CHANGING GLACIERS: SO MUCH MORE THAN SEA LEVEL RISE

How changing glaciers will influence every aspect of life on earth, case study: Iceland, and photo essay.

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Abstract: *Glaciology is an evolving science during a time in which our increased understanding of glaciers will become critical to understanding and adapting to our future of life on earth. Current glaciological research can predict the impacts of glacial change on a warming planet with steadily increasing precision in a variety of contexts. This study catalogues a diverse range of glacial impacts on human activity through a variety of geographic case studies. First, glacial influence on ocean currents and sea level rise is analyzed through our understanding of the Greenland and Antarctic ice sheets. Second, glacial influence on fresh water availability, agriculture, fisheries, tourism, and biodiversity is analyzed through our understanding of the Himalaya region, Wyoming state, Washington state, New Zealand, and California state. Third, glacial ice cores from Antarctica reveal information on past climate, and geological analysis of Yosemite National Park offers further insight. Fourth, the influence of glacial change on cultures and spiritual practice is analyzed. Because Iceland presents a unique combination of glacial influences, the geological and cultural impacts of glaciers there are analyzed. Finally, this study is further contextualized by a photo essay of Iceland's Glaciers by the author.*

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I found that we can have the very best data, statistics, and models chronicling glacier change, but if that information is not grounded within the human stories of place, then that information is largely powerless. If people do not see themselves in the story, then they are not part of the story.

- Dr. M. Jackson

Introduction

My academic focus and personal passion over the past two years have been focused on exploring the changing natural world. My interest was sparked by my travels in Norway, exploring the country's dynamic landscape. During one visit, I realized a profound truth: how quickly climate change is impacting our earth. I had returned to a glacier that I had climbed as a teenager, not so many years before, and saw that in those few short years the glacier had nearly vanished into the mountain. As if a fire had started in my heart, this realization consumed me and I became obsessed. Since then, I have made ice the focus of my studies, travels, and life's ambition. These studies and experiences have taken me all over the world, and it has become clear there is a mandate for a lifelong pursuit of the knowledge of how glaciers directly impact human societies.

Glaciers have changed my life. They have given me purpose and companionship and, standing in their majesty, I have found bliss and spiritual resolve. Glaciers are dramatically beautiful: the continuous movement of ice on rock, cutting crevasses and procuring sediment, chiseling mountain faces and carving wide valleys, fertilizing the land and rivers below, giving life to all those downstream. Glaciers are truly the greatest artists of the natural world. On a time scale, their movement and change is slow enough to miss with the naked eye, but fast enough to observe profound changes when revisiting. And changing they are, faster every day. Glaciers are the thermometers of a warming planet, but they are also so much more.

Physical science observes changing ice through measurements of mass-balance and glacial dynamics. Geomorphology observes changing ice through constantly evolving glacial foregrounds. In environmental science, glacier change is observed through influences on downstream ecosystems. Politics and economics observe glacial change through the fiscal value of ecosystem services a glacier can provide. Art explores the dramatic and subtle ways changing glaciers intersects with humanity and nature. Glaciers are also viewed through the eyes of communities whose cultures and spirituality are shaped by glacial change. Glaciology is the study of glaciers and, thus, the combination of all of these observations and more.

Defining Glaciers

Glaciers are found on every continent on the planet except Australia, which itself bears the scars of recent glaciations evident on Mount Kosciuszko. Glaciers are found in the Maoke Mountains in Indonesia, Mt. Kenya in Kenya, and Nevado Cayembe in Ecuador, all sitting on or just near the equator. Glaciers rest on the Andes, in the form of tiny glacierettes to large ice caps, along the entire western portion of South America, in Venezuela, Columbia, Ecuador, Peru, Bolivia, Chile, and Argentina. A glacier covers the caldera on Volcán Iztaccihuatl, just south of Mexico City, Mexico. In the U.S., glaciers can be found in the Colorado Rockies and the California Sierra Nevada. There are small glaciers in the Pyrenees in Spain. Four thousand glaciers cover the European Alps in France, Italy, Switzerland, Austria, and Slovenia. Glacial meltwater from the Himalaya provides a critical water source for 1.9 billion people, over a quarter of the global population, throughout Afghanistan, Pakistan, India, Nepal, China, Bhutan, Bangladesh, and Myanmar. Ice covers nearly the entire Antarctic Circle: 79% of Greenland, 10% of Iceland, and 5% of the state of Alaska. Glaciers cover 10% of the earth's surface. There are about 198,000 glaciers in the world, from glacierettes that barely cover 0.1 square kilometres to the Antarctic Ice Sheet that cover 14 million square kilometers. All of these glaciers are melting away, some faster than others, but all more rapidly than ever in Earth’s known history.

At its core, glacial formation is simple. Glaciers form when winter snowfall exceeds summer melt, creating positive mass-balance. Snow compresses over many years and pressure forms ice. Mass balance in glaciology refers to the accumulation or loss of mass in a glacier. A glacier with negative mass balance is losing ice while a glacier with positive mass balance is gaining ice. To be considered a glacier, however, the ice must be moving. Glaciers create outward and downward pressure that force the ice away from its accumulation zone with gravity. Like a river, the ice then flows away from the source towards its ablation zone or melt zone where the ice melts away during summer. Glaciers have an accumulation zone, where ice is formed, and an ablation zone where ice melts. For a glacier to be in equilibrium, the accumulation zone must be slightly greater than the ablation zone, though this is rarely the case. Throughout natural history, glaciers either advance or recede following global climatic changes, but local atmospheric and geological influences can also influence glacier change.

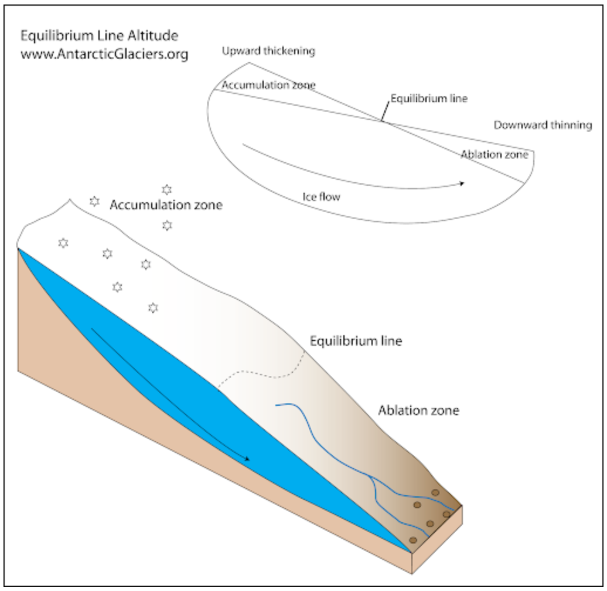


Figure 1: Glacial dynamics: The equilibrium line separates the upper accumulation zone, where the glacier increases mass, and the lower ablation zone, where it loses mass. A positive mass balance indicates the glaciers accumulation zone is greater than the ablation zone; a negative mass balance indicates a negative mass balance. In late summer, the accumulation zone on glaciers is covered in snow and the ablation zone is exposed ice. (AntarcticGlaciers.org)

There are many types of glaciers, and what differs between glaciers are mainly temperature and geography. First, there are two main types of glaciers when classified using temperature: *polar glaciers* and *temperate glaciers.* Polar glaciers are glaciers where the temperature within the majority of the ice is below 0 degrees celsius. These occur mainly in the globe's coldest climates at the poles. For instance, the majority of the glaciers in Antarctica and northern Greenland are polar glaciers. Glaciers in which the ice is mainly above 0 degrees celsius are called temperate. The Vatnajökull icecap in Iceland and the Juneau icefield in Alaska are temperate glaciers, in which meltwater is constantly moving through and under the ice. Glaciers that are neither polar nor temperate are referred to as polythermal glaciers or subpolar glaciers, in which there is as much ice below 0 degrees celsius as there is above 0 degrees celsius (Glasser, 2011). The surface ice and basal ice in these glaciers are temperate during the melt season while the core remains well below 0 degrees celsius. Many of the glaciers in Nunavut, Canada, and Svalbard, Norway, are polythermal glaciers.

Glaciers come in many shapes and sizes. In non-polar regions, the most common types of glaciers are valley glaciers and cirque glaciers. These are glaciers that form and flow from mountains. Valley glaciers often begin on the sides of mountains and flow down from the mountain in a single and concentrated direction through valleys. Cirque glaciers are often smaller glaciers that remain in high mountain basins and do not flow down into the valleys below. These glaciers hug the sides of the mountain face. These glaciers are common in the Cascade Range in the U.S. states of Washington and Oregon. If a valley glacier flows through a valley and terminates into the ocean, it is called a tidewater glacier. Tidewater glaciers are common in coastal Alaska, flowing from mountain ranges such as the Chugach Mountains and Kenai Fjords National Park.

Glaciers that cover entire landmasses and flow out in all directions are referred to as ice caps or icefields. The largest are referred to as ice sheets of which there are two in the world: the Antarctic ice sheet and the Greenland ice sheet. Ice caps can have valley glaciers flowing from them, such as the case as the Jostedalsbreen icecap in Norway which has tens of named valley glaciers flowing from the ice cap.

Glaciers Influence on Global Climate

Earth’s cryosphere is about as critical as a life-supporting system as the atmosphere. When glaciers melt, it will mean so much more than rapid sea level rise. Glaciers stabilize global climate, support ecosystems, provide freshwater and nutrients, hold landmasses in place and even keep volcanoes from producing devastating eruptions. Glaciers and ice sheets play a large role in the wind and ocean currents of the Earth. Ice directly affects the thermohaline circulation of the oceans by cooling water temperatures and trapping freshwater at the poles, therefore increasing salinity. Cold air temperatures influenced by the cooling of ice at the poles creates high air density and high-pressure systems at the poles which cause divergence: the movement of cold air away from poles and towards the tropics. Decreasing ice mass at the poles could, therefore, dramatically change these global systems, completely altering the globe's climate.

IPCC & Sea Level Rise

The most recent assessment report by the United Nations' Intergovernmental Panel on Climate Change (IPCC) in 2014 highlighted the dire state of the cryosphere. The report stated that current glacial extents are not in balance with current atmospheric temperature, meaning that, globally, glaciers will continue to shrink. As long as warming continues, that imbalance will grow (IPCC, 2014). The IPCC adopted the representative concentration pathway (RCP) atmospheric carbon concentration model to predict global atmospheric temperature trajectory. RCP2.5, referring to the concentration of greenhouse gases that will contribute to global warming at 2.5 watts per square meter, is the best case minimal warming scenario, RCP8.5 is the most extreme. This model is used to predict glacial change and subsequent sea level rise as ice mass decreases and will be referenced throughout this study. The latest IPCC report concerning the cryosphere and sea level rise estimates that under RCP2.5, global sea level will rise by 0.95 feet by the end of the century; under RCP8.5, sea level will rise by over 3.5 feet (IPCC, 2019). Nearly every coastal community in the globe will be impacted by this sea level rise as an estimated 200 million people currently live below where sea level is projected to be in 2100 (Kulp & Straus 2019). The consequences of such sea level rise are difficult to fathom and predict. As well, glacial melt is not the only contributor. Thermal expansion is also a factor in sea level rise, in which the water molecules expand under increasing temperature. The severity of consequences of sea level rise will depend on how we respond and adapt, but the ramifications could result in mass migrations and massive economic losses.

Albedo

Much is unknown about precisely how the melting of the planet's cryosphere will affect global systems, but we do know that melting ice will trigger global positive feedback loops that will further decrease ice mass and coverage and alter global climate. Possibly the best studied feedback loop is the ice-albedo positive feedback loop. Surface albedo refers to the reflectivity of a surface. Ice has a high albedo and reflects much of the sun's rays and, therefore, solar energy back into space, cooling and stabilizing the climate. But decreasing global ice coverage means that less solar energy will be reflected back into space as more solar energy (heat) is absorbed by less reflective surfaces. This will trigger further melt, decreasing ice coverage, and increasing global temperatures. Another factor decreasing ice albedo is the buildup of sediment, especially on ice caps and sheets as they melt. Sediment is much darker in color and attracts solar energy, further heating and melting the ice, exposing more sediment, another feedback loop.

What is not yet included in models predicting glacial melt, due to its rather recently discovered relevance, is bioalbedo. Bioalbedo refers to decreases in ice surface albedo due to the growth of microorganisms on the ice surface. Eukaryotic algae on Greenland's ice sheet, for example, can appear during spring algal blooms and can change the snow color to green or red in massive blotches, which can potentially have significant impacts on albedo (Benning et al. 2014). Bioalbedo is another of many factors influencing glacial dynamics and global climate that we are just beginning to comprehend.

Ocean Currents

While it is understood that melting ice will likely trigger intense feed-back loops that will further accelerate the rate of melt, less is known about how it could affect global ocean currents. The ocean's currents are driven by wind and differences in density caused by variations in water temperature and salinity. Glaciers and sea ice at the poles directly impact the salinity and temperature of the water. As currents move water towards the poles, the water becomes colder and increases in salinity, therefore, more dense. The increase in salinity is attributed to the freezing of sea ice, which freezes as fresh water, excluding salt and, in turn, making unfrozen sea water saltier. This increase in density triggers the water to sink and form deep water ocean currents where water travels back to the mid-Atlantic and upwells, producing what is called thermohaline circulation (O'Hare, 2011). This is precisely how the gulf stream works in the North Atlantic: wind-driven currents push warm water from the Gulf of Mexico to the Arctic, where it cools and becomes dense, and that water then sinks and moves back south. But melting ice will increase the amount of freshwater input into the Arctic and less sea ice and glacial coverage will lead to a warmer Arctic Ocean. One hypothesis is that the decrease in salinity, increase in temperature and the following decrease in density, could reverse the Gulf Stream. If the water is not dense enough to sink, then deep water currents from the Arctic to mid-Atlantic could fail, instead upwelling from deep ocean currents from the Antarctic could occur in the

Arctic, taking over in place of the Gulf Stream, water which would then travel south through the ocean surface effectively reversing the ocean current (O'Hare, 2011). Although it is also possible that the westerly winds that drive the warm surface water north from the Gulf of Mexico could intensify, pushing more warmer water north and counteracting any effects from decreased water density in the Arctic.

A study completed in 2020, conducted by NASA, discovered that the Beaufort Gyre in the Arctic Ocean is intensifying due to melting sea ice. The Beaufort Gyre is driven clockwise around the Arctic Ocean by westerly winds, collecting freshwater from glacial melt, sea ice melt, precipitation and river runoff that it then gradually releases into the North Atlantic when winds change direction every 5-7 years. But the westerly winds have not changed course in two decades, which has allowed the freshwater to collect in the gyre. As well, due to melting sea ice, more surface water has been exposed, allowing the westerly winds to intensify the current. Once the winds finally change course, it could release this freshwater in astronomical amounts, certainly affecting the density of sea water in the North Atlantic and therefore altering the Gulf Stream (Armitage et al. 2020).

A dead Gulf Stream may mitigate warming effects of climate change in the North Atlantic and Europe by decreasing water temperature as warm water stops flowing north. Alternatively, a Gulf Stream that remains intact will work to intensify climatic changes. But it is more likely that the effects of melting sea ice and glaciers in the Arctic will alter the Gulf Stream in ways that are difficult to predict. Whether weakening or intensifying the Gulf Stream, melting ice will certainly cause profound changes to ocean currents that will affect global climate and nutrient cycling.

Polar Glacial dynamics

Understanding glacial dynamics, especially in glaciers in Greenland and Antarctica, is critical in understanding how rapidly and to what effect changing glaciers will influence global climate systems. In Antarctica, ice shelves act like giant barriers that hold back glaciers on land from rapidly advancing and calving into the ocean. In 2002, the Larsen B ice shelf off Graham Land in the Antarctic Peninsula collapsed. The Larsen B ice shelf completely broke away and began drifting towards the Atlantic ocean and, in a sense, opened the floodgates to the glaciers from which it broke away. Glaciers on that part of the Graham Land, whose movement had been slowed by the ice shelf that lay in their path, suddenly surged into the ocean, creating thousands of icebergs that had previously been held on land. These icebergs melted, contributing to sea level rise.

The Larsen B ice shelf broke apart due to surface meltwater percolating through a deep crevasse in the ice (Scambos, 2004). Another factor that is contributing to ice shelf collapse and glacier surge in Antarctica is warming oceans. Warming ocean temperatures melt underneath these glaciers, pushing back what is called the "grounding line," where glaciers disconnect from land and are then held in water by buoyancy. This causes further glacial acceleration, breaking up the ice shelf as the glacier forces its way into the water. As ice shelves calve, they melt faster. With less ice shelves to hold glaciers back, glaciers continue to accelerate faster, a feedback loop that continually speeds up the melting process (Rignot et al. 2011). Antarctica is surrounded by these ice shelves which are thinning and calving, losing more and more mass every year. Knowing the thickness of these ice shelves, and the snow accumulation on the ice sheet, can help us understand how vulnerable they are to calving or completely breaking away.

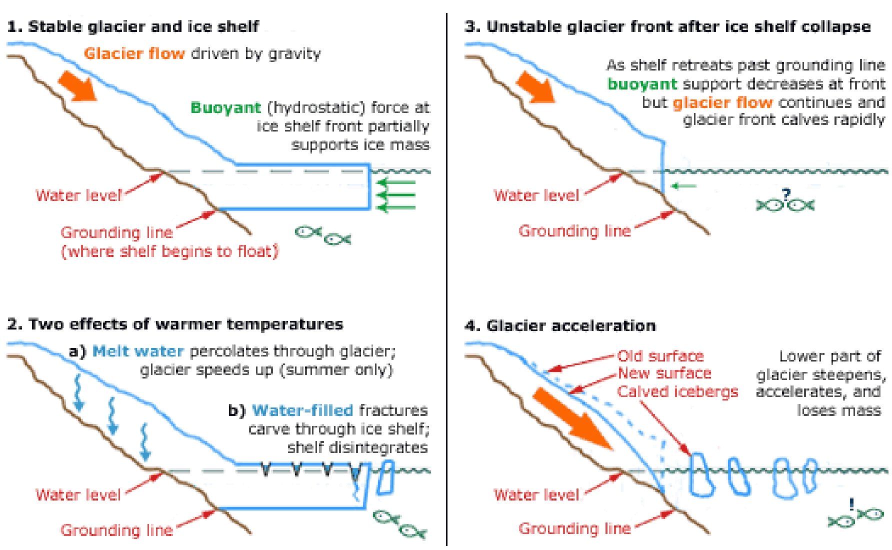


Figure 2: Illustrated glacial dynamics leading to ice shelf collapse and glacier acceleration (NASA)

Predicting major calving events, ice shelf collapse, and glacier advance are difficult endeavours. Our understanding of how these processes work is not fully developed. It is understood that the Greenland ice sheet is heading for total collapse due to a number of feedback loops, reduced albedo, percolation of water through and underneath the ice, and warming oceans. The ice sheet is melting and the glaciers are rapidly advancing into the ocean. Jakobshavn glacier is the major drainage stream of ice for the West Greenland ice sheet, this glacier has experienced record calving and acceleration. While the cause of calving and acceleration events is understood, predicting the timing of them remains out of reach of current models. In fact, according to some researchers, cutting edge glacial dynamics models may never catch up with the rapid retreat of the Jakobshavn glacier and the rest of the Greenland ice sheet (Gertner, 2019).

Operation IceBridge

While glacial dynamics are difficult to understand, Operation IceBridge is helping us understand the volume, extent, and changes of mass to our polar ice. Operation Icebridge, run by NASA, is the largest aerial survey of ice ever conducted. Operation Icebridge began in 2009, and began collecting data where NASA's Ice, Cloud and Land Elevation Satellite (ICESat) left off. The satellite largely left the polar regions unobserved and was de-orbited in 2010. NASA’s Operation Icebridge uses planes to collect data on the ice sheets instead of satellites and there are benefits and drawbacks to this approach. The drawback to using planes is that they are limited to seasonal missions, normally several weeks at a time, due to harsh polar winter conditions. As well, planes are limited to smaller areas of observation, whereas satellites can make observations all year long and observe vast areas. The major benefits of planes are that they can carry many more instruments on board, as can focus on specific areas. The instruments that NASA carries on its planes are the most important and groundbreaking instruments in radio-glaciology to date. These are radar instruments that measure snow accumulation, ice sheet depth, and the topography or sea surface below the ice. The Multichannel Coherent Radar Depth Sounder (MCoRDS) measures the ice sheet and bedrock topography while the Center for Remote Sensing of Ice Sheets (CReSIS) Snow Radar measures snow accumulation on top of the ice sheet.

MCoRDS has been one of the most important developments in radio-glaciology, allowing NASA to map the bedrock beneath the Antarctic and Greenland ice sheets and measure the thickness of an ice sheet with precision and detail. This radar is deployed in twin engine, long range, research planes and operated by scientists with the Center for Remote Sensing of Ice Sheets (CReSIS) during the entire flight line over the ice. Like echo-location, radar is helpful in the study of glaciers because the timing and strength of reflected signals may be used to map the shape and thickness of the ice below. MCoRDS uses the radio frequency receivers operating in the bandwidth [140-230] MHz. Each receiver has a tunable bandwidth to maximize the signal to noise ratio (SNR) of radio waves reflected from the ice.

CReSIS researchers deployed in Operation IceBridge planes fly over specific flight paths to map a section of the ice sheet or shelf that the scientists want to study. The machine fires radio waves as the plane flies, a radio wave is shot every few meters or so as the plane moves forward. The machine counts the amount of time, in microseconds, it takes for radio waves to bounce back off the ice sheet and bedrock and back to the plane. Then, the researcher, knowing how fast radio waves travel through air and ice, can calculate the distance it took for the radio waves to bounce back. The radio waves bounce off the ice surface as well as the bedrock. The final product of these flights is a map of the bedrock underneath the ice and the volume of the ice above the bedrock as determined by measuring the thickness. With these maps, scientists can better understand the flow of the ice across the bedrock. In Figure 3, a canyon is observed in the bedrock, highlighted in blue. Ice moves faster through this canyon because it is the path of least resistance, much like water in a river. As the ice moves through this canyon, it digs the canyon deeper, shaving off rock as it moves and pushing the bedrock down due to the immense pressure from the weight of the ice above. For instance, researchers have discovered that the center of the bedrock under the Greenland ice sheet is below sea level, forced down by the weight of the thousands of meters of ice above.

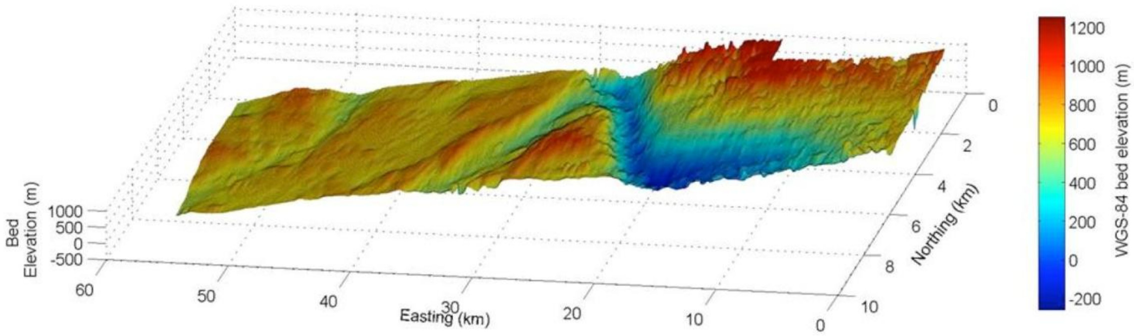


Figure 3: Bedrock topography produced by MCoRDS (NASA).

Glacial Influences Downstream

Shifting focus away from the glaciers of Antarctica and Greenland, which present global climatic impacts, we observe the impacts that alpine glaciers have on downstream (more local) economies, ecosystems, and cultures. We use "downstream influences" to indicate the effects alpine glaciers have on their immediate surrounding areas. The planet's ice, most notably alpine glaciers and icefields between the poles, provide one of our most critical ecosystem services: fresh water. Glaciers provide freshwater that supports the many different uses of humans: most importantly, domestic use and agriculture. Besides being our largest reservoir for freshwater, meltwater from glaciers is a critical part of downstream ecosystems. Glaciers influence downstream ecosystems in many important ways. For instance, they provide sustained flow and regulate temperature especially during late summer months when snowmelt is no longer contributing. This temperature and flow regulation sustains productive fisheries around the globe, namely salmon fisheries. They deposit glacial till, unorganized sediment resembling clay, which provides habitat and soil. Glacial meltwater provides nutrients downstream and can help dilute pollutants in watersheds. Glaciers can also produce outburst floods, or jökulhaups, that can fatally flood populated areas, temporarily damage ecosystems or completely alter landscapes.

Meltwater and its impacts on the immediate landscape is one aspect of the importance of alpine glaciers to their surrounding areas. Glaciers provide recreational and tourism opportunities that can be the backbone of local economies. And possibly the most overlooked, is that glaciers can form a sense of identity and be of critical cultural importance for communities that live near and far from ice. Categorizing the many impacts of glaciers to their respective downstream landscapes, ecosystems, and cultures, is difficult because, like all climatic changes, glacial change reverberates through all these systems and can have many indirect impacts. The more direct and more immediate impacts are easier to categorize. Glaciers have their largest direct impact on local economies, fisheries, agriculture, fresh water supply, and cultural identity.

Before introducing such impacts, it is important to define the difference in glacial-dominated watersheds and snow-dominated watersheds. Snow-dominated and glacial-dominated hydrological systems differ in their reservoir and timing of water discharge. Snow-dominated systems are limited by seasonal variability. Their reservoir for water will largely melt off in spring and summer once seasonal snowfall halts and atmospheric temperatures rise. As long as there is a glacier and energy to melt the glacier, there will be glacial melt. This is why summer to late summer waterscape in glaciated watersheds is primarily influenced by glacial meltwater, because by such time the influence of melting snowpack has decreased. The timing of such glacial meltwater discharge, while mainly occurring in summer, can be hard to predict, due to variability in summer temperatures, weather events, glacial dynamics, and even volcanic eruptions. In glaciated systems that rely on sustained year-round water, glacial meltwater provides sustained flow during late summer months. In many glacially dominated watersheds, glacier mass reduction due to climate change will eventually reduce or nearly eliminate late summer flows because of reduced or eliminated contribution to watersheds by glacial meltwater. In many systems, there will be an initial increase in glacial meltwater contributed streamflow over a few years as glacial melt rapidly increases and the bulk of glacial mass is reduced. But over the decades this summer flow will be reduced. This has far-reaching consequences downstream.

Fresh Water Source: Himalaya, the water tower of Asia.

If you live downstream of the Himalayas, the Alaska Range, the Coast Mountains of British Columbia, or Patagonia, the water you drink comes from glacial-dominated systems. Possibly nowhere else is this fact more consequential than the Himalayas. The Greater Himalayan range stretches from the Karakoram ranges of Pakistan in the west to Hkakabo Razi in Myanmar to the east. This range passes through the most populous countries on earth: China, India, and Pakistan, as well as Afghanistan, Nepal and Bhutan. The Himalaya and surrounding central Asian ranges are often referred to as the world third pole, because they contain the third largest deposit of ice and snow in the world, after Antarctica and Greenland. An estimated 1.9 billion people rely on freshwater that is sourced in glaciated catchments. Glacial meltwater is an important source of water, especially during dry months, but its importance varies across the region. For instance, in the Ganges River Basin, most freshwater is sourced from the monsoons, and only 3% of flow is sustained by glacial meltwater. On the other hand, the Indus River Basin can attribute 32% of its flow to glacial melt (Immerzeel et al. 2010). That being said, many studies have not accounted for seasonal variability in assessing contribution sources, and studies use a variety of different methods to assess glacial meltwater contribution. One study suggests that the Ganges River can attribute up to 58% of streamflow annually to glacial melt (Racoviteanu et al. 2013) and another study suggests that the Indus can attribute 80% (Zhang et al. 2013). The population of the Ganges River Basin is more than half a billion people. The population of the Indus River Basin is nearly 270 million people, mainly in Pakistan, all of which depend on that meltwater as a source of water for drinking and agriculture. The Indus River is over-allocated and considered one of the most depleted river basins in the world (Sharma et al. 2010). In addition, Pakistan withdraws 50% of its water for agriculture use from groundwater, which is severely overused and is being withdrawn faster than the groundwater can recharge itself (Watto et al. 2016). The region is likely to experience a growth in water use and a decline in water availability. Although glacial meltwater contributions may initially increase, which will be the case with glaciated systems as glaciers experience rapid melt, overtime as glaciers recede their contribution will significantly decrease. Hundreds of millions of people under severe water stress in a single location is a recipe for intense conflict and mass migration.

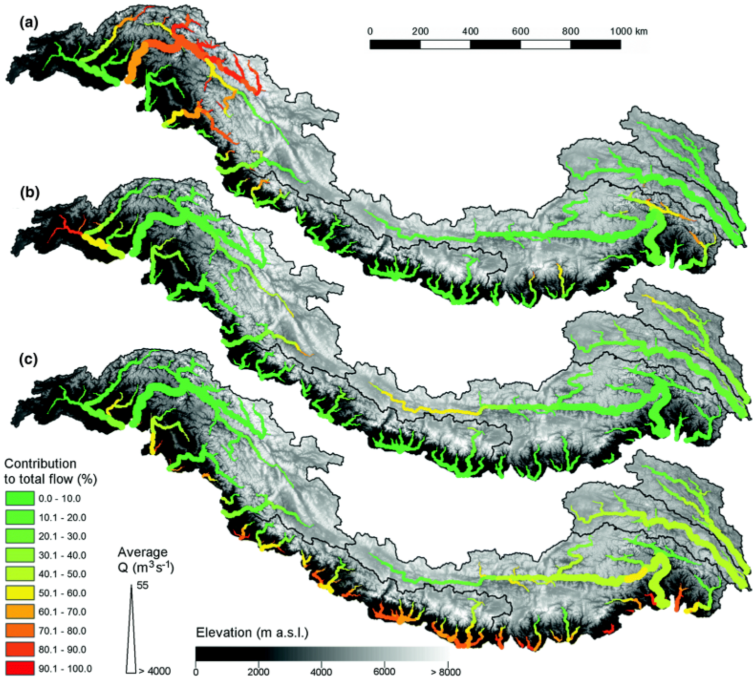


Figure 4: The Himalaya region. The Western basin is the Indus, followed by the Ganges and Brahmaputra to the East. Line thickness refers to the average total discharge, while color indicates the percentage of discharge that is contributed by each source. "Contribution to total flow by (a) glacial melt, (b) snowmelt, and (c) rainfall-runoff for major streams during the reference period of 1998–2007. Line thickness indicates the average discharge during the reference period" (Lutz, 2014)

While river basins, such as the Ganges and Brahmaputra, could attribute less of their annual flow to contributions from glacial melt than the Indus, seasonal variability is an important factor that requires further research in the Himalaya. For instance, in the Khumbu Valley, Nepal, a heavily glaciated catchment in the Ganges Basin, 80% of precipitation falls during the monsoon season in the months of June to September (Wood et al. 2020). The flow of the Ganges and its tributaries in non-monsoon months is much more likely to be sustained by glacial melt. For communities living in the high Himalaya catchment areas of those basins, such as the Khumbu Valley, glacial meltwater is critical in non-monsoon months. A study conducted in 2016-2020, found that 60% to 65% of the domestic water use in the region is sourced from glacial meltwater. In some communities, that number reaches 90% (Wood et al. 2020). Himalayan glaciers could lose two-thirds of their mass (calculated under the RCP8.5 climate model) by 2100 (Kraaijenbrink et al. 2017). In non-monsoon months, the 1.9 billion people that live in the shadow of the Himalaya, in glacial fed basins, could lose a majority of their freshwater access. Melting glaciers do not just pose water availability risks, but also geological hazards. Recently, a flood in the Indian Himalayas caused 50 fatalities, with another 150 still missing. The flood was caused when a massive overhanging glacier collapsed, causing a rock fall which sent tons of rock and ice debris flying into the valley below colliding with glacial sediment. This resulted in a large landslide that flowed into the Rishiganga River, causing the river to flood with a wave of rock and ice slush (Washington Post, 2020). Receding glaciers in the Himalaya are also uncovering a large number of pro-glacial lakes, which form at the tongue of glaciers. The increase in the number and volume of these lakes is increasing glacial lake outburst flood risks (Bajracharya et al. 2020) which can produce disasters like the deadly February 2021 flood in India.

In the Himalaya region, political conflict between the largest countries -- China, India, and Pakistan -- make coordinated research efforts difficult, if not impossible. This issue is compounded by the fact that the region's geology and geography is incredibly diverse and glaciology is a new science in the region. Much is not known about the Himalayan glaciers and their exact downstream impacts and how those impacts will vary under climate change. But the impacts are clearly significant and the consequences of change monumental, so further research is critical.

Impacts on agriculture: Wyoming

In the Indus River basin, glacial meltwater sustains a massive year-round agricultural economy. The size of the agricultural product produced, which can be attributed to glacial meltwater in the Indus River Basin, is hard to quantify. To better understand the impacts that glacial meltwater have on agriculture, we review a study conducted on the cattle industry and Wind River Range glaciers in the U.S. state of Wyoming. While a much smaller study area than the Indus Basin, Wyoming glaciers represent an intricate case study that is representative of our reliance on the many smaller glacial systems around the world. Wyoming contains the largest concentration of glaciers in the American Rocky Mountains, the vast majority of which occur in the Wind River Range in western Wyoming. Until recently, the glaciers in the area were largely unstudied. Among U.S. states, Wyoming ranks 8th in barley production and 20th in hay production, which is impressive given its small growing season of about two months or less. These crops feed Wyoming's cattle, which is an $800 million dollar business (Cheesbrough et al. 2009). The growing season coincides with maximum glacial melt, in late Summer to early Fall. Glacial meltwater from the Wind River Range supplies a steady and reliable source of water during these months. Fremont County, encompassing the Wind River Range to the east of their crest and the foothills and plains that follow, accounts for the majority of Wyoming's irrigation water use (Boughton et al. 2006). Seventy-seven percent of the glaciers of the Wind River Range are on the eastern slopes, where the streams and rivers of Fremont County are sourced (Vandeberg et al. 2016). The Wind River flows through Fremont County and supplies the vast majority of surface water to the region. Three of its major tributaries are sourced in glaciated catchments in the Wind River Range. During the late summer months and the Wyoming growing season, one of these tributaries, Torrey Creek, could attribute an estimated 82.7% of its flow to glacial meltwater, which in turn attributed to 10.32% of Wind River flow (measured upstream from next tributary) (Vandeberg et al. 2016). The second major tributary, Dineywood Creek, could attribute an estimated 53% to 59% of its flow in 2007, which was a dry year, to glacial meltwater (Cable et al. 2011). The third, Bull Lake Creek, could attribute 55.6% of its flow to glacial meltwater (VanLooy et al. 2019).

Glaciers in the Wind River Range decreased in mass by 25% from 1985-2005 (Cheesbrough et al. 2009). Given temperature and precipitation data since 2005, the glaciers in this range are likely experiencing their peak melt rate and will soon begin to decline. These contributions to the Wind River represent a significant enough portion of late summer surface water contribution to significantly impact agricultural production in the region, especially compounded by reduction in overall snowpack and precipitation. Changes in glaciers in the Wind River Range will also have impacts on the surrounding ecosystems, including the impact of reduced streamflow to the state's trout populations.

Impacts on fisheries: Washington Salmon

Another critical resource, and a keystone species of the American West, that depends on late summer flows from glacial melt are fish. I use “resource” not in its strictly economically centered definition, but to represent something whose value can be appreciated beyond financial value, with cultural and emotional value as well. The America West is known for its abundance of trout and salmon, which form the cornerstone of many indegenous cultures and countless fisheries, and serve as the backbone of the recreational sector. But this resource has been critically abused for over a century. Through population growth in the Western United States and the consequent increased demand for water during the 20th century, the federal Bureau of Reclamation was founded in order for water in the West to be "reclaimed" for beneficial economic use. Thousands of dams were built, daming nearly every single river in the West and creating tens of thousands of reservoirs. This was done without a single thought to the long-term economic viability of such development and with no concern for the ecosystems that would be impacted. As a result, countless ecosystems were destroyed or crippled. For salmon, this meant that they were obstructed from completing a critical part of their life cycle: spawning up river. The Columbia River that runs between the U.S. states of Washington and Oregon was once home to the world's largest and most diverse salmon runs, but is estimated that of the 10 to 16 million salmon that once spawned in this river, less than 2% remin today (New York Times, 2019). Dams and habitat loss pose a major threat to salmon. Dam removal projects are showing signs of hope in the return of salmon, such as the return of fish following dam removal in the Elwha River, Washington (Brenkman et al. 2019).

Salmon in the Pacific Northwest are facing another threat: decline in summer streamflow and subsequent water temperature increase. The state of Washington is expecting dramatic decreases in snowpack as the global temperature increases over the next few decades. The warm season (April to September), when streamflow is primarily influenced by snowpack melt and glacial melt, is expected to experience a 34% to 43 % decline by 2080 (Elsner et al. 2010). While the total annual streamflow is expected to increase on average 4% to 6% across the state by the 2080s, due to increased late fall and winter precipitation, the majority of the increase in precipitation in these months will fall as rain and, therefore, not contribute to the snowpack (Elsner et al. 2010). A study in the Nooksack River watershed inWashington highlights the importance of glaciers to summer/fall streamflow. The Nooksack River is fed by glaciers on Koma Kulshan (Mt. Baker), a heavily glaciated stratovolcano in the North Cascades. The Nooksack River watershed is separated into three basins: the north fork basin and middle fork basin are both glaciated, while the south fork is unglaciated. The glaciated basins and the unglaciated basin discharge does not significantly differ in winter/spring, but during late summer there is a significant difference in daily discharge, with the glaciated sub-basins receiving significantly higher daily discharge than the unglaciated sub-basin (Bach, 2002). High elevation snowsheds and glaciers in the north and middle fork basins contribute significantly to this late summer discharge. It is estimated that these contributions equal 30% of summer discharge in the entire Nooksack River basin (Bach, 2002).

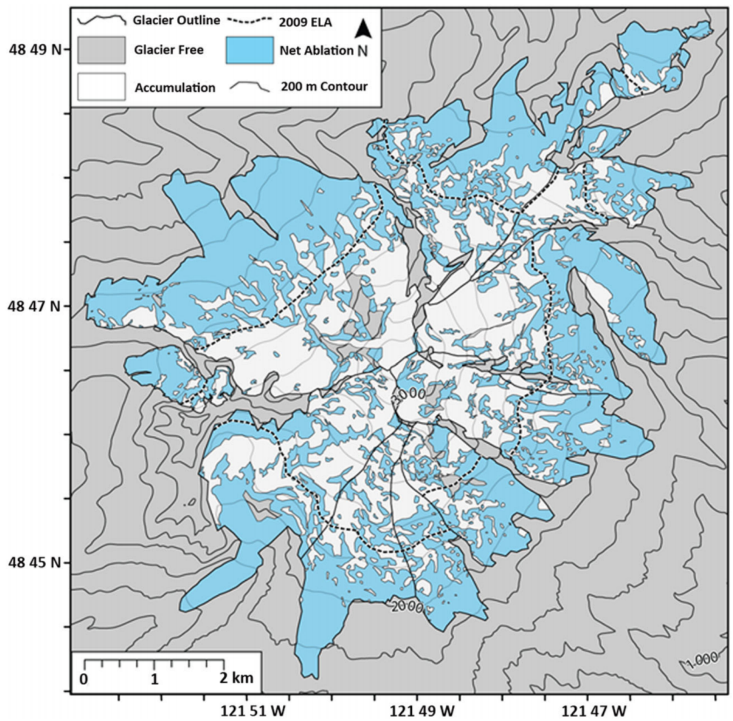


Figure 5: Accumulation area ratio (the ratio between a glacier's accumulation area, and total area.) observations are frequently below 30% on Mt. Baker.
Increase of ablation zone and decrease of accumulation zone is the clearest sign of a receding glacier.

(Pelto & Brown, 2012)

Glaciers on Mt. Baker had a negative mass balance entering the 21st century. From 1990-2010, glaciers on Mt. Baker lost 12% to 20% of their mass (Pelto & Brown, 2012). Under the RCP4.5 climate model, glacial extent in the North Fork Basin is estimated to decrease by 66% by 2099; under RCP8.5, it is estimated to decrease by 88% (Murphy, 2016). It is expected that glacial contribution to streamflow will increase mid-century then rapidly decrease as glacial mass is lost. As glacial mass is lost and snowpack decreases, late summer streamflows could be reduced by 40% in the Nooksack River by 2075 (Dickerson & Mitchell, 2013).

The Nooksack River watershed supports nine species of salmonids including populations of Chinook and Coho salmon. Chinook and Coho are already critically endangered in the watershed due mainly to habitat degradation. Already, current stream temperatures of the South Fork Nooksack frequently exceed 20°C, and sometimes exceed 24°C, well in excess of the temperature ranges considered optimal for Chinook incubation (11– 15°C) and juvenile rearing (14.2°C –16.8°C) (Beechie et al. 2012). Low summer flows will cause a lack of deep pools and side channels for habitat, and even further warming of stream temperatures due to increased air temperatures. High temperatures stress spawning fish and increase susceptibility to disease, which can cause pre-spawn mortality or otherwise reduce reproductive success. Continued increases in stream temperatures and reduced meltwater from glaciers due to climate change will further stress all nine species of Nooksack River salmonids during all of their life stages, including migration, spawning, rearing, and out-migration (Grah & Beaulieu, 2013).

Glacier Tourism: New Zealand

Glaciers provide more than a valuable source of freshwater. They also provide outdoor recreational opportunities, which in 2019 accounted for nearly $460 billion, or 2.1%, of the U.S. gross domestic product. Glaciers are direct and indirect contributors to revenue generated from tourism. For instance, Alaska's national parks generated $2 billion in 2018 (Koontz & Thomas 2019). Two of the most visited national parks, Denali National Park and Glacier Bay National Park, are heavily glaciated areas. These glaciers drive visitation and, in turn, generate revenue, as people wish to observe these glaciers. This is an indirect impact on tourism, as there are many other reasons people visit Alaska's national parks. However, there are many places where glaciers are the main reason for visitation and the direct source of revenue. Glaciers are dramatic and fascinating parts of our landscape and there are few places where glaciers are easily accessible. Visitors to Alaska's national parks get can within viewing distance of glaciers, but often not much closer, due to difficulty of access. Places where glaciers occur in accessible areas, or where infrastructure to reach glaciers has been built, often experience a growth or dependence on glacial tourism. Glacial tourism takes many forms, but often revolves around physically accessing the glacier. Popular forms of access include hikes to and on the glacier, ice cave tours, ice climbing, or access by boat/kayak to a glacier terminating into a proglacial lake. Glaciers are undeniably beautiful and stand in stark contrast to their surrounding landscapes, coupled with the sense of adventure that climbing/hiking on glaciers inspires, they create attractive destinations for tourists.

A study observed the impact of glacial retreat on glacial tourism in New Zealand (Purdie, 2013). New Zealand's southern alps are home to more than 3,000 glaciers (Chinn, 1999), three of which flow into low-lying valleys which make these glaciers easier to access. These glaciers, the

Franz-Joseph, the Fox, and the Tasman glaciers, have been supporting glacier related tourism since the late 19th century, which has only experienced significant growth particularly due to the influx of international tourists (Purdie, 2013). This growth in glacial tourism has generated $81 million in annual revenue in New Zealand and attracted 700,000 visitors to the glaciated region of New Zealand southern islands west coast (Purdie, 2013). However, these glaciers are receding. The Tasman glacier terminus has receded rapidly, leaving behind a proglacial lake into which the glacier now terminates. This lake did not exist in the late 20th century. The glacial retreat in recent decades has exposed a lake almost 7 square kilometers (Dykes & Brook, 2010). This event has created new opportunities for glacial tourism, including boat rides to the glacier's calving face, now terminating into the lake. The public knowledge of New Zealand's receding glaciers has also driven a phenomena coined “late-chance tourism” where people are attracted to landscapes that are disappearing or changing rapidly (Lemelin, 2010). This phenomena is not exclusive to New Zealand's glaciers, nor is it to glaciers. For instance, bleaching events in the Great Barrier Reef are driving an increase in tourism. Last Chance Tourism is driving an increase in methods used to access glaciers, as tour providers respond to the increase in demand. In New Zealand, helicopters are being used to bring tourists onto the Franz Joseph and Fox glaciers. As these glaciers recede, they are exposing steep and unstable slopes on valley walls normally held in place by ice (debutressing) and they have left behind large lateral moraines (Ballantyne, 2002). Both of these hazards increase the risk of rock fall and increase the risk of injury for anyone en route on foot to the glacial terminus. Methods used to increase safe access to glaciers, to accommodate the increase in “last chance tourism” visitation, can cause unintended environmental consequences. Consider the building and maintaining of roads and carbon emissions from an increased use of motorized vehicles, such as boats and helicopters, while these consequences have not been quantified, they are likely having an impact. The glacial tourism industry will adapt to glacial change and tourist operations will likely increase in size and revenue, at least while the glaciers remain. New Zealand is estimated to lose more than 80% of its glacial mass by the end of the century, according to IPCC reports (Marzeion, 2020) and glacial tourism cannot exist without glaciers.

Biodiversity & Endemic Species: Trinity Alps, CA

Glaciers are fascinating components of our environments and can harbor species endemic to specific glaciers. In the Trinity Alps in Northern California, the first major paper was published in 2020 concerning the remnants of two once active glaciers in these mountains. Unique climatic and topographic properties in the Trinity Alps once supported California's lowest elevation glaciers, the only glaciers in the state below treeline. But following California's devastating 2012-2016 drought, one of these glaciers melted away and the other broke apart, its ice now stagnant. The ice was found to harbour populations of a beetle (*Nebria praedicta*) that is endemic to the Trinity Alps, and thrives, fascinatingly, in ice and snow (Garwood et al. 2020). The beatles' survival is very much tied to that of the Grizzly glacier, whose stagnant ice points to a grim future. This ice is part of an incredible and diverse interconnected ecological system. The ice sources a stream in the high alpine ecosystem that forms a creek that flows down to the Trinity River, which is full of Chinook Salmon. These salmon swim past Redwood forests, containing the tallest and most carbon dioxide absorbent trees on earth. The Chinook Salmon's decaying body provides essential nutrients for the Redwood tree. In turn, the Redwoods provide habitat for the Chinook to spawn. A bit of that water, in which the salmon swim and the Redwood roots soak, came from the ice in the mountains above. That bit of water is a drop in a lake compared to the other surface water sources in the Trinity watershed, but it is still there. There have not been studies that have quantified the contribution of stream flow that can be attributed by the Grizzly glacier and it is likely not significant, but it is fascinating and tragic to think about how a dying glacier is providing a bit of life to the world's tallest tree. The glacier's immediate impact on its surrounding environment is much more significant. What cascading impacts could extinction of the ice-loving beetle have on surrounding ecosystems? What happens when such an incredible part of an environment vanishes, no matter how small its contribution to that environment may seem? There are countless species in countless ecosystems whose dependence on glaciers is similar to that of the beetle in the Trinity Alps, all are at risk.

What Glaciers can Tell us about the Past

Ice Cores

Glaciers do not just act as the thermometer of a changing world, they are also record keepers of past climates. Snow accumulation on glaciers traps bubbles of gas, that snow is then compacted and the air bubbles become trapped in ice. This process occurs annually on the glacier accumulation zone and the bubbles preserve within them a record of atmospheric composition from that year. Researchers are able to discern the annual layers in the ice due to annual variations in snowfall and snow accumulation on the ice. As the ice gets deeper and more compressed, layers can be harder to discern. Another way ice can be dated, especially in deeper ice, is through layers of ash that accumulate on the ice surface. Layers of ash often indicate major volcanic eruptions. Antarctica and Greenland are areas with the longest and best kept records of climate in ice, the oldest ice in Antarctica is estimated to be 800,000 years old (Augustin et al. 2004).

Ice cores present us with incredible amounts of accurate information that help us reconstruct past climates. Thicker layers indicate higher rates of snow accumulation and precipitation for the year being analyzed. Bubble free layers indicate melt years with higher summer temperatures, these layers form through to the percolation of meltwater through the snow then freezing. Although possibly the most valuable information is from the gaseous composition of the trapped air bubbles. By analyzing the carbon dioxide and overall greenhouse gas content of these air bubbles, researchers can discern the overall atmospheric greenhouse composition for the year they are analyzing, this has allowed us to reconstruct atmospheric carbon content dating back 800,000 years. This has allowed us to observe the massive impact anthropogenic emissions have had on current atmospheric carbon content.

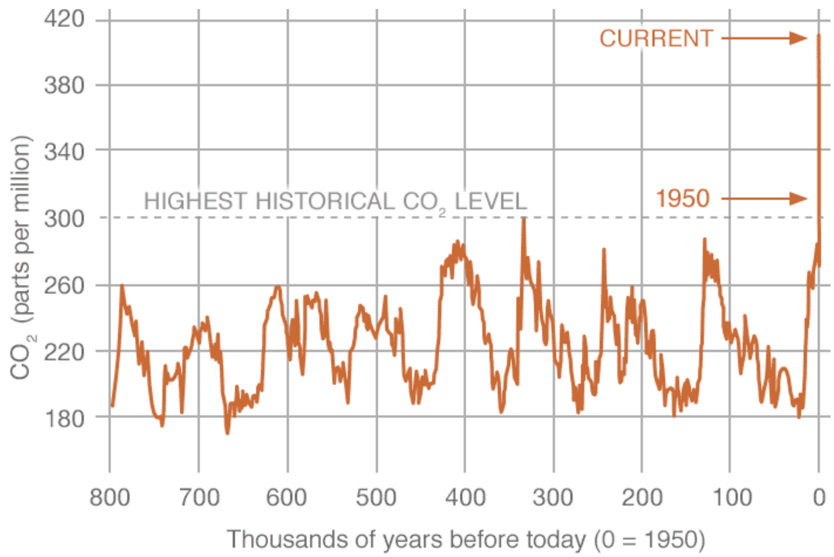


Figure 6: Atmospheric carbon dioxide content in parts per million over the last 800,000 years from data derived from ice cores. Historically carbon dioxide content never reached over 300 ppm, today it reaches over 400 ppm. (NASA)

Previously glaciated landscapes: Yosemite, CA

John Muir was one of the first people to understand the historic extent of glaciation in the Yosemite region of the Sierra Nevada range, California. A pioneer of his time, Muir spent five summers in the 1870's studying the remaining glaciers of Yosemite and observing the geological features of the mountains that indicated previous glacial extent (Muir, 1875). Wide U-shaped valleys of polished granite, sharp mountain ridges (arêtes), steep granite walls (El Capitan), large granite domes (Half Dome), hanging valleys (Little Yosemite Valley), and wide bowl-shaped cirques just below the mountain peaks, many such as Mt. Lyell, still glaciated. Muir discovered Lyell glacier when it was a mile wide and a little less than a mile long. He stuck wooden stakes into the ice and upon revisiting these stakes, he discovered this glacier was moving at about an inch a day. At the time, no one knew glaciers were present in the Sierra Nevada, much less that the valley was shaped by them. Muir published a revolutionary paper with his findings titled "Living Glaciers of California." In the paper Muir noted: "How much longer this little glacier will live will, of course, depend upon climate and the changes slowly effected." Lyell glacier is now stagnant and technically no longer considered a glacier, due to climatic changes (Stock et al.

2016). The Lyell glacier was one of the last remaining glaciers that formed during the Little Ice Age, that once carved the great granite formations of Yosemite national park.

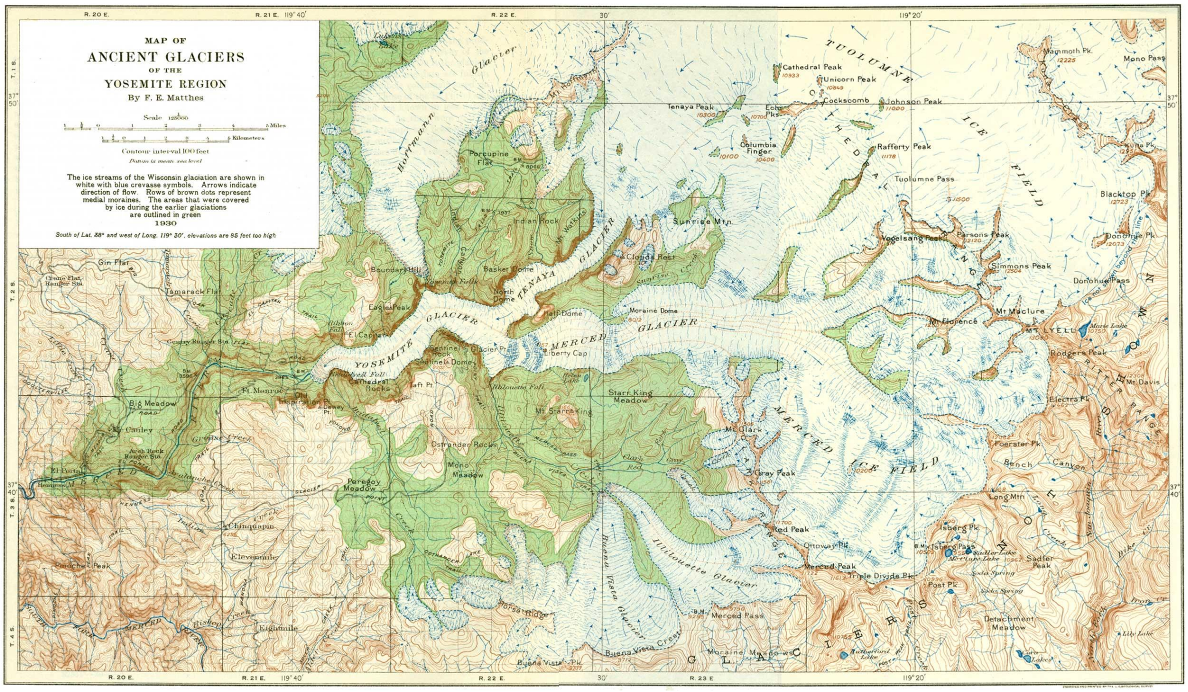


Figure 7: Topographic map of Yosemite national park during one of the last major glaciations highlighting previous glacial extent (USGS, 1930).

Yosemite is an excellent exhibit on how previous glaciations shape and completely transformed the landscape often in spectacular and dramatic ways. Mountainous regions all over the world have been shaped by glaciations from Mt. Kilimanjaro, Tanzania, to the Bolivian Andes. As the architects of the mountains, such as Lyell glacier, recede, more of these landscapes will be uncovered.

Glacial Impacts on Culture and Identity

Dr. M Jackson, an Oregon state-based glaciologist and leader in research concerning the cultural and spiritual perceptions of glaciers and glacial change, writes that glaciers are more than just single stories of melting ice. Glaciers represent so much more than global thermometers or climatological records: glaciers represent spiritual and cultural cornerstones of human life. But these stories are not often included in glaciological research. Jackson argues that this is due to a purely theoretical and eurocentric dominated field of glacial research and that incorporating a more open framework for researching glacial change could help integrate and understand the many stories of glacial change. Glaciology is a science founded in Europe, so it is understandable that it is dominated by eurocentrism. A more open framework investigates the epistemological questions relating to our gathering of glacial knowledge by investigating who has historically dominated the production of glacial knowledge, gendered structures in science, domination of eurocentric systems of science and alternative representations of glaciers (Carey et al. 2016). This framework presents us with a path to explore the perceptions of glaciers outside a single story of glacial change and explore glacial perceptions outside a purely theoretical view. For instance incorporating more qualitative knowledge in our understanding of ice could be of value to the field, for instance incorporating indegenous understanding of ice. This being said, quantitative evidence of glacial change is not to be undervalued by including these observations, rather put into context with broder stories of glacial change.

Indigenous Perspectives

Often missing from glacial science and glacier stories are indigenous peoples perspectives, it has been a science dominated by a eurocentric view (Carey et al. 2016). Many of the glaciologists and researchers I have mentioned thus far have studied ice through such a lens. But human interaction with ice goes beyond the study of changes in mass and its physical impacts, ice, especially through the stories of indigenous peoples, is interacted with through profoundly spiritual and emotional lenses. For instance in the Andes mountains of Peru, the Quechua peoples believe that a receding glacier on Mt. Ausangate near where they live, is a sign of the departure of their gods from the landscape and the introduction of a new Epoch (Allison, 2015). Tens of thousands of Quechua would take part in a pilgrimage to the glacier each year to honor the appearance of Christ on the mountain, part of the ceremony would be to take a chunk of the glacier back to share with family and livestock. In order to try and preserve the glacier, the practice of taking ice from the glacier has been banned (Allison, 2015). For peoples living on the Tibetan Plateau, Mount Yulong Snow, a glaciated peak in the region, is considered their spiritual home (Shijin & Dahe, 2015). The residents of this region have a deep understanding of climatic changes, over 97% of the population according to surveys conducted, understood they may need to leave their ancestral home once the glacier recedes due to climatic changes, which will impact the regions habitability (Shijin & Dahe, 2015). In Nepal, glacial recession is understood as a rebuke from the gods as humans move away from a moral life by polluting the planet (Allison, 2015). For many of these cultures, glaciers are understood as an *axis mundi*, a center of the world. Their recession represents the consequences of human immorality in regards to the treatment of the planet, a shift away from balance with the earth and spirituality.

Indigenous communities in North America have long perceived the connection between humans and glaciers. Indigenous communities in the Yukon interior and Alaska coast living amount the St. Elias mountains have long viewed glaciers as sentient beings. Glaciers can see, listen, smell and make moral judgments, they can take on bodily forms and transform. Surge glaciers, glaciers that rapidly advance without warning, are common in this region, and are believed to be the response of glaciers to human activities. The Lowell glacier is known as the Na`ludi by the Southern Tutchone peoples of Yukon. The Na`ludi means "fish stop" because it surged and blocked the salmon migration in the Alsek River (Cruikshank, 2012). It is believed to have done this in response to a colonial trader comparing the bald head of an indigenous shaman to the head of a glacier. It was listening, it made a moral judgment, and so transformed and surged.

The concept of glacier sentience is one that is recognized across cultures. Glaciers' constant and unpredictable movement, the otherworldly sounds they create and echo across the landscape, the glacial sourced creek ebbing and flowing like a heartbeat, and the collapse of seracs and calving of glaciers terminates to create powerful perceptions of sentience. Glaciers respond quickly to the world around them and with dramatic effect, such as we are seeing with global climate change. M Jackson writes in her book, *The Secret Lives of Glaciers*, "Perhaps thinking about a glacier's aliveness is to think about living, about what living means, about how we respond to the livingness of the world around us. In many ways, thinking about glaciers is also thinking about us." Glaciers have shaped human societies in profound ways, our existence very much intertwined, what we can take away from cultural and spiritual perceptions of glaciers is that this will always be so. Glaciers are much more than thermometers or record keepers, they are living representations of humans. There is no quantitative evidence to point to glacier sentience, but qualitative evidence, indegenous perspectives, show us the power of ice to influence cultures. Including this perception in our research of glaciers could deepen our understanding and our sense of dependence on glaciers.

Iceland

In the Fall of 2020 I travelled to Iceland on an undergraduate study program centered on climate changes impacts on the Arctic. I stayed in Hali, Hornafjörður, just a few kilometers from Breiðamerkurjökull. The following are my findings and observations as I researched the impact of glaciers to the geomorphology of the landscape and the lives of Icelanders.

Iceland presents us with a unique area in which the many impacts of glaciers experienced in different parts around the world are experienced all in one heavily glaciated area. Ten percent of Iceland's landmass is covered in glacial ice, 8% of which is covered by Vatnajökull, the largest icecap in the country and in Europe. Ever since Iceland was settled in the 9th century, people's lives have been heavily impacted by the country's constantly changing ice. This is especially true in Southeast Iceland, where people settled the thin stretch of coastline between the sea and Vatnajökull. People there have learned to adapt to the ever-changing ice and the hazards it poses to life on the island, such as sudden glacial outburst floods (jökulhlaup) and surging glaciers that plow over homesteads and farms. There are few places on earth where people have developed such a close connection to ice, sometimes living and farming within a few hundred meters of a glacier terminus, or unexpectedly closer. This has formed incredibly unique perspectives on glacial change during a time when Iceland's glaciers are receding faster than anytime in recorded history. These impacts are leaving profound scars on landscape and changing livelihoods -- as they always have, but current changes threaten to be permanent and highly consequential.

Geological Impacts

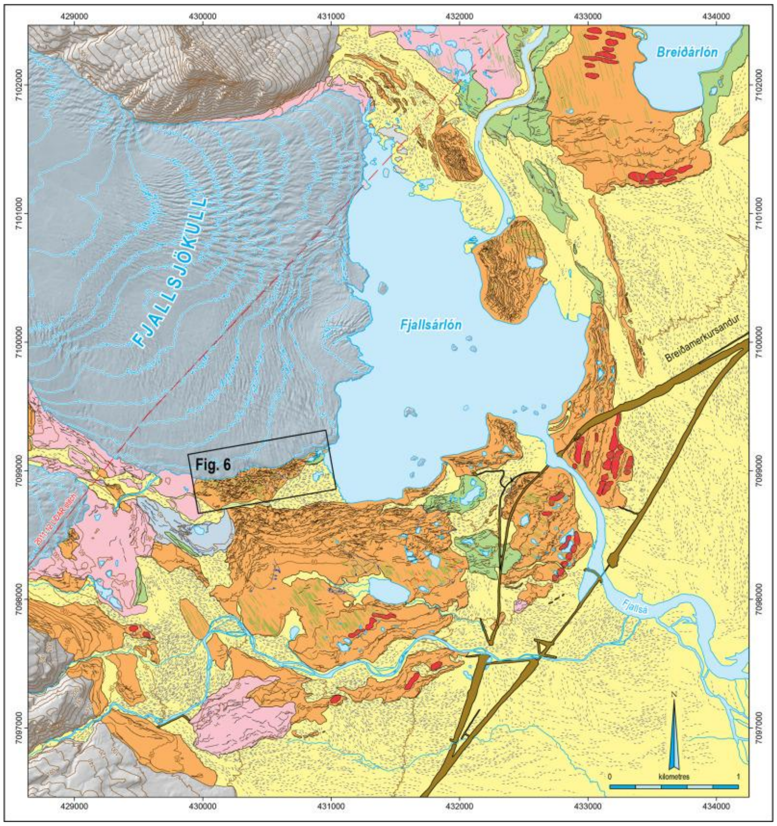
Since the mid 20th century, the post Little Ice Age retreat of Vatnajökull outlet glaciers has been increasingly influenced by anthropogenic forcing over natural forcing. Increasing temperatures since the industrial revolution have correlated with the increasingly rapid recession and loss of mass balance of Vatnajökull outlet glaciers, especially glaciers in southeast Vatnajökull in the Hornafjörður region. Rapidly changing glacial behavior has caused major changes to the proglacial landscape in the Hornafjörður. The glaciers leave behind their scars in the forms of moraines, eskers, and ever-moving glacial river networks spread across vast sandurs. Most recently, however, the receding outlet glaciers of Vatnajökull have revealed ever-expanding lakes, proglacial lakes, into which the receding glaciers now terminate (Schomacker, 2010). Of all of the proglacial lakes in Iceland, none are more vast or faster growing than the one formed by the Breiðamerkurjökull outlet glacier, which is simply called jokulsarlon or glacier lagoon (Evans, 2014).

Proglacial lake behavior is directly intertwined with glacial behavior and, therefore, directly linked to climatic changes (Carrivick, 2013). The formation of proglacial lakes can be attributed to the previous advance and subsequent retreat of glaciers. Advancing ice creates terminal moraines and the overdeepening of bedrock underneath the glacier. As the glacier retreats, it leaves behind the moraine and a depression in the surface between the glacial terminus and the terminal moraine created when it was at its furthest extent. Glacial meltwater becomes dammed by the moraine, as well as by the glacial terminus and pools in the depression, creating the proglacial lake (Carrivick, 2013). As for the outlet glaciers of Vatnajökull, the terminal moraine was created by the furthest extent occurred during the Little Ice Age. The most significant change and the defining factor [between natural recession] since the Little Ice Age is the change from land-terminating to water-terminating glaciers (Evans, 2014).

Natural and Anthropogenic, Post Little Ice-Age Recession

Glaciers in Iceland advanced during the Little Ice Age (LIA), a period of global cooling from 1300-1870 (Mckinzey, 2005). At the beginning of this period, Iceland's glaciers were smaller in size than they are today. A dip in temperatures of -0.6 degrees celsius, on average, in the northern hemisphere during this period triggered a massive glacial advancing event (Rafferty, 2011). The extent to which these glaciers advanced is well preserved in the geological record by the large terminal moraines near the outlet glaciers in southeast Iceland. During the LIA, the glaciers pushed up these terminal moraines as they advanced. Once the outlet glaciers began to retreat, they left behind clearly defined and orderly mounds of rock and debris that precisely marked their farthest extent (Evans, 2016). Glacial retreat after the LIA maximum was initially caused by what most scientists accept as a period of natural warming post LIA, at the start of the 20th century. But as we progressed into the early-mid 20th century, anthropogenic forcing became the primary influencing factor of the glacial retreat of Vatnajökull. The glacial recession now is driven by warming atmospheric temperatures caused by climate change, or the anthropogenic emissions of greenhouse gasses positively influencing the atmospheric greenhouse effect. Defining the periods of natural retreat and anthropogenic retreat in southeast Iceland since the LIA maximum is important in assessing the extent to which anthropogenic forcing is accelerating glacial retreat. Equally important, when assessing the differences between these periods, is predicting geomorphological changes to the pro-glacial landscape, such as the formation of proglacial lakes.

Focusing on the main outlet glaciers of the Vatnajökull icecap in the Hornafjörður region of southeast Iceland, it is possible to assess the varying position of the glaciers as they have retreated since the LIA. This assessment can be done by observing the geological features of the proglacial landscape (Evans, 2014). For instance, the most notable feature in a proglacial landscape is what is referred to as a moraine. In a proglacial landscape, the most common is a ground moraine, which is not as notably defined as its cousins, since it consists of unorganized deposits of rock formed as a glacier moves over a landscape. It is formed by sediment deposited underneath the glacier, by small streams or by the glacier hitting various landforms. Once the glacier retreats, the ground moraine is revealed. The most notable and easily spottable moraines in a proglacial landscape are terminal moraines and lateral moraines. Lateral moraines form at the sides of a glacier. As the glacier scrapes off rock from the sides of valleys, the debris is deposited along the valley sides when the glacier retreats (Evans, 2016). Terminal moraines form at the terminus of a glacier during a period of advancement. They are formed as the glacier picks up and moves debris while advancing and when depositing the debris at its terminus. From there the glacier retreats, leaving the terminal moraine. Terminal moraines provide the most accurate information on past glacial positions. Other proglacial landscape formations also provide hints about glacial activity, such as eskers, or piles of rock and sediment [that is, or was, ice-cored] (Chandler, 2020). Fig. 8 demonstrates how these formations are spread across a proglacial landscape.



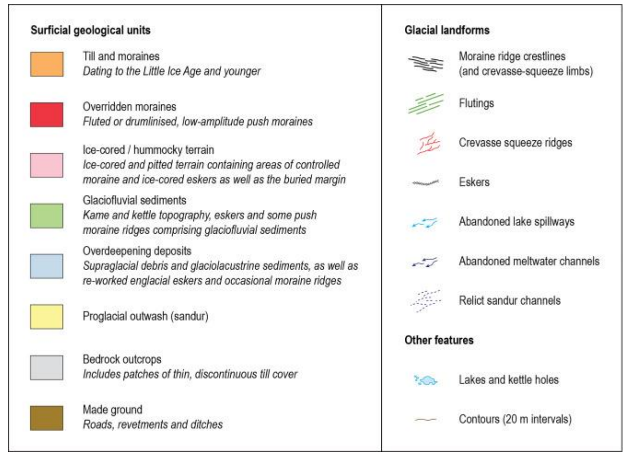


Figure 8 & 9: (Chandler, Benjamin M.p., et al. "The Glacial Landsystem of Fjallsjökull, Iceland: Spatial and Temporal Evolution of Process-Form Regimes at an Active Temperate Glacier.") Map of Fjallsjökull outlet glacier and pro-glacial landscape. Highlighted are the geological features that can help determine the previous position of the glacier terminus.

Determining the difference between anthropogenic recession and natural recession can be accomplished by analyzing temperature trends through the 20th century and comparing them to previous glacial positions at Vatnajökull. Since the end of the Little Ice Age, there has been an overall recession trend and, since the turn of the 21st century, this recession has accelerated. A trend emerges when comparing atmospheric CO2 concentration, global temperature, southeast Vatnajökull glacier terminus (Hoffellsjökull) and local climate. At the turn of the 21st century, as CO2 and average global temperature increased (due to anthropogenic emission), Hoffellsjökull's average summer temperature also rose, while the volume of Hoffellsjökull decreased. In Fig. 11, the data shows that decreases in the Hoffelsjökull glacier volume correspond to periods when local average temperatures increased, while Fig.10 shows similar periods of warming and cooling across the globe.

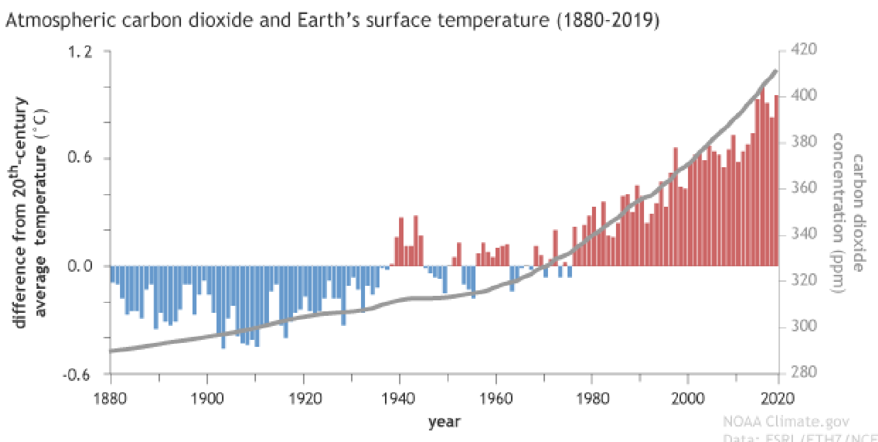


Figure 10: (NOAA Climate) Average global annual temperature compared to global atmospheric CO2.

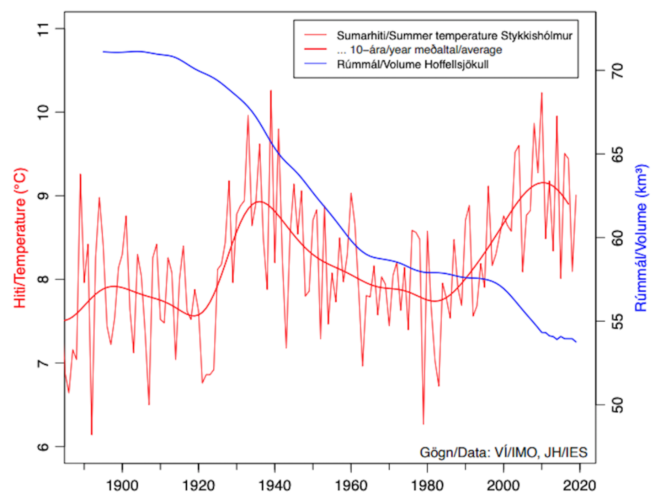


Figure 11: (Icelandic Meteorological Office: Melting Glaciers end of 2019 newsletter)
Volume of Hoffellsjökull glacier (Vatnajökull outlet glacier) in kilometers squared combined with local annual summer temperature from 1900-2020.

Proglacial Lake Formation & Glacial Behavior

Proglacial lakes in southeast Iceland form because of a process called overdeepening. Overdeepenings are subglacial basins that mark the area of maximum erosion in the bedrock due to valley glacier movement during a certain and extended period of glaciation. They occur at the equilibrium line of the glacier, between the accumulation and ablation zone, because this is the area of the glacier that reaches maximum velocity. The most erosion of bedrock occurs at this location because of the fast-moving ice (Evans, 2014). Bedrock that is picked up as debris at the area of overdeepening is carried and transferred to the terminus of the glacier, forming a terminal moraine which helps dam and deepen the depression. As the glacier exits this period of glaciation and retreats, the depression in the landscape is revealed. This depression fills with sediment and glacial meltwater, forming a proglacial lake. Many of the outlet glaciers in southeast Vatnajökull formed these depressions through overdeepening during their maximum extent in the LIA (Evans, 2014). Since the turn of the 21st century, these glaciers are revealing -- and terminating into -- their proglacial lakes.

Lake terminating glacier behavior differs from land terminating glaciers. Glacier ice terminating into water experiences accelerated movement and accelerated ice mass loss through many mechanisms. Mainly, liquid water maintains heat better than ice, therefore, lake contact with ice will enhance melting (thermo erosion). Also, the formation of basal crevasse due to thermo erosion and accelerated movement increases the likelihood of calving. Lake terminating glaciers are buoyant and proglacial lake level fluctuates, further stressing the glacier, increasing movement and crevasse development (Carrivick, 2013).

Future of the Southeast Iceland Landscape

The future of southeast Iceland will inevitably include much less ice. Even if anthropogenic greenhouse gas emissions are immediately and drastically cut, feedback loops will continue to increase temperature to melt a majority of the ice mass of Vatnajökull and certainly the outlet glaciers of southeast Vatnajökull (Björnsson et al. 2008). This glacial recession will reveal the proglacial lakes that are now partially, or nearly, covered by ice, such as those surrounding Oraefajökull in Fig 12.

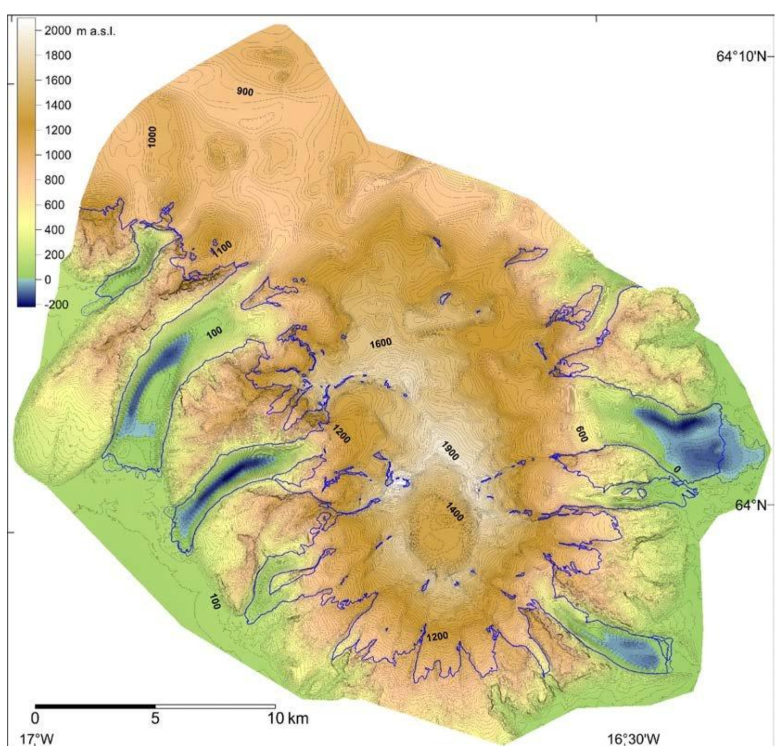


Figure 12: (Magnússon, Eyjólfur, and Finnur Pálsson. “Removing the Ice Cap of Oraefajökull Central Volcano, SE-Iceland: Mapping and Interpretation of Bedrock Topography, Ice Volumes, Subglacial Troughs and Implications for Hazards Assessments.” *Jökull*, vol. 62, 2012.)
A topographic map of the bedrock of Oraefajökull, the blue shaded areas indicate depressions in the bedrock, areas of overdeepening, dug by outlet glaciers. The blue lines indicate current ice extent.

Iceland is a highly volcanically active island, with the most significant recent eruption occurring in 2010. The eruption of Eyjafjallajökull, a glaciated volcano in southern Iceland, occurred in April 2010, and resulted in the near complete grounding of flights in Europe as the ash cloud covered most of the continent for one week following the initial eruption. In Iceland, the eruption triggered massive glacial outburst floods (jökulhlaup) that flooded rivers and glacial outwash plains (sandur). Jökulhlaups often occur in Iceland due to the rapid melting of ice over a volcano due to an eruption, or the burst of an ice dammed proglacial lake. Throughout Iceland's history, early settlers and current residents alike have had to adapt to these relatively frequently occurring floods, which have destroyed infrastructure, homes, and farmland. Most of Iceland's major volcanoes are covered by glacial ice. For instance, the highly active volcanoes of Grímsvötn and Bárðarbunga both lie under Vatnajökull. Melting glaciers in Iceland, and the subsequent loss of ice mass resting on top of the island's volcanoes, could increase volcanic activity. During Iceland's last cooling period, between 5,500-4,500 years ago, there was significantly less deposits of volcanic ash, suggesting that an increase in ice mass correlates with a decrease in volcanic activity (Swindles et al. 2017). This is because Iceland's glaciers act as a bottle cap on the country's volcanoes, suppressing volcanic activity. Therefore, the removal of this cap could, the melting of the ice, could reduce volcanic suppression and increase activity, possibly leading to more frequent high severity eruptions such as the 2010 eruption of Eyjafjallajökull.

Another way in which Iceland's decreasing ice mass is impacting the country is through isostatic rebound. Isostatic rebound occurs when the weight of ice is removed from a part of the earth's crust and causes the land to rise. During glaciation, the downward pull of the weight of the ice causes the crust underneath to sink into the lithosphere (isostatic depression). When the weight is removed during periods of deglaciation, the crust rebounds and rises. In Iceland isostatic rebound is occurring at an incredible rate and accelerating every year as ice from the island's major ice caps melt away. Currently uplift rates in central Iceland and the surrounding area exceed 30mm/yr and are projected to exceed 40mm/yr in the next few years (Compton et al. 2015). A port in the town of Höfn, southeast iceland, is rising much faster than current sea level rise, and many of the fishing boats are now unable to enter the port at low tides, disrupting the local fishing economy upon which it relies.

Cultural Impacts

Icelanders live with changing glaciers and are raised hearing stories of glaciers that either rapidly advanced or retreated. This has created an interesting perception of glacier change among Icelanders. Many, of course, recognize the dramatic impact climate change is having on their ice. In 2019, about 100 people held a funeral for Okjökull, a glacier that had recently melted away, placing a bronze plaque where the glacier once stood. The plaque read, "In the next 200 years, all our glaciers are expected to follow the same path. This monument is to acknowledge that we know what is happening and what needs to be done. Only you know if we did it." But many do not share the same perception of glacier change. Interestingly, different perceptions of glacier change are observed in the coastal communities of the Hornafjörður region, where residents live just a few kilometers from Vatnajökull. In 2016, glaciologist Dr. M Jackson was living in the Hornafjörður region exploring Icelanders perceptions of glacial change, which she recorded in her book *The Secret Lives of Glaciers*. Many who live here grow up with stories of their ancestors and relatives farms and homesteads being washed away by jokulhaups or plowed by advancing glaciers. Many of the elders live with fresh memories of such incidences. Glaciers present a constant struggle to the region, a constant battle with the elements, and many are relieved by the receding glaciers no longer threatening their livelihoods. Others are so used to glacier change and stories of glaciers receding and advancing that they believe climate induced changes to Iceland's glaciers are just part of the cycle, saying that glaciers have always been changing. Breiðamerkurjökull means "broad forest glacier" in Icelandic. At the time of settlement Iceland's glaciers were smaller than they are today. A forest of native birch once stood where the glacier is today, a period of global cooling caused the glacier to advance over this forest. Today that glacier is receding again, leaving a large sandur where birch sprouts are beginning to grow once again.

Iceland's Booming Tourism

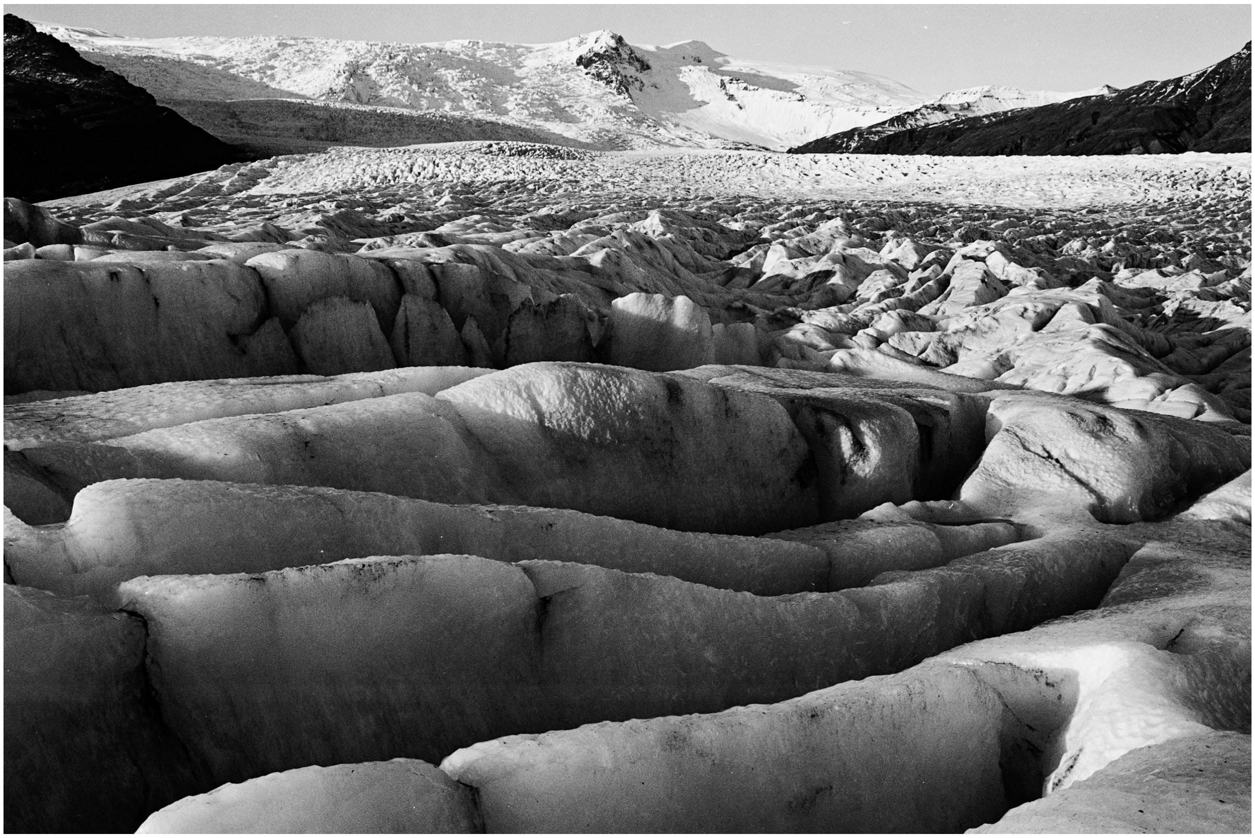
In Iceland, perceptions of glacier change are also being shaped by the growth of glacier tourism in the region. Tourism in Iceland has skyrocketed during the recent decade to become one of its highest grossing economic sectors, leading Iceland's economy to be highly dependent on tourism. Of all of Iceland's attractions, Vatnajökull National Park has attracted the most visitors, especially Jökulsárlón, the ever expanding proglacial lake that fills with icebergs calving from the outlet glacier Breiðamerkurjökull. This has created many new economic opportunities for Icelanders and currently employs thousands. As glaciers in Iceland recede, tour providing operations are becoming increasingly aware and constantly adapting to the impacts of climate change. And as the knowledge of rapid glacier recession in Iceland grows, tourism to Iceland's glaciers increase as people wish to experience the ice before it leaves (Welling et al. 2020). Creating a sort of ironic situation as the emissions from transport to Iceland and the glaciers contributes to the greenhouse effect melting the ice. Some tour operations, such as Glacier Adventure, run by Haukur Ingi Einarsson in Hali, are increasingly focusing on educationally centered tours hoping to increase awareness of climatic changes and glacial recession and are conscious of their carbon footprint as well as their impact on the landscape. But many of the larger tour operations primarily focus on getting as many clients to the ice as possible creating large crowds, a heavily trodden landscape, and much waste for an area that cannot sustainably handle the influx of people. Although the pandemic has created a pause in tourism, while economically devastating, it has given the national park time to consider sustainable paths forward for the region.

PHOTO ESSAY: VATNA > JÖKULL

Perhaps thinking about a glacier's aliveness is to think about living, about what living means, about how we respond to the livingness of the world around us. In many ways, thinking about glaciers is also thinking about us.

- Dr. M Jackson

In Fall 2020, I travelled to Iceland on an undergraduate study program centered on climate changes impacts on the Arctic and stayed in Hali, Hornafjörður, just a few kilometers from Breiðamerkurjökull. I was quickly exposed to islands changing glaciers and to the lives of those who centered around glaciers. Through experiencing and learning about Icelanders interaction with glaciers and perceptions of glacial change, I developed a sense of how powerful these bodies of ice were. Coupled with moments walking along the ice, the crunch of my crampons interrupted by the deep and full echos of moving ice, pulsating glacial streams, and the loud thud of ice calving off the glacier terminus and into the water, I began to understand why some Icelanders perceive glaciers as alive. The intense beauty of the ice that would stop me in my tracks, as I paused to breathe with the glacier, to feel and listen to its heartbeat, and try and comprehend what was before me. This glacier demands my respect, our fates tied together, and through that connection, it was hard not to feel its aliveness myself. With the photographs I captured, with my 35mm Canon AE-1, I hope to capture that feeling….



Conclusion

The case studies that have been presented are only a few of the many examples of the impacts of glacial change, every place on earth will be impacted by glacial change either directly through downstream changes or indirectly through global changes. There are countless stories to tell about how people interact and connect with ice. Our understanding of glaciers must dramatically improve if we are to best prepare ourselves for the inevitable changes that will occur. Our understanding must be rooted in stories that help connect people with ice and our dependence on it as much as it must be rooted in our physical understanding of ice. It is through our increased connection with, as well as understanding of, glaciers that we may come to better adapt to the changes that will occur and try to prevent the total loss of our planet's diverse and magical ice.

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There are so many people I wish to thank in my process of developing my understanding of glaciers and glacial change, and the incredible places it has taken me and the soul filling experiences it has exposed me too. My mothers for their never-ending support of my passions. Jordan Hanson, my mentor, who has guided me through this work and whose own work in Antarctica has inspired mine. Cheryl Swift, for expanding my capabilities in field work and showing me the joy of working in the field. Haukur Igni Einersson, owner and operator of Glacier Adventure, for inviting me to Hali, Iceland to experience the glaciers of his homeland and generously providing a helping hand whenever it was needed. My thanks, as well, to Mike Reid, lead guide at Glacier Adventure, for showing me how to properly travel and climb across glaciers and have a whole lot of fun doing it. My thanks to Þorvarður Árnason, for showing me the beauty of working at "the border of art and science," whose photographs of the glaciers of Iceland are and will continue to be an inspiration. To Whittier College, NOLS, and SIT: Study Abroad for providing me with the opportunities to discover my passion for glaciers. My family and friends, whose adventurous spirits and full hearts make life exciting and meaningful.

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