of food too. With these vulnerable groups losing their livelihoods, it is predicted that millions more people will be pushed into poverty because they will be unable to support themselves and their families (LSE, 2019). There are also much less obvious impacts; for example, in the coming years, glacial meltwater production will increase until peak melting is hit. It is predicted that floods and outbursts from the increase in melting and rain events, instead of snow on glaciers, will overwhelm irrigation systems. This will include reservoirs and channel systems that are used to transport glacial meltwater hundreds of kilometers across land in order to irrigate crops farther away. This process is predicted to lead to floods of many downstream communities, which could cost millions of dollars of damage along with leading to an increase in the loss of lives from these glacial floods (Rasul and Molden, 2019).

Another major issue with glacial meltwater for agricultural use is that the water temperature and sediment load can be problematic for irrigating crops. The runoff channels and mountain sides downstream of glaciers are frequently found to be unstable, often because glacial areas are prone to steep slopes with avalanche activity. This in turn can lead to high suspended sediment load in the runoff streams. If this sediment is not filtered out or somehow trapped before it is transported to agricultural areas and then used for crop irrigation, it can cause a lot of issues in the agricultural process. The sediment can clog channels and drains, it can stunt or cease the growth of smaller seedlings, and it can alter terrace and field landscapes. Then this silt can negatively affect some farming practices and machinery if the glacial water is being used directly. However, sild can also add fertility to the soil if the fields are planted after flooding. Floodplains are often very productive because silt is deposited and adds imported nutrients to the soil, such as calcium, iron and potassium. When these floodplains are used for farming *after* the deposition of silt and other glacial sediment, they can be very productive fields (Butz, 1989).

With these issues in mind, farmers need to assess how they use glacial meltwater for agriculture and what practices they can use to prevent suspended sediment from causing problems. In the coming years, as the melting rates of glaciers increase with climate change, the suspended sediment load will also increase. These farmers need to be aware and to prepare for the problems this will cause. Another big issue is that the meltwater temperature is very difficult to control. Simply put, it is very cold because it is just warm enough to melt. Cold water temperatures can lower the soil temperature and decrease the growing season because the soil needs extra time to warm up. Cold soil temperature affects not only the length of the growing season, but also affects the size, health, and productivity of the plants themselves (Butz, 1989). This is because most plants have specific environments that they grow best in, so when a key factor like the temperature is changed, the way that the plants function can also change.

Farmers will need to adapt in many ways in order to prepare for the decrease in glacial meltwater, including by finding new water sources and by changing some of their farming practices. Given the decrease in glacial meltwater, some other options to sustain agriculture in these vulnerable communities are rainwater harvesting, improving and increasing the use of constructed reservoirs, and increasing the use of groundwater where it is available. Although these ideas work for the short term, most of these sources are not sustainable sources of water and will quickly become depleted when their use is increased in lieu of glacial meltwater. Sustainable water use is balanced between the rate of use and the rate of recharge, so as glaciers continue to melt, human use should decrease as the glacial ice recharge rate decreases (LSE, 2019). Aside from changing their water sources, farmers might also need to change their farming practices. This can include changing their growing calendar to alter when they sow, rotate, and harvest plants. Ideally farmers could change when they grow water demanding plants to wetter seasons so that they have sufficient water. In reality, it will be difficult to change when they grow plants, as all plants are particular about the conditions and time under which they grow (LSE, 2019). Apart from this, farmers might also be able to grow alternative crops that can still be eaten by the local communities. Many crops, such as rice, have such a strong cultural connection that it might be hard for communities to grow a replacement crop for them.

4.4 Direct Consumption by Humans and Animals

A third common use for glacial meltwater is direct consumption by animals and humans. As snow and glaciers melt during the dry, hot months of summer, they feed into the rivers that supply water to the 1.4 billion people in downstream communities and regions (Immerzeel et al, 2010). Similar to how glacial melt patterns play a key role in the water supply for hydropower and agriculture, glacial meltwater is most important to the communities during the dry, hot months (Tandon, 2021). This glacial meltwater can be used for many different purposes by humans including drinking, cooking, cleaning, and completing all other water related tasks in everyday life (Wood et al., 2020).

Drinking water is a valuable resource that is extremely difficult to replace. For hydropower, alternative energy sources can be used, and for agriculture, other plants can be planted that might grow more efficiently while using less water. Glacial meltwater is often one of the only large drinking water sources for communities that rely on it because it is what they have always used. Given this information, it is most important for scientists to find alternative drinking water sources, not only for humans but also for animals as well. Along with agriculture in these communities, there are animals that are raised for human consumption that need water to survive and grow. Finding alternative water sources for these animals is just as important as finding alternative water sources for humans because they are a human food source and a livelihood for millions of people in the areas.

As the total volume of glacial meltwater decreases, there is the potential for conflict in downstream communities. Billions of people rely on glacial meltwater for their livelihoods and everyday lives, so as this resource becomes more scarce, it is predicted that conflict and war might start to arise and worsen as access to this vital resource becomes more limited (Bassetti, 2021). It has been found that in some places, where glacially fed rivers run through multiple countries, there can be major conflicts when the controllers of the river and the first upstream communities take a lot of water. If these communities and countries overdraw or dam the rivers, the flow is significantly decreased, which can negatively affect the communities downstream. These downstream communities lose their ability to withdraw as much as they need. Many scientists believe that this will lead to conflicts in the next few decades as we hit the peak flow of glacial melt and then see a rapid decline in overall discharge of these glacially fed rivers (Albinia, 2020).

High elevation mountain communities that rely on meltwater as their main water source may be one of the most vulnerable communities to the negative impacts of quickly receding glaciers. These communities tend to be vulnerable to degradation of all natural resources because they often face difficult living conditions, being so remote and set back from other communities. These communities along with some slightly more downstream communities are seeing increased water scarcity because of a combination of population growth and the effects of climate change. Some high elevation mountain communities in the Andes region are already seeing changes in their regular glacial runoff patterns, and this variability is causing them water scarcity problems. These water scarcity problems can have a wide range of negative impacts including halting economic growth and development. This in turn leads to food scarcity issues, health problems, ecosystem imbalances, and the promotion of poverty and gender inequalities (Bassetti, 2021).

4.5 Potential Natural Hazards and Economic Impacts

There are many negative economic impacts that can arise from the increase of glacial meltwater that will occur before the rapid decline. This increase in meltwater can lead to major flooding events called glacial outbursts; these events can breach the banks of rivers and canal systems and can destroy communities and take many lives. This can cost billions of dollars to repair and can destroy the homes and livelihoods of millions of people (Albinia, 2020). In many high elevation communities, glaciers were once solid masses of ice that only melted enough during the dry, warmer months to keep the rivers running and provide the communities with water. Now with rising global temperatures, these glaciers are seeing much higher melting rates. Climate change has not only changed the overall atmospheric temperatures, but it has also led to an increase in large rain events and storms. When these storms rain on glaciers, it can lead to alarmingly high melting rates, which rapidly increases the discharge rates of rivers because the rivers are now flowing with both rainwater and glacial meltwater. This increase in discharge of glacially fed rivers has already destroyed many communities and washed away infrastructure like homes, hotels, office buildings and orchards. Not only does this destroy the livelihoods of billions of people that live downstream, but it also costs billions of dollars to restore these communities and make them inhabitable again (Kääb, 2011). On a very similar note, another hazard of melting glaciers is called a displacement wave. These waves are created when a landslide, avalanche, or large chunk of snow falls into a glacial lake and the impact creates a wave. These waves can lead to major flooding and economic damage if they create overflow of a lake or overtop a dam (Kääb, 2011).

Aside from the water-related hazards from glaciers, there can also be a variety of rock slides, landslides, and other mass movements from deglaciated areas that can cause economic and human harm in downstream communities. As glaciers retreat, they can leave rocks and land uncovered for the first time in hundreds of years. This can lead to rock falls, especially if the ground underneath the rocks gets undercut from glacier meltwater, leaving the land unstable underneath rocks. With momentum, when these rocks are large enough, they can travel far downhill into communities and destroy buildings and infrastructure, costing millions of dollars to fix. Similarly, a wide variety of mass movements can occur when the hydraulics of the land are changed because water moves over the land instead of glacial ice. This can lead to a wide range of mass movements like landslides, rock slides, and rock avalanches. These rock avalanches frequently have more speed than rock slides, so they are usually much more harmful to communities and cost even more to repair the damage that occurs. Another really common and similar natural hazard from glaciers are debris flows, which mostly occur when moraine material is left behind and runoff washes this material downhill.

Where there are glaciers on volcanoes, there is an additional hazard called a lahar. . Although this is less common than the other natural hazards because not all glaciers are on volcanoes, the interaction between glacial ice and volcanoes can be extremely devastating for downstream communities. Lahars can occur when there is a sudden increase in ash, debris, and heat that quickly and suddenly melts glacial ice. This mostly occurs when there are volcanic explosions and the glacial ice on the sides of the volcano breaks away and can cause ash, ice, and debris filled lahars. These lahars are the most dangerous mass movements that can occur because they move at incredibly high speeds and can occur without any warning. Although lahars might become more common in the coming years while there is still more glacial ice, as glaciers continue to melt and get smaller, the risk of lahars will become significantly reduced. These conditions make them extremely difficult to escape, so entire communities can quickly be destroyed by these mass movements (Kääb, 2011).

4.6 Himalayan Glaciers as Water Sources

The Himalayan Mountain range contains thousands of glaciers that are a common fresh water source for billions of people downstream of the glaciers. In recent years, scientists have noticed an increase in the melting rates of glaciers in the Himalayas and they have started to focus more on the details of this melting. On a regional scale in the Himalayas, one 2019 report by the International Centre of Integrated Mountain Development found that even if every country in the world achieves their emissions targets to decrease the rise in global temperatures, one third of the Himalayan Glaciers will be completely melted away by the end of the century (Wester et al., 2018). This report found that until the Himalayan glaciers meet the point of maximum melting and the peak discharge rate, the glaciers will actually continue to melt rapidly.

As this happens, the downstream communities will have an abundance of water to use until the peak melting point is reached (Wester et al., 2018).

One study found that the melting of Himalayan glaciers isn't contributing to sea level rise as much as the glaciers in Greenland and Antarctica (Maurer, Rupper, and Schaefer, 2016). This is due to the fact that melting in Greenland and Antarctica mostly goes directly into the ocean, whereas the melting in the Himalayas feeds other water sources that are used by humans downstream. This water either evaporates before flowing all the way to the ocean, or is damned and used for human consumption as it flows downstream. It was found that there will be both surges and shortages in glacial melt water in the Himalayas. Surges will happen when melting rates increase rapidly from climate change and the frequency of extreme weather events that lead to melting. Shortages will happen when these surges start to slow down because the glaciers have less ice to melt. The surges in glacial ice will predictably precede the shortfalls and will eventually lead to the disappearance of the glaciers. With these surges and shortages, hundreds of millions of people in the region will be affected because they rely on the glacial meltwater to feed rivers used for hydropower, agriculture and drinking water supply (Maurer, Rupper, and Schaefer, 2016).

In the Himalayas, it was found that the rural and urban poor are at the highest vulnerability to changes in their water supply. This is due to the fact that these communities are unable to rebuild or adapt when they are faced with new risks because of the financial pressures they are faced with. Given this information, there has been growing political tension between leaders that are trying to address the social and economic complexities within the region. Leaders need to work together in order to create monitoring systems to analyze the change in water supply and to create more equitable plans to deal with the predicted changes across the entire region (National Research Council, 2012).

4.7 Andean Glaciers as Water Sources

The Andes Mountain range is home to thousands of glaciers that act as a water source for a variety of activities in the downstream communities. One study found that glaciers in the Andes have aesthetic and recreational value that are important for ecotourism around these communities (Rojas, 2021). Glaciers bring tourism into the Andes region each year and are an important source of income across the region. Climate change has greatly affected the stability of glaciers and as more large crevasses develop, it can make mountaineering too dangerous and difficult to complete (Moens, 2020). Not only are glaciers becoming dangerous to travel on, but the rapid melting is also altering the downstream landscapes. As these downstream landscapes are changing, they are becoming less visually appealing, which is predicted to lead to a decline in tourism (Wang and Zhou, 2019). Many communities along the Andes rely on glacial related tourism to help build and support their economies. As glaciers are losing their stability and appeal to visitors, these communities will need to find other sources of income to support themselves.

One of the biggest impacts on the Andean communities from climate change is that the increased melting of glaciers now will affect the long term availability of water to these communities. The Andes have a lot of hydropower facilities and many of these are within glacially fed basins. Over the next few decades, as glacial melt continues to increase, these hydropower systems will be making a lot of power; however, as the glacial melting begins to slow because of the reduction in ice, these hydropower facilities will not be able to produce the same amount of energy they did before. Aside from hydropower use, one study found that glacial meltwater is not used the most for human and animal water consumption, but that it still plays a large role (Schoolmeester et al., 2018). This study also found that during extreme drought conditions, the fraction of human and agricultural water coming from glacial meltwater dramatically increases. This means that in future years, as climate change begins to change weather patterns and the Andes get less precipitation and more glacial melting, these areas might face major drought conditions and the communities would need to find alternative water sources (Schoolmeester et al., 2018).

5.0 Current Water Trends in The Himalayan Region

5.1 What Each Community Relies on Glacial Meltwater the Most for

There are many different ways that communities use glacial meltwater in their daily lives. As discussed in previous sections, humans around the world use glacial meltwater as a water supply source for hydropower, agriculture, and direct consumption by humans and animals. When there is a change in the rate of glacial meltwater, there can be an increase in a variety of natural hazards and there can be negative economic implications for the communities downstream of the glaciers. Although there are many different ways that communities can rely on glacial meltwater, the Himilayan communities rely on glacial meltwater for some of these ways more than others. One way that Himalayan communities use glacial meltwater is for agriculture and crop irrigation. A study found that 129 million farmers use glacially fed rivers and streams to irrigate their crops and they grow food for the 900 million people living in three of the main river valleys of the Himalayan region (LSE, 2019). With a reliance like this, it will be very difficult for these farmers to sustain their crops when the rivers and streams they use are no longer fed by glacial meltwater and they don't have a replacement source of water.

Another one of the main ways that Himalayan communities rely on glacial meltwater is as a source of drinking water for humans and animals. Although there is not a lot of research about how many people use strictly glacial meltwater as their main drinking water source, it has been found that there are about 1.4 billion people in the Himalayan region that rely on rivers fed by glacial meltwater to live (Immerzeel et al, 2010). In terms of animals, one report recently found that the freshwater supply has decreased and there's less water to grow healthy grass for yaks to eat. Many rural farmers and communities use yaks for many different purposes including labor and meat, but with less water and grass, the sizes of the herds have been reduced by up to

75 percent (Augustin, 2021). This means that these communities will need to find another way to get drinking water because the rivers will substantially lose their discharge in the coming years as glaciers continue to rapidly melt.

5.2 Glacial Mass and Size Predictions

The Himalayan Mountain range is known as the “Water Tower of Asia” because it is one of the main water sources for much of this part of the world. Glacial meltwater feeds some major rivers such as the Indus, Ganga, and Brahmaputra rivers which provide water to 900 million people and many agricultural areas in the mountains and plains below (Immerzeel et al, 2010). The Himalayan region is subject to warming that is greater than the global average because this area has an elevation-dependent warming phenomenon. A combination of many factors, including snow albedo, surface-based feedbacks, water vapor changes, and surface heat loss lead to increased warming rates at higher elevations. Given the high elevation of the Himalayan Mountain range, this area has become more susceptible to an overall average temperature increase (Mountain Research Initiative, 2015). With this increase in overall temperature, the melting rate of the Himalayan glaciers has already increased and it is predicted that it will continue to increase even faster in the coming years (Sabin et al., 2020).

Many regions in the Himalayas are seeing rapid economic and population growth, but a decrease in water availability. The Himalayan region, along with many populations in the world are seeing exponential population growth because more people are able to have children and grow families. This increase in population leads to more water needed for every day consumption. As the population increases, more crops need to be grown in order to sustain the population, which uses even more water. This creates a cycle that will be very hard to sustain in the coming years as the water supply in this region decreases (Sabin et al., 2020).

Scientists have also studied the mass of glaciers in the Himalayan region and have tried to come up with predictions for the current glacial mass (Kulkarni et al., 2021). In Figure 8, the average glacial mass of three main river basins in the Himalayan region can be seen in varying reports that use different methods of data collection and calculations. This graph can be used to predict the amount of glacial meltwater that is available to the communities (Kulkarni et al., 2021).

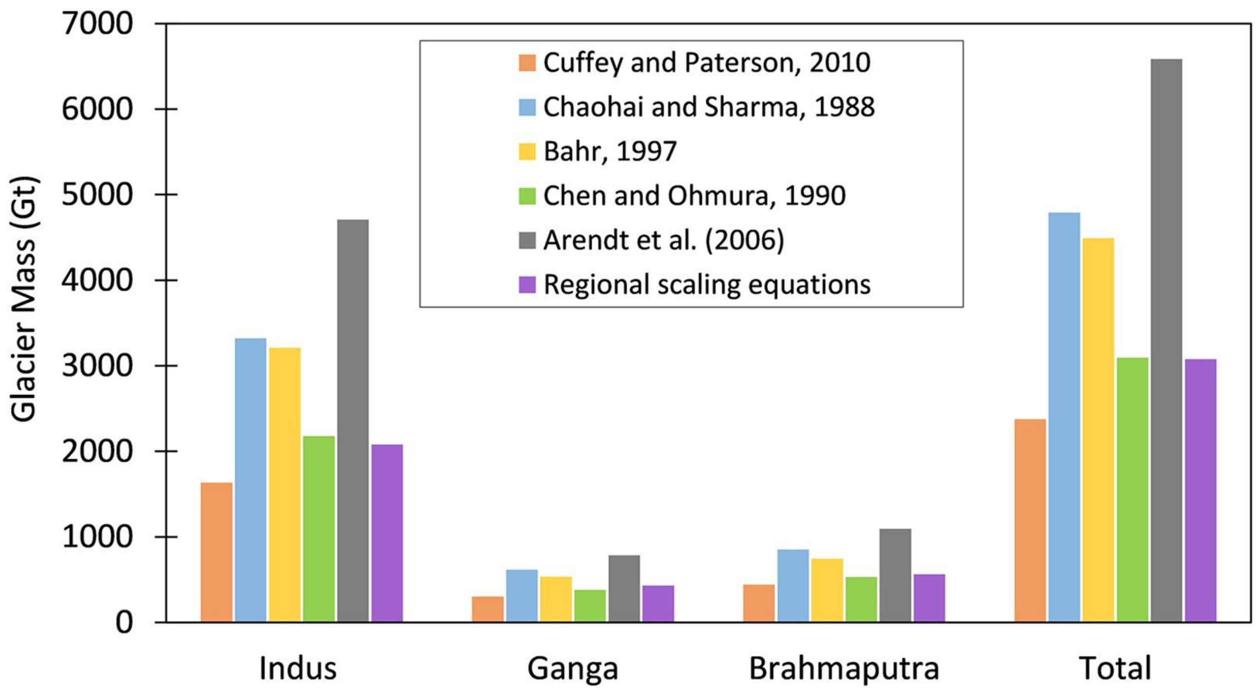

Figure 8. The estimated glacier mass in three major river Basins in the Himalayan region, including the Indus, Ganga, and Brahmaputra river basins. The estimated glacial mass is in gigatons and includes the total for the region. Each color is a different study that uses varying methods to determine the predicted glacial mass. Figure courtesy of Kulkarni et al (2021).

5.3 The Number of People that Rely on Glacial Meltwater

There are five main river basins that rely on glacial meltwater from the Himalayas, including the Indus, Ganges, Brahmaputra, Yangtze, and Yellow rivers. Figure 9 puts into perspective the vast area of the land that each river basin takes up and where they are located in relation to the Himalayas. This figure can be useful in visualizing the size and location of each of these basins when looking at the information presented below.

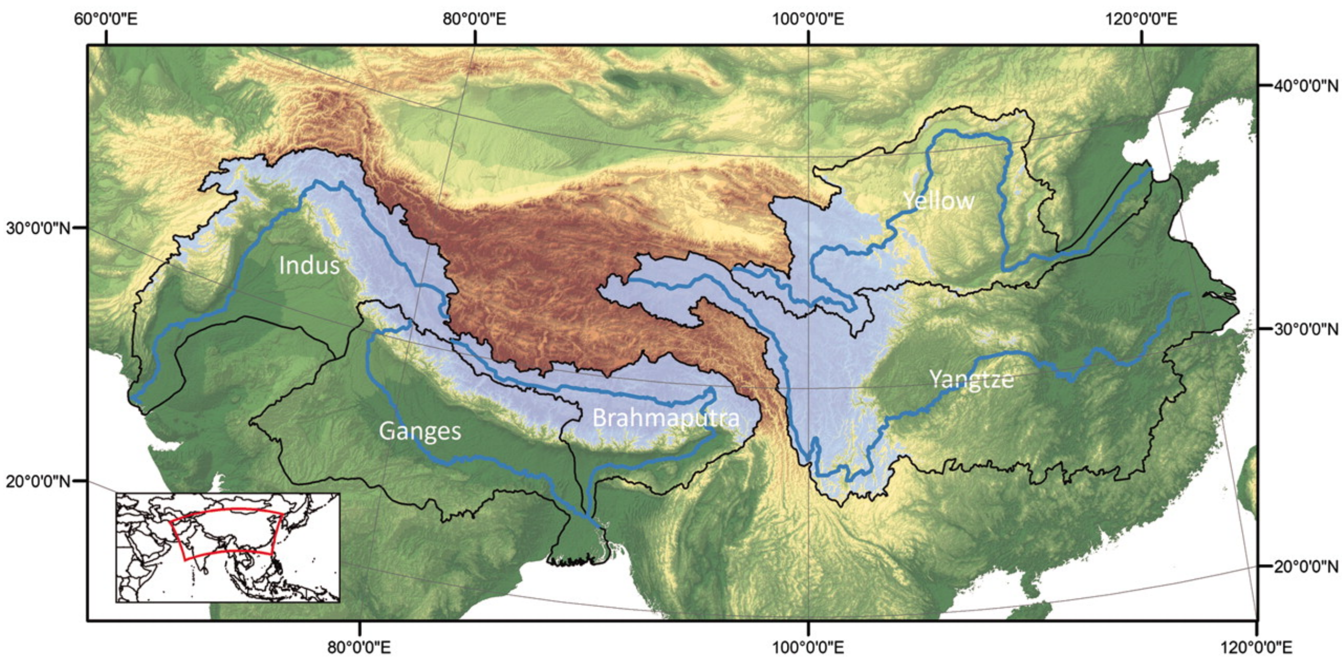

Figure 9. The location of the five main rivers and river basins that rely on the Himalayas for glacial meltwater, including the Indus, Ganges, Brahmaputra, Yangtze, and Yellow rivers. This is a topographical map where the dark green areas are the lower elevations and the darkers brown areas are the highest elevations. Figure courtesy of Immerzeel et al (2010).

There are many studies that have been conducted in the Himalayas that look at how many people rely on glacial meltwater as their main water source, so there is a variety of data that has been presented. One study found that 129 million farmers in the Indus, Ganges and Brahmaputra river basins of the Himalayan Mountain range rely on rivers that are fed from glacial meltwater for the irrigation of their crops. These farmers grow enough food to support the 900 million people that live within three of the major river basins, so the changing of glacial meltwater will not only affect the livelihoods of the farmers themselves, but they will also affect the health and safety of millions of other people if they lose one of their main food sources (LSE, 2019). Another study found that 1.4 billion people (which is about 20 percent of our global population) in the Himalayas use glacial meltwater as either a direct water source for consumption or as an indirect source for hydropower or crop irrigation (Immerzeel et al, 2010). This study found that the Brahmaputra and Indus bains alone are very prone to being negatively affected by the decrease in glacial meltwater and that in these basins 60 million people's lives will be threatened from food scarcity (Immerzeel et al, 2010). This study calculated the Normalized Melt Index (NMI) of each of the five main river basins in the Himalayan region and then compared them to find that the Indus river basin has the biggest reliance on glacial meltwater to increase the discharge of the river, followed by the Brahmaputra river basin. The NMI is a calculation of the amount of the discharge in a river that comes from snow and glacial meltwater. As seen in Figure 10, the Indus river depends on glacial meltwater much more than the other rivers (Immerzeel et al, 2010). The Indus river basin is oriented northwest to southeast, so it catches the most rain and snow, whereas the Ganges and Brahmaputra are oriented east to west, so they get less snow accumulation.

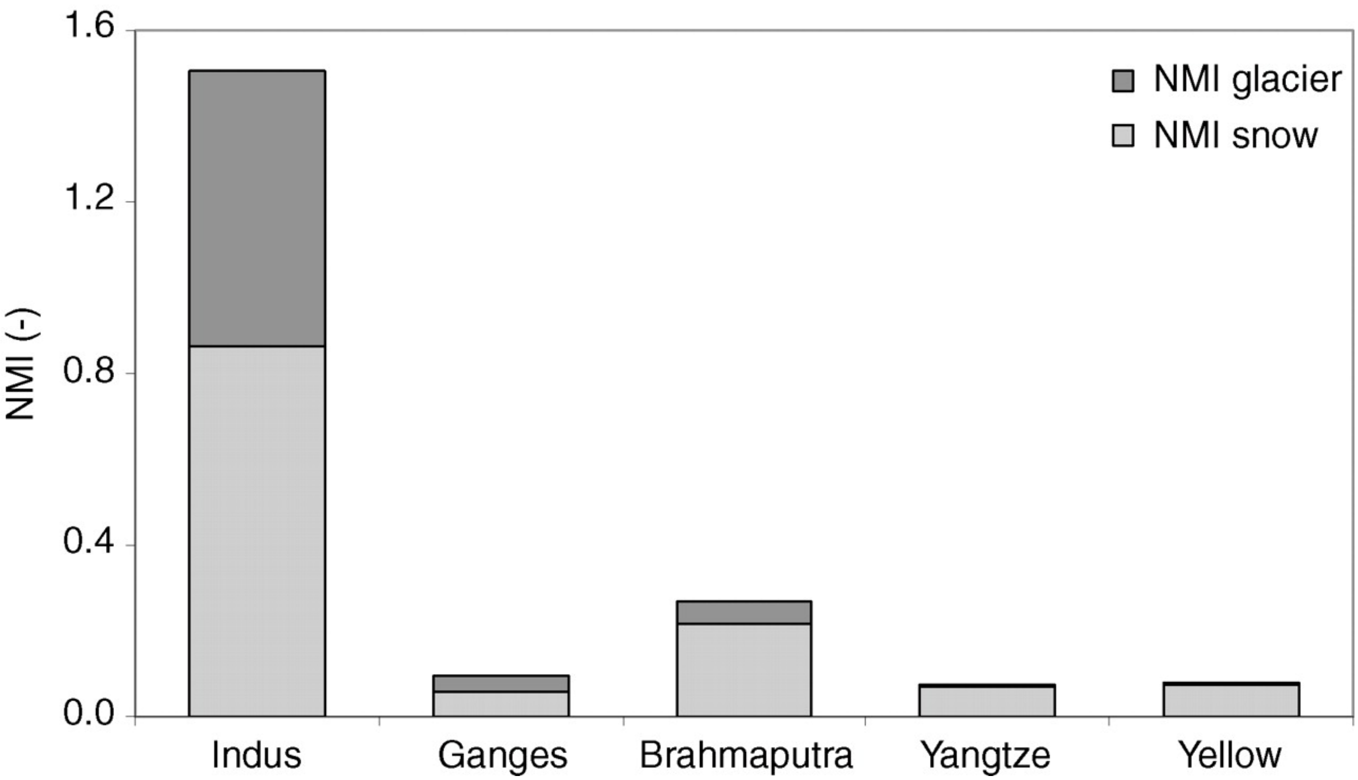

Figure 10. The Normalized Melt Index (NMI) of the glacial meltwater and snowmelt (the snow from around the glaciers) from the five main river basins in the Himalayan region from the year 2000 to 2007. Figure courtesy of Immerzeel et al (2010).

5.4 Predicted Peak Flow Date and Runout Date

At some point in the coming years, some scientists think by 2100, the Himalayan glaciers will hit a point of maximum melting and peak discharge rate (Wester et al., 2018). Until this happens, the melting of glaciers will continue rapidly, so there will actually be an increase in the amount of discharge flowing off of the glaciers. With this, the communities downstream will have an abundant amount of water flowing through their rivers that they will have access to. After the peak flow date, the amount of discharge from the glaciers will gradually start to decrease until the glaciers are completely melted away. There are many predictions for when this peak flow rate date will occur, but one study found that unless global emissions are reduced enough to keep the average global temperature from rising by more than 4 degrees Celsius by

2100, that the Himalayas would lose 66 percent of their ice and affect the 1.4 billion people that live downstream (Immerzeel et al., 2010).

5.5 Natural Hazards

In February of 2021, the Nanda Devi Glacier, located near the city of Tapovan in the northern state of Uttarakhand, India, experienced an avalanche and deluge of water and debris that flowed down the valley and into Tapovan, killing at least 31 people; hundreds more people went missing. It was found that climate change caused the ice of the temperate glacier to become closer to its melting point, so easier to melt. This means that it takes less warm weather for melting of a glacier to occur, so there is an increase of overall melting of that glacier (Ghosal, 2021). When the ice is closer to its melting point, there is more water between the glacier and the ground below, allowing the glacier to move faster. This glacier is experiencing regelation or pressure melting because the weight of the glacier is increasing the pressure at the bottom of the glacier, lowering the melting point of the ice, and leading to an increase in the melting of the ice (Verma, 2011). The increased frequency of melting events also leads to the triggering of more avalanche events through brittle deformation. In this case, it was found that the newly exposed valley allowed for the water and debris released from the avalanche of the glacier to build up more speed, making it much more powerful and dangerous to the city below (Ghosal, 2021).

5.6 Glacial Traditions and Cultural Connections

Across the Himalayan region communities have a variety of glacial traditions and cultural connections. The Ganges River runs through one of the most populated places in Asia and the river is considered to be sacred and spiritually pure. The river is believed to be embodied by the goddess Ganga who is the river deity. The Hindus that live near the river perform rituals on the banks of the Ganges to bring fortune and wash away the impurity within their communities. Other ancient hindu scriptures say that the Ganges can cleanse you of your sins after bathing in the river. There are hundreds of Hindu festivals held on the river banks of the Ganges each year. One example is the month of Jyestha where communities celebrate the river to purify their sins and heal them of ailments (Das, 2019). After glacial meltwater in the Himalayas reach its peak, the water supply on the Ganges River will decrease and this change in water supply might make it difficult for the rituals and deities to continue.

5.7 Community Coping Mechanisms

There are many things that Himalayan communities are starting to do in order to adapt to the changing water patterns. To start, farmers are beginning to pay more attention to the timing and patterns of the snow melting and when the grasses begin to grow. By tracking these patterns they are better able to utilize the water they are getting by matching the timing of the crops to the timing of when the most water flows. The length of the growing season along with the timing of the seasons has changed significantly for many of the crops. For example, the season to grow barley and maize is already about a month earlier than it used to be. With this change in harvest times, it has been more difficult for farmers to find seasonal employees to help grow their crops. Communities will need to change the timing of seasonal employment so that they are able to support the local farmers in growing crops for the community. Another major issue that these farmers are facing is that their fields are starting to no longer support agriculture because of the lack of water and lack of nutrients that meltwater can bring. Some farmers are trying to implement new techniques that are more efficient in their water use. One study found that in three villages, 60 percent of their fields are unable to be used due to droughts caused by climate change. Where possible, farmers are also moving their fields and farm animals higher up on mountains to be closer to the source of water (Padma, 2021).

There are a variety of techniques that farmers are using in order to be more successful in adapting to the changing climate. Many farmers are trying to find and use drought-resistant crops that are much more efficient in their water use. Farmers are also using intercropping which is when they grow multiple crops in the same field so they can benefit from each other and be more space and water efficient. One main issue with this change in the crops that the farmers are growing is that the Himalayan people need to also adapt their diet in order to get the same nutrients they were before. This means that many of their traditional cuisines also need to be changed, so they are losing part of their culture as well (Padma, 2021).

6.0 Current Water Trends in the Andes Region

6.1 What Each Community Relies on Glacial Meltwater the Most for

The Andean communities use glacial meltwater for a variety of activities including for human consumption, agriculture and energy production through hydropower. Glacial meltwater is also commonly used for aesthetic and recreational purposes, including to bring money in through the tourism industry. Rivers are commonly used for swimming, recreational fishing, and white water rafting and kayaking adventures. They can also be used by photographers, painters, and artists alike for their aesthetic values. Agriculture is one of the main purposes that Andean communities use glacial meltwater for. The water is often diverted and stored in reservoirs and then transported through canals to agricultural fields farther downstream than it would have reached naturally. This glacial meltwater is even more important in the tropical Andes during the dry season where there is no precipitation to increase the discharge of rivers. In the tropical Andes, the temperature doesn't change much throughout the season but the precipitation rates are higher during the wet season. In the southern Andes that are not tropical, the summers are warmer and more wet, while the winters are colder and more dry (Park, 2021).

6.2 Glacial Mass and Size Predictions

The glaciers in the Andes Mountain Range are a really important water source for many of the communities that are downstream. One study found that the greatest loss in mass balance was found in the Patagonian Andes at -0.78 +/- 0.25 meters of water equivalent (m w.e.) per year and in the Tropical Andes at -0.42 +/1 0.24 m w.e. per year, whereas there was a smaller loss in mass balance in the Dry Andes at -0.28 +/- 0.18 m w.e. per year (Dussaillant et al., 2019). Meters of water equivalent take the volume of water divided by the area. A loss of mass balance occurs when a glacier is ablating more than it is accumulating, so the glacier is getting smaller overall.

6.3 The Number of People that Rely on Glacial Meltwater

The Andes Mountain range extends through seven countries in South America, providing water resources for the 160 million people that live in these countries. These 160 million people all benefit from the glacial runoff in some way, whether that be through hydropower generation, agricultural use or as a drinking water supply source (Mishra and Verbist, 2017). Of the 160 million people that live within these seven countries, around 75 million of them live directly in the Andes Mountainous region. These 75 million people benefit more directly from the glaciers because they have more access to the glacial meltwater for drinking and agriculture (Schoolmeester et al., 2018). Many of the valleys in the Andes are seasonally dry, so these communities are dependent on the glacial meltwater to replenish aquifers and groundwater systems and to keep the rivers and streams running (Mishra and Verbist, 2017). One study found that the communities in the Andes rely on glacial meltwater as a drinking water source for humans and animals, for hydropower, and for agriculture. During the dry season for the Rio Santa river it is predicted that 40 percent of the discharge of the river comes from the glaciers in the Cordillera Blanca in Peru. This river is used as a water source for agriculture and drinking and affects everyone that lives in the communities downstream. Given a decrease in river discharge from glacial meltwater occurs during the dry season, all communities in the Cordillera Blanca range will be negatively affected by this decrease. During the dry season there is less precipitation, so without the melting of glacial ice through rainwater, there is less glacial meltwater (Milner et al., 2017).

6.4 Predicted Peak Flow Date and Runout Date

There is a wide variety of studies and data that look into when the peak flow date might occur for glacial runoff in the Andes Mountain range. One study used models to predict the total runoff for five glacier catchments in Cordillera Blanca in 2050 and 2080 given two different potential emission rates. An emission rate is the amount of harmful emissions that will be inputted into the atmosphere over a given time period. As seen in Figure 11, this study found that by 2080, no matter the emission level, the amount of runoff will significantly increase in the wet season and will significantly decrease in the dry season. This change will occur because the glaciers will experience more melting during the wet season; this occurs because there is still precipitation, but they will experience less melting in the dry season, so they won't be able to increase the river discharge as much as they used to be able to. In the monsoonal climate, which is found between 5 and 30 degrees latitude on either side of the equator, the temperature difference between the wet and dry seasons isn't very high, so the discharge is much higher in the wet season (Juen, 2006).

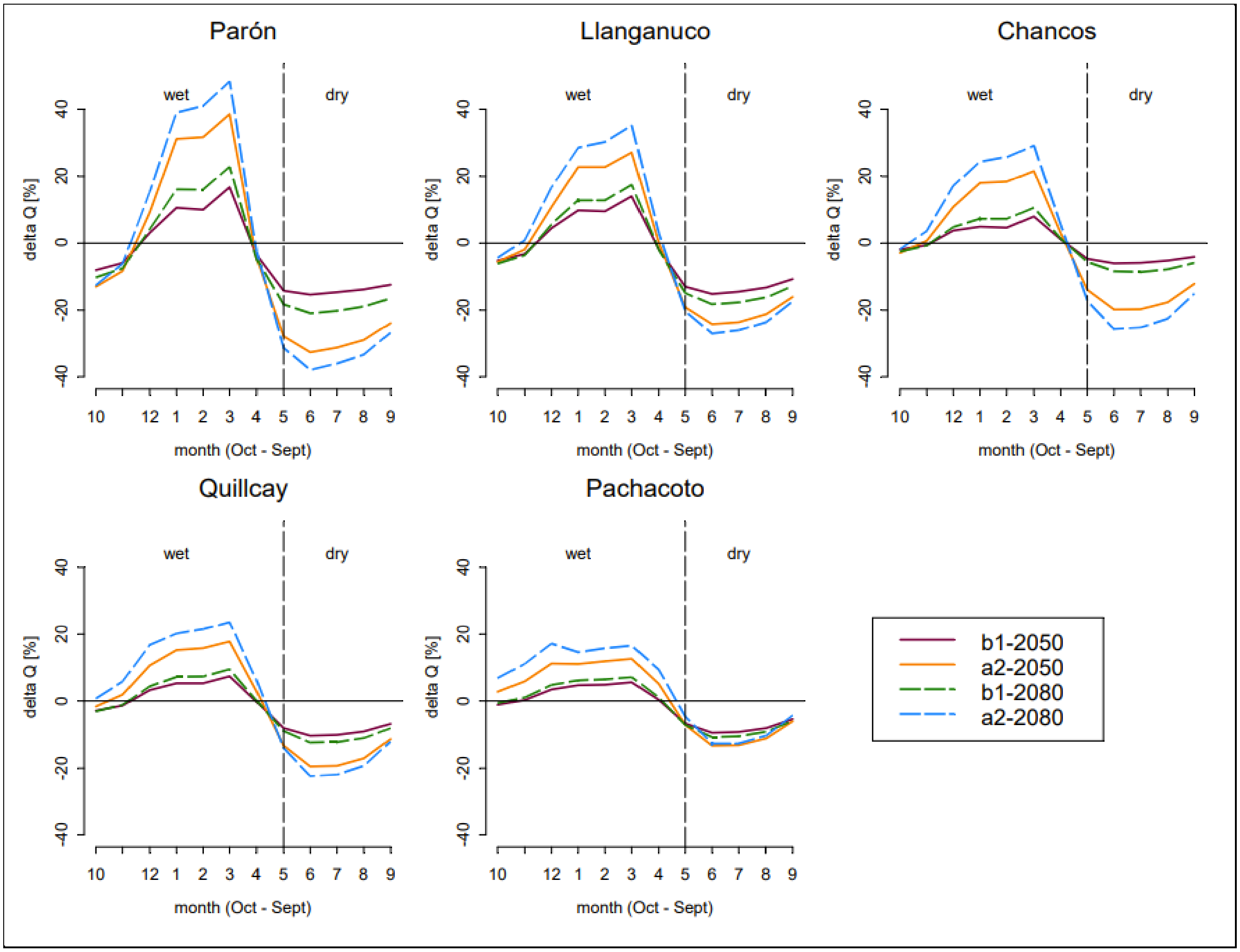

Figure 11. The simulated change in runoff from five different glacier catchments in the Cordillera Blanca in 2050 and 2080, based on two different emission predictions. B1 is a low emission prediction and A2 is a higher emission prediction; the emission predictions are based off of IPCC data recently published. Figure courtesy of Juen (2006).

6.5 Natural Hazards

In recent years, with the increase in melting, the Andean region has also seen a rise in the frequency of natural hazards. One of the most common natural hazards is glacial lake outburst floods (Seehaus et al., 2019). These floods occur when glacial meltwater forms lakes below the glaciers and behind the moraines that are left behind from glacial debris. When these lakes overtop, they can lead to destructive floods that have damaged communities and killed thousands of people. These floods are predicted to increase and destroy many more communities as the Andean glaciers continue to melt (Seehaus et al., 2019). Natural hazards are among the many effects of melting glaciers that Andean communities need to prepare to deal with.

In another location in the Andes, in 1941, a large piece of glacial ice calved off the Palcacoha glacier and fell into the glacial lake below it. When this happened, the glacial moraine that acted as a dam to create the lake failed, and a large mudslide was released downhill. This mudslide, full of rocks, water, sediment, and other debris, completely buried parts of a nearby town called Huaraz. Over 18,000 people died from this event, and this is only a single example of this type of hazard. Given this happened about 80 years ago, before the heavy onset of climate change, predictions are that these events will happen more frequently in the coming years as climate change quickly worsens (Davies, 2020).

6.6 Glacial Traditions and Cultural Connections

Before climate change significantly impacted the health and size of the glaciers in the Andes, the Quyllurit'i festival took place each year at the Colquepunco glaciers in Peru. During this festival, there were parties and ceremonies to honor the glaciers and thank them for what they provided. One tradition consisted of a large chunk of ice that would be cut off the glaciers and carried down into the valley. Since the glaciers have seen a massive decline in ice over the last few decades, this tradition has had to come to an end because the community members don't want to harm the glacier and make the situation worse (Moens, 2020). In the Andes there is a very spiritual connection to the glaciers, so even though this loss of culture is less relevant to survival in terms of the decrease in water, it is still important to acknowledge.

The glaciers in the Andes also play an important role in the lives of thousands of indigenous people. (Rojas, 2021) The glaciers are a sacred part of their lives. There are festivals, pilgrimages, and rituals that various indigenous groups take part in every year. As climate change is rapidly reducing the snowfall and increasing the ablation rates of the glaciers, these groups are losing their culture and traditions that rely on the health and size of the glaciers. As these indigenous groups are quickly losing the resources that glaciers provide to them, for example water for both drinking and irrigation, they are losing faith in nature and hope for the health of the glaciers. Although many groups have said they won't lose their faith in the natural forces that maintain glaciers, they said that with the loss of glacial mass, they will be losing a massive piece of themselves and their culture that dates back many centuries (Magnani, 2021).

6.7 Community Coping Mechanisms

The communities that benefit from glacial meltwater are starting to prepare for the loss in glacial ice that is occurring. Communities are starting to have conversations about water supply, most specifically in urban areas to make sure they are attempting to use their water sustainably (Bradley et al., 2006). Many other communities are starting to invest in more green infrastructure and they are starting to evaluate their decision making process in order to implement a better water management process. This is a proactive way to try to use the available water more sustainably and to do their part in reducing the global greenhouse gas emissions that are perpetuating climate change (IRD, 2013). Some farmers are also trying to change their agricultural techniques and the crops they grow so they are less water intensive. The scientists from one study are completing intensive studies on how the changing climate is affecting the melting rate of these glaciers (Bradley et al., 2006). These scientists are even creating models to simulate the different ways that climate change might affect melting rates, and looking at how we might be able to prepare for the decrease in the water supply and change in runoff patterns (Bradley et al., 2006).

7.0 Discussion and Comparison

Both the Andean and Himalayan regions have an extremely high reliance on the glaciers and the water they provide to the surrounding communities. Despite this similar reliance, there are about 1.4 billion people within the Himalayan river basins while there's only about 260 million within the Andean river basins. About 20 percent of the world's population lives within the Himalayan river basins while only about 260 million lives within the Andean basins. Given there are almost ten times more people that are affected by the Himalayan glaciers, it can be concluded that the scale of the problem for the Himalayan communities will be greater than the scale of the problem for the Andean communities.

Although there are more people that live within the Himalayan river basins that will be affected by the loss in glacial ice and freshwater, the effects on the communities will be fairly similar in the Andes and the Himalayas. Communities in both the Andes and the Himalayas greatly depend on glacial meltwater to increase the discharge of the rivers during the dry seasons. Both communities use these glacially fed rivers for a variety of activities, including for agricultural irrigation, for direct human and animal consumption, and for hydropower. From the research collected, it seems that the Himalayan communities are very worried about the loss of glacial meltwater for irrigation purposes because the farmers in the Himalayan river basins grow food for millions of the people that live within and around the Himalayan region. Similarly, the Andean communities also use the glacial meltwater for agricultural irrigation, so it seems that these communities are equally as worried about the reduction of glacial meltwater because it will affect their ability to grow crops.

Based on the research collected above, it can be argued that in both places agriculture will be the most impacted by the reduction in glacial meltwater because it is extremely hard to find another renewable source of water large enough. In terms of hydropower, communities can find other sources of electricity such as wind turbines or natural gas. Although some of the other energy sources might not be as environmentally clean as hydropower, it will still be possible for these communities to generate the electricity they need in a more sustainable way. In terms of drinking water, it would be possible to import clean drinking water to the communities in need. Although it would take a lot of money and time to import enough clean water for the communities to drink, it would technically still be possible for these communities to get the water they need to sustain themselves. These communities can also use a variety of techniques, such as rainwater collection, in order to take advantage of this key natural occurrence. Rainwater collection is a viable water source in the Himalayan region where they get much more precipitation, but less of a viable water source in the Andes . The northern and central Andes get much less precipitation compared to the southern Andes, so rainwater collection is less of a viable water source (Deutscher Wetterdienst, 2020). In terms of agriculture, it would be extremely difficult to continue to grow the amount of food these farmers produce by importing water. Agriculture uses the most water and so it would not be possible to import the water they need on such a large scale. Given all this information, it can be argued that the biggest impact of the loss of glacial meltwater would be on agriculture in both the Andes and the Himalayas.

Building off the idea that agriculture would be the most difficult activity to find a replacement source of water for, it can be argued that this would be a much bigger problem in the Himalayas than the Andes. The Himalayan region farmers grow enough food for the 1.4 billion people that live within the region, so the lives of not only the farmers, but also all the citizens that won't have enough food will be affected. Although the Andean region farmers will also have a hard time to replace their water source after the glaciers are fully melted, it will affect a lot less people compared to the Himalayas. Given this information, it can be concluded that agriculture in the Himalayas will be one of the most greatly affected activities in either the Andes or Himalayas after the glaciers are completely melted.

On a similar note, it is extremely hard in both the Andes and the Himalayas to predict when the peak flow of glacial meltwater will occur. One study suggests that peak flow has already passed in the Andes (Park, 2021), and another study with 200 scientists concluded that two thirds of glaciers will be completely melted by 2100 in the Himalayas (Wester et al., 2018), but these are all just scientific predictions. Given that all the information we can ever provide about the rate of glacial melting are scientific predictions, society needs to be prepared for anything to happen. The ablation rates and loss of glacial mass balance are very complex ideas that involve so many different factors, which makes it incredibly difficult to make reliable predictions. Depending on how much humans around the world are able to reduce emission levels and prevent the average global temperature from rising, the glaciers will melt at very different rates. Similarly, the use of glacial meltwater is very dependent on the human populations in downstream communities. Although the human population is often growing exponentially, depending on the area, this factor plays a big role in how much glacial meltwater needs to be conserved. The population is growing at about one to two percent per year in the Himalayan region while the population is only growing at about zero to one for the Southern Andes and one to two percent per year in the Northern Andes (Fisher, 2021). Given how complex the mass balance of glaciers are, it can be extremely difficult for scientists to make predictions for when peak glacial meltwater will occur and when the glaciers will completely melt away.

Another notable idea seen in the research presented above is that it appears there is more information on the cultural connection that the Andean communities have with the glaciers compared to the Himalayan communities. Across different Andean communities there are festivals and ceremonies that have taken place for hundreds of years to celebrate and thank the glaciers for all they provide for the communities. There are many articles and much research regarding these festivals and this cultural connection to the glaciers. Although there does appear to be some cultural connections on a smaller scale to the Himalayan glaciers, such as Indian religious practices that include river deities (Das, 2019), it doesn't appear to be nearly as strong as and as important as it is in the Andes. Given cultural identity is really important, it seems that the loss of glacial mass in the Andes will more greatly affect the communities there.

Although in the long run the loss of glacial mass in the Himalayas will affect more people, it is predicted that the Andes will melt sooner because of the worsening of El Nino years. There is not a comparable climactic event that is affecting the Himalayan glaciers, but the El Nino years are greatly affecting the recession rates of the Andean glaciers. El Nino years are not only becoming more frequent, but they are also becoming more intense, so the ocean water is even warmer and the winds are even warmer still. This is leading to a huge increase in the glacial ablation, and therefore recession of the Andean glaciers, because they are experiencing more melting. Given that the Himalayan glaciers are not being affected by such an influential climactic event, they are predicted to recede a little bit slower.

Both the Andean and Himalayan communities are in a place where the melting of their glaciers is inevitable, so they need to begin to prepare. Even if the average global temperatures only rise by 2 degrees Celsius, the glaciers would continue to melt throughout the twenty-first century and a third of all mountain glaciers would completely melt away. This means that the

Andes and Himalayas will lose a third of their ice no matter what we do to stop it, so these communities need to start preparing immediately (University of Innsbruck, 2018). Human emissions are not stopping today and will take many years to reduce enough to prevent the average global temperatures from rising, so it is nearly impossible to avoid the melting of the Himalayan and Andean glaciers. At this point, it is crucial for both of these regions to begin to prepare to lose the glaciers that act as their water towers.

7.1 Preparations for the Loss of Glacial Mass

There are many ways that the Andean and Himalayan communities can prepare to lose their glacial mass. To start, it is important for the local and national governments to create policies for water use. If there are reservoirs storing the meltwater or large quantities of groundwater, this can include things like water restrictions depending on the season, so each farmer or person is allotted a set amount of water that they can use over a set period of time. It is also important for these governments to work with scientists to figure out safe and effective ways to store the glacial meltwater in lakes or reservoirs. This stored water can then be used to supply rivers to run hydropower plants or to release down rivers in the dry seasons when there is a huge reduction of precipitation. Another way that communities can prepare for the reduction of glacial meltwater is by looking into alternative water sources such as groundwater. The groundwater is often replenished by glacial meltwater, but it is important for scientists to continue to research if aquifers will be sustained without the addition of glacial meltwater. Once the Andean and Himalayan communities know how much water they have available to them, it is important for them to create plans to use this water sustainably. Without the sustainable use of the water sources in the Himalayan and Andean communities, it will be impossible for these communities to sustain themselves when their water sources are completely depleted.

Given all of this information, it is of the utmost importance to look at who is paying for this loss of glacial ice. Based on the research presented above, it seems that the low income farmers in remote parts of the Andes and the Himalayas will be the most affected group that will be paying for the loss of glacial meltwater. These farmers are soon going to lose the ability to run and operate their farms because they won't have the water they need to sustain the crops. If these farmers are wholesale farmers that make their money from selling crops to stores or people, they will lose their main source of income and need to find other sources of work. Not only this, but if these farmers rely on their own crops to sustain themselves and their families, they will also quickly lose their ability to feed themselves as well. Given these farmers often have very few economic assets, it will be even harder for them to adapt to the changing conditions. These farmers will be in the worst place and will be the most affected group because they will lose their source of food and income, and without income they won't be able to buy food too. Given this, it seems to be a crucial time for governments and communities to start preparing to support these farmers for what is to come.

8.0 Conclusion

Both the Andes and the Himalayas are extremely dependent on glaciers, but we should be the most worried about the Himalayan region because there are 1.4 billion people that live within the region and will be affected by the loss of its main water source; within the Himalayas, the poorest farmers are predicted to be the most impacted by the loss of the glacial meltwater because it is nearly impossible to find an alternative water source for agriculture given the sheer amount of water that it needs. The other most common uses for glacial meltwater can more easily be replaced by other sources of water. For example, although it would be expensive, drinking water can be imported and communities can find alternative sources of electricity to replace the use of hydroelectric power. When looking at the entire issue, the Himalayan farmers that grow enough food for the entire 1.4 billion people that live within the Himalayan river basins can't find another source of water to help irrigate their crops. We all need to be paying attention to and worrying about finding a solution to this problem. We also need to address the irreversible cultural damage that has already occurred and will continue to worsen as the glaciers melt.

In the grand scheme, we are talking about billions of people being affected and entire food systems that will need to change in both the Andes and the Himalayas. It is of the utmost importance for us to start looking into ways to help these communities. At this point the melting of at least parts of these glaciers is inevitable, so the earlier we can begin to prepare to lose this water source, the better off these communities will be.

Beyond glaciers, water shortages are already a problem in the midwest of the United States, where they are having to restrict farmers and local communities on the amount of water they can use. Rivers and reservoirs that were once running freely and were filled, are now lower and moving more slowly than ever. Due to climate change, this shortage of freshwater from glaciers and groundwater around the world is a pressing issue that we all need to worry about because it will affect our ability to survive.

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