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Using Repeat Photography to Document the Effects of Climate Change on Glaciers in Iceland Change on Glaciers in Iceland

Madeleine Gassin

USING REPEAT PHOTOGRAPHY TO DOCUMENT THE EFFECTS OF CLIMATE CHANGE ON GLACIERS IN ICELAND

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Senior Honors Thesis: Environmental Studies

Using Repeat Photography to Document the Effects of Climate Change in Iceland

Madeleine Gassin (2023/2024)

ABSTRACT

Climate change is a worldwide, multifaceted phenomenon that impacts our world today and will continue to impact our world in the future with even greater severity. Although climate change can sometimes be considered an abstract topic due to its being somewhat intangible, one direct way of observing the effects of climate change is by studying glaciers. This study combines a literature review with repeat photography in order to demonstrate the tangible effects of climate change on glaciers in Iceland and explore the secondary impacts on sea level elevation (SEL), water availability and distribution, hydropower, natural hazards, and tourism in Iceland. The literature review explores past research on both short-term and long-term glacial changes as well as future glacial change projections in Iceland. Results of the literature review showed a general consensus that Iceland's glaciers have been steadily declining since the early 1990s, with one study even determining that over a 129-year study period, half of the observed mass change on Vatnajökull glacier in Iceland (-240 +/- 20 Gt) occurred during geological years 1994/1995 and 2018/2019 (Aðalgeirsdóttir, G. et al., 2020). For repeat photography, the outline of Vatnajökull glacier from photographs taken in 2013 and 2023 were compared, showing a general trend of glacial volume loss occurring throughout the 10-year period, aligning with the results of the literature review. By using the highly visual nature of repeat photography and combining it with the review of previous glacial research, this study allows for scientific research surrounding the effects of climate change on glaciers to be easily visible to the general public, thus rendering a previously considered intangible concept tangible. This study may, therefore, be seen as a starting point for bridging the gap between scientific discourse surrounding climate change and information for the general public

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1. INTRODUCTION

Glaciation is a powerful geomorphic process that has historically shaped many of the landscapes that we know today. Although glaciers once covered approximately eight percent of the earth's surface in the Last Glacial Maximum (LGM) (US Geological Survey, 2023) glaciers today are primarily considered to be Arctic and Antarctic features. Although they have always been the source of interesting studies, in recent years, stories about glaciers have been especially salient, most likely due to an increased interest by the public in the effects of climate change. Climate change, a process where increasing greenhouse gas emissions since the Industrial Revolution has increased our planet's greenhouse effect, has not only led to a warmer global climate but has also increased the melting rate of glaciers all around the world. However, while a warming climate is largely considered to be a global phenomenon, its effects have been documented to be more intense in higher northern latitudes as a result of the Arctic Amplification Effect, a process that is primarily driven by the loss of sea ice greatly lowering the region's albedo, or reflectivity (Icelandic Met Office, 2018; NASA, Earth Observatory, 2023). As the region's albedo is lowered, its ability to reflect solar radiation back into the atmosphere is hindered and therefore increases atmospheric air temperatures (Serreze and Barry, 2011; Iceland Met Office, 2018). In fact, in the last few decades, the rate of warming in Iceland, and more generally in the Arctic, has been documented to be well above the global average (Figure 1, NASA, Earth Observatory; Icelandic Met Office, 2018). In an effort to demonstrate climate-change induced glacial retreat in Iceland, this study combines an analysis of previous glacial studies with repeat photography.

Despite efforts of global policy attempting to limit global temperature rise as a result of climate change to 1.5°C, the world has seen insufficient environmental action. Almost eight years since the Paris Agreement, the first global stocktake revealed that while countries have taken widespread action to try to combat climate change, the world is not on track to meet its Paris Agreement goals (UNFCCC, UN Climate Press Release, September 8, 2023). Although the effects of insufficient climate action can be seen all over the world, these effects are sometimes difficult to recognize as being directly related to climate change. Glacial retreat can therefore be considered a unique effect in that it is extremely visual by nature, especially in areas where glaciers are an important part of the landscape's identity or of the area's culture.

As glaciers continue to retreat all over the world, studies project that approximately two thirds (68%) of all land-based glaciers may disappear by 2100 (Rounce et al., 2023). According to the study, the world is currently on track for a 2.7ºC temperature rise since pre-industrial times, which would lead to losing 32% of the world's glacier mass and contribute to around 115 mm +/- 40 mm in sea level elevation (SLE) (Rounce et al., 2023). However, while glaciers around the world are feeling the effects of climate change, the effects have been especially strong in the Arctic and Antarctic regions. In fact, in Iceland, located near the margin of the Arctic Circle and where glaciers are a key feature of the landscape, the general public has already observed their glaciers' continuous retreat.

In 2019, Iceland held its first funeral for Okjökull glacier in which around a hundred people hiked up to the glacier to hold a ceremony (France-Presse, 2019). A bronze commemorative plaque was also mounted on a bare rock where the glacier once stood (France-Presse, 2019). While Okjökull glacier measured 16 square kilometers in 1890, by 2012 it covered only 0.7 square kilometers before finally being stripped of its title as a glacier in 2014, a first for Iceland (France-Presse, 2019). Julien Weiss, an aerodynamics professor at the University of Berlin, who attended the ceremony in 2019 states that while "You don't feel climate change daily, it's something that happens very slowly on a human scale, but very quickly on a geological scale" (France-Presse, 2019). While climate change may be something that feels somewhat obscure for most of the population, since it is difficult to see the exact effects in our everyday lives, as Professor Weiss states, "Seeing a glacier disappear is something you can feel, you can understand it pretty well and it's pretty visual" (France-Presse, 2019).

Glacial retreat can therefore be said to be a very visual effect of climate change, especially in landscapes where glaciers seem to be an important part of the landscape's identity. However, in addition to changing the aesthetics of a landscape, climate-induced glacial retreat is projected to not only contribute greatly to global sea-level rise, but also have severe global impacts on water availability, hydropower production, natural hazards, and tourism (Compagno et al., 2021). As glacial ice continuously melts, part of the mass that the glacier loses is transferred to oceans. Since more mass is being added to our oceanic systems, sea-levels rise. Additionally, as sea temperature also rises, individual water molecules gain more energy and therefore move more rapidly, which results in water molecules being farther apart thus causing the initial water volume to increase. Consequently, this temperature dependency leads to the expansion of water molecules already present in our oceans due to increasing ocean temperatures only further accelerates global sea-level rise. Although sea-level rise is primarily impacted by water mass being added to oceans through the melting of large ice caps, such as those found in Greenland and Antarctica, smaller glaciers and ice caps like those found in Iceland still contribute (Icelandic Met Office, 2018).

However, while glacial melt in Iceland may contribute to global sea-level rise, it has somewhat of the opposite effect on Iceland itself. The loss of mass from Icelandic glaciers has led to crustal uplift, in which the elevation of the earth's surface increases due to a decrease in downward force, which can be seen in much of the interior of Iceland as well as near the south-east and southern coast near Vatnajökull (Icelandic Met Office, 2018). An Icelandic climate report from 2018 states that measurements south of Vatnajökull have shown a 20 mm/year and continuous GPS measurements from Höfn, a harbor town southeast of Vatnajökull show a steady uplift of over 10 mm/year (Icelandic Met Office, 2018). The effects of this uplift can be seen in Figure 2, depicting a marine terrace near Snæfellsjökull, on the southern coast of Iceland. The presence of the marine terrace demonstrates a previously higher sea-level elevation than currently, most likely due to deglaciation-induced crustal uplift. Additionally, the decrease in sea-level elevation in Iceland is further impacted by the melting of Greenland's ice sheet, which is so large that it is associated with a significant amount of gravity (Kottasová and Doran, 2022; Icelandic Met Office, 2018). In fact, according to Thomas Frederikse, a postdoctoral fellow at the NASA Jet Propulsion Laboratory, "The ice sheet is so heavy that it pulls the ocean towards it, due to gravity. But if the ice sheet melts away, this attraction starts weakening and the water moves away. […] The farther away you are from the ice sheet, the more water you get" (Kottasová and Doran, 2022). In fact, according to the National Snow and Ice Data Center, the melting of 166 Gt of ice per year of Greenland's ice sheet could correspond to as much as a 0.60 mm drop in sea-level elevation per year surrounding Greenland's coast (Michon, 2023).

As a result of this decrease in sea level, in harbor towns like Höfn, ships are having an increasingly difficult time coming into the harbor due to their keels (the bottom of the ship) coming increasingly close to the ground (Kottasová and Doran, 2022). Thus, according to Þorvarður Árnason, director of the University of Iceland's research center in Höfn, while sea level continues to drop, the danger of the keels of ships hitting the bottom, possibly leading to leaks in the hull, financial loss, or even shipwreck, increases (Kottasová and Doran, 2022).

Furthermore, as a drop in sea level would impact Iceland in its entirety, the increased danger and difficulty in fishing could have a major impact on the country's economy, which heavily relies on marine product consumption and export (Iceland Responsible Fisheries, 2023). As glaciers' crustal uplift in Iceland and the melting of Greenland's ice sheets decreasing gravity effect lowers sea levels in the Arctic, the impacts on the Icelandic fishing industry may continue to worsen. However, while Iceland will have to cope with decreasing sea levels, other parts of the world will be subjected to a rise in sea-level elevation due to the increased water volume from both glacial ice melt and from displaced water from the Icelandic shoreline.

In addition to sea level rise, global glacier decline is expected to have severe impacts on water availability and security for many communities. Glacial melt can affect river runoff and contribute to freshwater resources available for communities (drinking water, irrigation, etc.). As glaciers decline in response to climate change, meltwater is released from "long-term storage" from the glacier (IPCC, 2023). Although the release of meltwater from storage initially results in an increase in glacial runoff (peak water), thus increasing the flow of glacial rivers, glacier runoff and its contribution to river flow downstream will eventually decrease due to the shrinkage of the "glacial reservoir" (IPCC, 2023; Davies, 2022). As the glacial influence on river flow decreases and eventually disappears, water availability may become more seasonal than before and may lead to droughts in dry years or dry seasons (Davies, 2022).

Although the impacts of glacial melt on water availability in Iceland may not be as severe as for communities in mountainous tropical and subtropical regions (Andes, Himalayas, among others), glacial retreat has still lead to significant changes in hydrological conditions for the Icelandic landscape. In Iceland, as the course of glacial rivers has been altered, new pro-glacial lakes have been formed and existing ones have either grown or dried up, possibly affecting communities' future water sources and reliability (Icelandic Met Office, 2018). These hydrological changes to water distribution, availability, and reliability may prove to be especially important for Icelandic hydropower production, farming, and cattle-raising. Despite an increase in glacial runoff leading to an increase in potential hydropower production, current Icelandic power plants and electricity distribution systems are not equipped to capture this potential energy production increase (Icelandic Met Office, 2018). Although changes to this system have been planned in order to capture this increase, Iceland's current energy system would only be able to capture a fraction of the total increase (Icelandic Met Office, 2018). Additionally, changes in hydrological conditions due to increased glacial runoff, such as altered courses of glacial rivers, may further impact hydropower production and increase hydrological variability (Schaefli et al., 2019). Furthermore, as glaciers continue to retreat, glacial runoff will also decrease and eventually stop completely. Although runoff will continue due to snowmelt and groundwater sources, the absence of glacial runoff would result in a greatly decreased water volume, thus requiring important changes in Iceland's energy system, which relies heavily on geothermal and hydroelectric power production (27% and 73% respectively according to Iceland's Ministry of the Environment, Energy, and Climate, 2023).

While the effects of glacial retreat on sea level, water availability, and hydropower production are already significant, their impacts do not end with these topics. Although natural hazards are expected to increase due to general climate warming, their increasing risk of frequency and severity are also directly linked to glacial retreat (Icelandic Met Office, 2018). While the thawing of permafrost may lead to destabilization of slopes and therefore increase the risk of landslides, the effect is reinforced by the destabilization of steep slopes that were previously supported by the retreating glacier (Icelandic Met Office, 2018). This increased risk of landslides is even more concerning in areas where landslides would intersect with pro-glacial lakes, potentially extending the slide run-out and resulting in catastrophic flooding (Icelandic Met Office, 2018). Additionally, as deglaciation and a warmer climate may allow the Icelandic landscape to produce more shrubbery, the risk of wildfires in Iceland is also expected to increase (Icelandic Met Office, 2018).

Another important natural hazard to consider regarding deglaciation in Iceland is the risk of volcanic eruptions. Although volcanic eruptions may seem unrelated to glaciers, as one is a system that functions under the earth's lithosphere and the other occurs on the earth's surface, the two may be more interrelated than previously thought. In Iceland, many volcanoes are located underneath glacial ice. In fact, according to the UNESCO World Heritage Convention, Vatnajökull glacier alone numbers eight subglacial volcanoes. As glacial ice retreats and ice mass is lost, lithostatic pressures on subglacial magma chambers will decrease, leading to an increased rate of magma production, which could lead to more frequent or longer-lasting volcanic eruptions (Icelandic Met Office, 2018). As a result, rapid deglaciation may actually promote volcanically generated jökulhlaups, a kind of glacial outburst flood in which a large amount of water is subglacially released due to the heat emitted from subglacial volcanoes (Bierman and Montgomery, 2014). These increased risks of jökulhlaup frequency and severity could have catastrophic consequences on the Icelandic landscape as a single jökulhlaup may result in a flattened landscape, the destruction of vegetation and wildlife, and may even result in the loss of human life (Bierman and Montgomery, 2014).

Some of the changes in the Icelandic landscape that are currently occurring due to climate change and will continue to do so in the future may also have implications for Iceland's overall economy. Although acute disasters such as a large jökulhlaup would most likely negatively affect the country’s economy due to loss of infrastructure and general repair costs, the slower process of glacial recession, in general, may also have an important impact. According to the OECD (Organization for Economic Cooperation and Development) Library, tourism in Iceland accounts for approximately 39% of the country’s economy. However, tourist destinations in glacial environments heavily rely on the presence of ice for their attractiveness to tourists (Welling et al., 2020). Although the prospect of retreating glaciers may serve as a motivator for tourists to visit Iceland, glacial retreat also triggers certain hazards, like falling boulders or cave-ins, and hinders glacial accessibility and impacts the aesthetic view of the landscape (Welling et al., 2020). Additionally, as glacial retreat continues to progress and some of Iceland’s most famous features, like Jökulsárlón glacial lake, change or disappear, Iceland may, in turn, lose some of its most famous tourist attractions associated with them (such as ice cave exploring, glacier hiking, ice climbing, etc.) (Vargas, 2017). Although there is little research in how the loss of glaciers in Iceland will affect global tourism, it is possible that these losses could further impact Iceland’s total attractiveness as a tourist destination and thus negatively affect the country’s economy.

The significant projected and observed impacts of climate change-induced glacial retreat in Iceland would suggest the importance of the subject being studied thoroughly. While many studies have used remote sensing and modeling data to observe glacial change over specific periods of time (Chandler et al., 2016, Ingólfsson et al., 2016, Aðalgeirsdóttir et al., 2005) very few studies have combined visual representations of climate change induced glacial retreat with scientific data. In an attempt to bridge this gap, this study uses a combination of literary review and repeat photography to determine the effects of climate change on glaciers in Iceland. The first section of the research in this paper will focus on a literary review whereas the second part will demonstrate the findings of the repeat photography. Four different Vatnajökull outlet glaciers were photographed in an effort to present the rapid decline of Icelandic Glaciers: Breiðamerkurjökull, Fjallsjökull, Hoffelsjökull, and Skaftafellsjökull. The baseline images used in this study were taken in the summer of 2013 by Professor Doug Thompson and the repeated images were taken in the late winter of 2023 by Madeleine Gassin. Finally, the last section of this paper will synthesize the findings of the literary review with the findings of the repeat photography as a tool for communicating the effects of climate change on glaciers in Iceland.

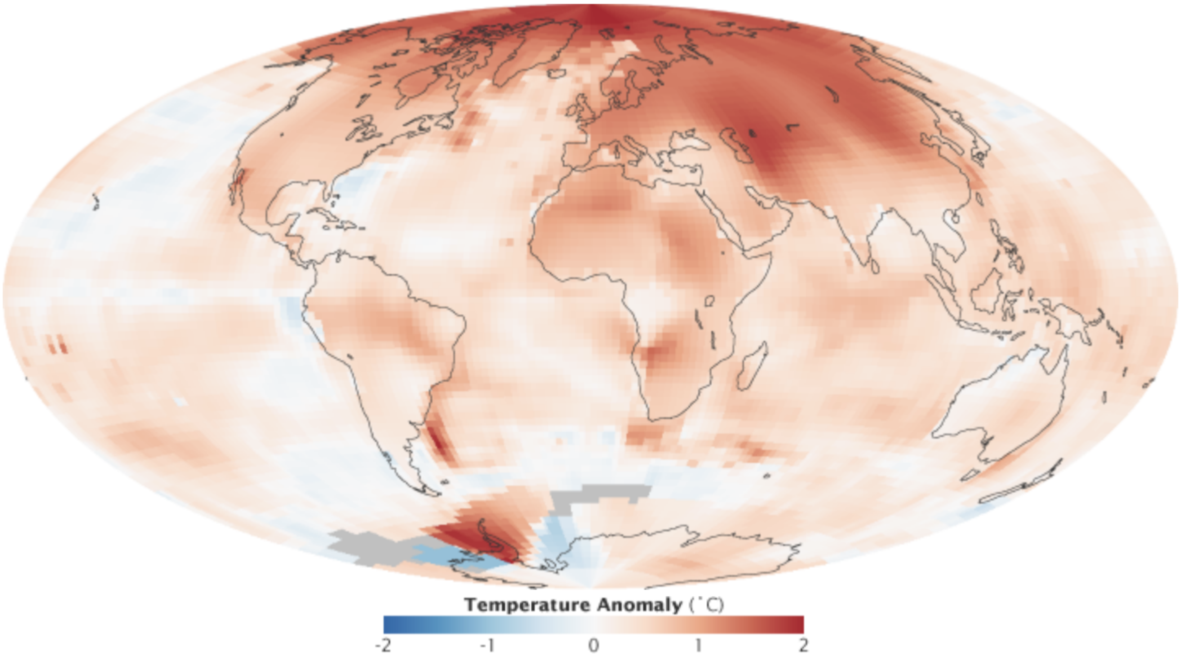

Figure 1: Map showing global temperature anomalies from 2000 to 2009. The map does not depict absolute temperature but depicts how much warmer or colder a region is compared to the average for that region from 1951 to 1980. Source: NASA Earth Observatory, “Arctic Amplification”.

Figure 2: Marine Terrace near Snæfellsjökull, on the southern coast of Iceland. Photograph taken by Doug Thompson (2013)

2. BACKGROUND

2.1 Glacial Background

2.11 GLACIERS: Formation and mass balance

Glaciers form when large amounts of snow are put under extreme pressure over long periods of time causing the snow to lose its air and compress into glacial ice. When snow or precipitation first falls during the wet season, it usually consists of 90% air and only 5-10% solid with a density of 0.9 g/cm^3 (Bierman and Montgomery, 2014). Once the snow is on the ground and starts to age, it loses its intricate crystal formations that we attribute to snowflakes and changes to larger, more rounded, and compact grains, what is commonly known as corn snow. Over the melt season, the snow further compacts becoming firn once the snow has gotten down to only 25% air (0.4-0.8 g/cm^3). Over time, the pressure produced by the overlying snowpack continues to compact the firn making it denser and less porous until it eventually becomes glacial ice with a density of 0.9 g/cm^3 (Bierman, Montgomery, 2014). Although this transformation takes place more quickly in temperate climates due to the freeze-melt processes associated with the region speeding up the transformation process, it can take hundreds of thousands of years in colder climates like the Arctic or Antarctica. Additionally, while the ice transformation process itself may take a significant amount of time, the accumulation of snow for this process to take place also requires time. While more temperate regions may see more precipitation, warmer temperatures can also negatively impact ice accumulation. Conversely, while colder Arctic and

Antarctic climates may support snow accumulation, not only do these regions see little precipitation but the lack of regular freeze-melt processes prolong the ice transformation process.

Glaciers lose ice through different processes such as meltwater, sublimation, and calving, the combination of which, known as ablation, is responsible for removing mass from a glacier (Bierman and Montgomery, 2014). Glaciers lose mass as ice and snow melt and leave the glacier by forming meltwater streams. Mass can also be lost through sublimation where water transitions from its solid state directly to a vapor state. This process is especially important for polar glaciers, glaciers that are below freezing temperatures throughout their mass throughout the year, in arid or semiarid regions as it occurs due to water vapor pressure gradients when wind moves undersaturated air over the ice (Bierman and Montgomery, 2014). Glaciers also lose mass when ice is lost by the calving of ice margins into bodies of water, leading large chunks of ice to come off of the glacier and form icebergs.

Once a glacier is formed, two different zones can be distinctly distinguished. The accumulation zone, located at the head (top) of the glacier, is where net mass gain occurs while the ablation zone, located at the glacier's snout (bottom of the glacier) is where net mass loss occurs (Bierman and Montgomery, 2014). The accumulation zone, being at a higher altitude than the ablation zone is more likely to see lower temperatures and increased precipitation, therefore leading the zone to primarily contribute to the accumulation of ice on the glacier. Consequently, the ablation zone being at a lower elevation than the accumulation zone is more likely to see warmer temperatures that can contribute to the loss of glacial mass. These two zones are separated by an equilibrium line, which is determined by the elevation of where the amount of mass gained and lost is the same over an average year (Bierman and Montgomery, 2014).

The results of the combination of the accumulation and ablation processes of a glacier is known as the mass balance and can determine the stability of the glacier (Bierman and Montgomery, 2014). If the amount of mass that is lost exceeds the mass that is gained, a glacier's equilibrium line, an elevation that shows where there is a balance between accumulation and ablation, will move up the glacier, thus also decreasing the area of the accumulation zone. Although the equilibrium line moves up in elevation, it is important to note that the glacier will continue to flow downgradient. A glacial retreat occurs only when the rate of ice ablation at the margin exceeds the rate of ice flow to the margin leading it to move up in elevation. However, if mass gains exceed the amount of mass lost, more accumulation than ablation, the glacier will grow and the margin will advance (Bierman and Montgomery, 2014).

Although some variation exists, alpine glaciers found at high altitudes (Himalayas and Andes) or at lower altitudes in higher latitudes (Iceland and Alaska), are primarily considered to be temperate glaciers, as they exist at the pressure-melting point leading liquid water to coexist with glacial ice (Bierman and Montgomery, 2014). Alpine glaciers are therefore especially responsive to changes in climate and are more susceptible to advance or retreat based on changes in temperature due to the presence of meltwater below the glacier that speeds up the movement of the ice and therefore accelerates advances and retreats. In fact, alpine glaciers can advance and retreat on a yearly to decadal basis. While ice sheets and ice caps can also respond quickly to climate change at their margins, these glaciers have greater inertia causing them to take centuries to fully respond to a new climate and even millennia to fully disappear due to climate change (Bierman and Montgomery, 2014).

2.12 GLACIERS: Energy balance

The energy balance of a glacier is essential in determining its stability. By detailing the amount of energy added to and lost from the glacier, the energy balance mechanism can help us determine the impacts of the melting, sublimation, and calving rates of a glacier. Sunlight can add energy to the glacier's surface, leading to loss of mass through both sublimation and by melting snow and ice and leading to meltwater streams. However, when a glacier is covered by highly reflective snow, its albedo is high, and less energy from sunlight is directly absorbed and is instead reflected, therefore decreasing the possibility of sublimation and melting. Contrastingly, if the snow or ice is covered in dust or volcanic ash or has already started to melt, the glacier's albedo decreases, leading more energy to be directly absorbed into the ice and increasing the possibility of loss of mass through sublimation and melting, thus creating a positive feedback loop (Bierman and Montgomery, 2014). However, sun radiation is not the only form of energy that affects a glacier's loss of mass. Sensible heat can also contribute to mass loss as it can be transferred to the ice by warm air masses, supplying some of the energy required for the ice to transition from solid to liquid. Latent heat can also be transferred to the glacier's surface through condensation or moisture, adding large amounts of energy to the glacier's system. Additionally, glaciers are also subject to small amounts of geothermal heat transferred from the rock below the glacier. While the impact of geothermal heat on glaciers is usually small, this effect is heightened in geothermal hotspots like Iceland, which is home to many subglacial volcanoes. Although all of these energy inputs, and therefore the energy balance of a glacier, are deeply tied to mass balances as they can seriously impact the melting, sublimation, and calving rates of a glacier, only some of them can be directly tied to climate change. Whereas the albedo of a glacier may be somewhat linked to climate change due to the impacts of glacial retreat on subglacial volcanoes, increased temperatures from climate change directly affect the amount of sensible heat transferred to the glacier by warmer air masses, thus contributing more energy to transition ice from solid to liquid form (Bierman and Montgomery (2014)

While all of these factors can impact a glacier's energy balance, only some of them are actively influenced by climate change. Sensible heat and latent heat that can transfer energy to glacial ice through warm air masses or condensation or moisture are directly influenced by a warming climate. The higher the air temperature, the more energy, in the form of latent heat, that will be transferred to the glacier. Similarly, warmer air temperatures may lead to more evaporation in surrounding areas, possibly causing increased moisture, condensation, and precipitation with associated latent heat. By contrast, geothermal latent heat originates from the rock below the glacier and is independent of both climate and weather. Additionally, the albedo effect itself relies on the presence or absence of volcanic ash or dust on the glacier in order to absorb or reflect sunlight and energy. Although volcanic ash and dust may seem independent of climate and weather, it may be possible that a change in climate could impact winds that may bring volcanic ash and dust onto the surface of the glacier. The convoluted nature of this process further expresses the complexity of studying the nature of glacial energy transfers.

2.13 ACCUMULATION AND ABLATION OF GLACIAL ICE

The area of a glacier where net mass loss occurs is called the ablation zone and the area where net mass gain occurs is called the accumulation zone (Bierman and Montgomery, 2014). These two zones are separated by the equilibrium line, which occurs at an elevation where, over an average year, the amount of mass gained and lost is approximately the same. The equilibrium line altitude (ELA) is largely controlled by climate. In a warming climate with increased temperatures and decreased snowfall, the equilibrium line altitude rises whereas in a cooling climate with decreased temperatures and increased snowfall, the equilibrium line altitude falls.

For alpine glaciers, many spatial and temporal changes in glacier accumulation and ablation are seasonal. During winter months, when snowfall is high and temperatures and incoming solar radiation are low, glaciers typically gain mass (accumulation). During summer months, increased temperatures and incoming solar radiation, and decreased snowfall increase ablation and decrease accumulation, leading glaciers to lose mass (ablation).

Elevation is also heavily tied to accumulation and ablation rates as air masses cool in order to rise above higher-elevation terrain. In fact, the average change in temperature with elevation, or the lapse rate, falls between 0.6° C and 1° C for every 100 m of elevation (Bierman and Montgomery, 2014). Additionally, as air masses gain elevation and cool, the water in them condenses, leading to an increase in precipitation. This orographic effect usually means that the upper section of glaciers usually receives more total precipitation as well as more of that precipitation falling as snow than the lower-end sections of a glacier, thus not only contributing to the elevation of the equilibrium line but also to the overall area of the accumulation zone. However, with many alpine glaciers, the winter mass balance remains somewhat constant, as there is a decrease in snow accumulation in higher altitudes due to wind-driven snow transport downslope (Bierman and Montgomery, 2014). Contrastingly, the summer mass balance is highly driven by elevation due to the lower sections of a glacier usually being above-freezing temperatures and therefore having a higher melt rate than the upper sections of a glacier.

2.14 GLACIAL MOVEMENT, FORMATIONS, AND DEFORMATIONS

Once a glacier forms, it is a persistent flowing body of ice and does not remain static (Bierman and Montgomery, 2014). Glaciers are constantly responding to the shear stress induced by gravity, causing the glacier to continuously move downhill. This leads to different types of glacial ice and glacial features existing within the same glacier. As glaciers continuously move downhill, they change shape due to the amount of force exerted on a specific area. The process of internal ice deformation is referred to as ice creep. Additionally, temperate glaciers also exhibit basal sliding, which occurs when the glacier slides at the bed/ice interface. Warm-based basal ice seen in temperate glaciers is not frozen to the bed and as a result, can slide over the bed in addition to deforming internally through ice creep. This process is often accelerated during summer when warmer air temperatures increase the amount of meltwater in the glacier further facilitating basal sliding. Meltwater, specifically subglacial water, reduces the effective normal stress on the bed and thus facilitates the movement of the glacier (Bierman and Montgomery, 2014). The presence of subglacial meltwater in low-arctic temperate glaciers in Iceland therefore results in them being particularly sensitive to climatic fluctuations (Chandler et al., 2016).

Any increase in glacial slope and ice thickness increases the amount of shear stress exerted on the glacier (Bierman and Montgomery, 2014). The rate of deformation with shear stress thus limits the thickness and surface slope of alpine glaciers, which determine the area of the landscape covered and eroded by ice. As shear stress increases, ice starts to deform plastically, moving more ice and limiting increases in ice thickness. In plastic deformation, the top of the glacier tends to move faster than the bottom of the glacier due to a decrease in bed friction from the increased distance of the location of the bed friction. Friction along the glacier is strongest along the boundary of the glacier (the bottom and the sides) and progressively diminishes towards the top of the glacier. The further away ice is from the bed, the less friction is transmitted to that location, allowing the ice to move more quickly along the surface of the glacier (Singh et al., 2011)

However, the shear strength of glacial ice is not the only important factor when considering glacial flow speeds. The shear strength of the bed underlying the glacier may be just as important as it controls the shape of the ice sheet (Bierman and Montgomery, 2014). Weak beds with low critical shear strength are more susceptible to deformation from the shear stress of glacial ice and therefore, usually result in gently sloping ice sheets. Contrastingly, strong beds with high critical shear strength only deform under high shear stress conditions, making them less susceptible to deformation from the shear stress of the glacier. As a result of the lack of deformable sediment, glaciers with strong underlying beds usually form steep ice margins. While weak beds can usually be found in areas where ice overruns weathered material high in clay and silt, or where subglacial water is prevalent, strong beds are usually found in areas of scoured rock with little basal water and/or deformable soil (Bierman and Montgomery, 2014).

When glaciers terminate in water, called tidewater glaciers, the ice thickness of the glacier in combination with water depth will determine whether the ice will float or maintain contact with the seabed (Bierman and Montgomery, 2014). When glacial ice remains grounded, the maintained contact with the seabed restricts the glacier's rate of flow due to high basal shear stresses resisting any movement thus limiting glacial calving (Bierman and Montgomery, 2014). Contrastingly, floating ice is supported by the water below causing little to no resistance thus leading the glacier to flow and calve rapidly. As a result, floating ice can sometimes catalyze a rapid loss of ice, which can further significantly decrease the ice volume and elevation of the source glacier or ice sheet. This process is further exacerbated by rising sea levels as formerly grounded ice margins begin to float and therefore calve more rapidly (Bierman and Montgomery, 2014). This only adds to the positive feedback loop that helps end glaciations. As the increased calving adds more mass to the ocean, it further raises sea levels and again accelerates deglaciation. This process is further accelerated by the fact that melting thins glacial ice, thus requiring less water in order for it to float. Although the calving of the floating ice itself does not increase sea levels, such calving can pull grounded land-based parts of the glacier further down. As ice is transferred from land to the sea and then melts, the volume of ocean water increases, thus also raising sea level (Bierman and Montgomery, 2014).

2.15 GLACIAL SENSITIVITY AND DIFFERENCES BETWEEN WEATHER AND CLIMATE

Additionally, some glaciers can also surge, in which ice flows very rapidly (meters to tens of meters per day) for a short period of time, which is usually followed by a more consistent, slower ice flow (Bierman and Montgomery, 2014). When a glacier surges, it decreases its overall elevation, therefore subjecting it to warmer conditions that may increase the glacier’s meltwater runoff. These glacial surges can only loosely be related to direct changes in climate or the hydrologic system and are therefore better considered as indicators of instability within the glacial system. During a surge, large amounts of glacial ice flow towards the glacier’s margin where it quickly advances and then stagnates after the surge. The large amounts of meltwater that are released during a glacial surge further suggest that surges occur due to changes in bed hydrology. As the glacier’s hydraulic head increases, the total energy of water (at a certain point) also increases, thus reducing the glacier's resistance to basal sliding (Bierman and Montgomery, 2014).

Glacial surging primarily occurs in temperate glaciers as they are not frozen to the bed and are characterized by an abundance of meltwater during the melting season (Bierman and Montgomery, 2014). Due to Iceland's glaciers being primarily temperate, glacial surges are somewhat common. In fact, according to a study by Ingólfsson et al. (2016), all major ice caps in Iceland, including Vatnajökull, Iceland's largest ice cap, have surge-type outlet glaciers and it is estimated that at least 28 surge-type outlet glaciers currently exist in Iceland. Additionally, some studies suggest that the mass transport during glacial surges for Vatnajökull outlet glaciers could be up to 25% of the total ice flux of individual glaciers (Ingólfsson et al., 2016, Aðalgeirsdóttir et al., 2005).

Although glacial surges alter the shape and spread of the glacier, usually resulting in rapid frontal advance to the ice margin, the advance itself does not alter the overall ice mass (Bierman and Montgomery, 2014; Ingólfsson et al., 2016). As surging glaciers accumulate more mass over time, the flow of the glacier moves too slowly to remain in balance given the accumulation rate, leading to a rapid frontal advance of the glacier (Bierman and Montgomery, 2014; Ingólfsson et al., 2016). Surge-type glaciers are therefore characterized by surge cycles consisting of an active phase, with fast glacial flow lasting months to years, and a quiescent phase, with reduced glacial flow in which there is net accumulation/mass build-up in the accumulation zone and net ablation and mass wastage in the ablation zone (Ingólfsson et al., 2016). Once enough excess mass has been collected in the accumulation zone, it is rapidly transferred to the ablation zone, resulting in a rapid ice-marginal advance. Since glacial surges cannot be directly linked to changes in climate or hydrologic system, these glaciological events are generally thought to represent instability inherent to the glacial system itself, possibly due to a combination of global or local variations in precipitation and temperature (Bierman and Montgomery, 2014; United States Environmental Protection Agency, 2023). This may suggest that while some of the glacial changes that we observe today may be due to short-term weather variability, any observed long-term glacial trends would suggest more regional or global climatic change.

2.2. SITE-SPECIFIC BACKGROUND

2.1. A BRIEF HISTORY OF GLACIAL RESEARCH ON VATNAJÖKULL

Iceland is home to over 250 named glaciers, including Vatnajökull, Langjökull, and Hofsjökull, Iceland's largest glaciers (Aðalgeirsdóttir, G. et al., 2020). The combined volume of glaciers in Iceland currently corresponds to ~3,400 km^3, which translates to approximately 9 mm of potential sea-level rise (Aðalgeirsdóttir, G. et al., 2020). An inventory made around the year 2000 showed around 300 glaciers (Aðalgeirsdóttir, G. et al., 2020; Sigurðsson and Williams, 2008) but a 2017 update of this inventory showed that several of those glaciers had disappeared, and been categorized as dead ice, or during their retreat had split into two or more glaciers or ice patches *(*Aðalgeirsdóttir, G. et al., 2020).

With an area of approximately 7700 km^2 and an average thickness of around 373 m, Vatnajökull is the largest glacier in Europe and is also the largest non-polar ice cap in the world, an ice cap being a glacier covering a large area of land measuring less than less than 50000 km^2 (Aðalgeirsdóttir, G. et al., 2020; Calluy et al., 2005). Located in Southeast Iceland, the ice cap's volume measured around 2870 km^3 in 2019 and covers around eight percent of Iceland's land mass (Aðalgeirsdóttir, G. et al., 2020; Calluy et al., 2005). The ice cap is located within an active volcanic zone and it is therefore important to note that it can be affected by factors like volcanic ash that can change the albedo as well as direct melting during volcanic activity due to contact from the lava, both of which affect the energy balance of the glacier. According to Thörarinsson (1964) and Johannesson (1997), due to Vatnajökull's size, "Few, if any, glaciated areas seem more likely than Vatnajökull to furnish us with sufficient data for the solution [for understanding catastrophic glacier advance]" (Thörarinsson, 1964; Johannesson, 1997).

The retreat of Icelandic glaciers first started being studied in 1930 when a country-wide voluntary monitoring program was initiated (Aðalgeirsdóttir, G. et al., 2020). This initial program then continued to exist thanks to the Icelandic Glaciological Society, founded in 1950, and annually measures thirty to forty terminus positions, the observations of which are posted on their website (Aðalgeirsdóttir, G. et al., 2020). The surface and bedrock topographies of Iceland's largest ice caps have been measured since 1977 through radio-echo sounding (RES) surveys, in which a radio wave is transmitted to and reflected from layers within and beneath glacial ice (Aðalgeirsdóttir, G. et al., 2020). Although these surveys had already been carried out on cold polar ice caps, the campaigns carried out on temperate Icelandic glaciers were found to require much larger electro-magnetic wavelengths than the ones used previously on polar ice caps (Aðalgeirsdóttir, G. et al., 2020).

However, despite today's prominence of glacial studies due to the effects of climate change, glaciology in Iceland has been of interest since the late 1700s (Evans, 2016). In fact, in 1796 and 1798, Sveinn Paulson published accounts of his travels to Iceland's glaciers and produced some of the very first maps of Vatnajökull (Evans, 2016). Paulson recorded significant glacial snout oscillations in outlet glaciers such as Breiðamerkurjökull, likely being the first to recognize that the glacier undergoes occasional surges (Evans, 2016). Interest in Iceland's Vatnajökull glacier continued into the 1800s and the 1900s when several teams crossed the glacier as a part of their expeditions (Evans, 2016). The first modern scientific discoveries of the ice cap were made in 1919 when H. Wadell and E. Ygberg identified the Grismvötn caldera (Evans, 2016). Research expeditions continued from 1934 to 1936 and then from the turn of the

20th century to the 1960s (Evans, 2016). The most notable results of these expeditions were by Emmy Mercedes Todtmann, who first reported on features around the southern margin of the Vatnajökull glacier in the early 1930s, early 1950s, and the 1960s (Evans, 2016). Additionally, in the early 1930s, Gudmundur Barðarson delivered an assessment of the state of Iceland's glaciers, therefore providing us with valuable information on the early stages of glacier snout recession on Vatnajökull during the end of the Little Ice Age, a period of temperature cooling in the Northern Hemisphere from the early 14th century to the mid-19th century (Jackson et al., Encyclopedia Briannica, 2023).

From the 1930s to the 1960s, Sigurður Þórarinsson, known as one of the most active and influential Vatnajökull researchers delivered numerous summaries of Vatnajökull's glacier activity, including the first detailed account of historical glacier oscillations around south Vatnajökull, as well as reports on contemporary field research on its ice margins and their forelands (Evans, 2016). As glacial research continued, European Universities outside of Iceland began to also take various expeditions to Vatnajökull. However, despite the multitude of glacial research based in Iceland, it wasn't until 1950 that the Icelandic Glaciological Society was founded, thus marking a milestone in Icelandic glacial research. Since then, various universities have continued to use Vatnajökull as a base for geomorphic study. In fact, a significant development in glacial geomorphic research happened in the mid-1960s when the University of Glasgow used Breiðamerkurjökull as the location for a high-precision foreland mapping project from 1964 to 1967 (Evans, 2016). Vatnajökull glacier has since continued to be a base for glacial study with multiple milestone discoveries having been made on the said glacier. These discoveries have only continued to increase in complexity not only as technology evolves but also as glacial research itself evolves.

Continuous monitoring of Vatnajökull's ice thickness by the Science Institute of the University of Iceland has allowed the compilation of three-dimensional maps of the subglacial topography of Iceland's ice caps as well as the geothermally controlled subglacial lakes and ice-marginal lakes (Evans, 2016). This important data has not only enabled today's understanding of the development of glaciers' drainage systems in a time of glacial recession, but also in the production and mapping of jokulhlaups. The various observations and experiments originating from the Vatnajökull ice cap and its outlet glaciers have marked the ice cap as one of the most important locations in the history of glaciology and glacial geomorphology. This is especially true for the outlet glacier Breiðamerkurjökull due to it being the location of Geoffrey Boulton's experiments, which enabled the identification of the third mode of glacier flow, subglacial bed deformation. The plentitude of discoveries from the study of Vatnajökull has only encouraged more modern experiments and observations. In fact, the British Geological Survey has established a long-term glacier monitoring project on Virkisjökull and Falljökull (Evans, 2016). This project involves meteorological measurements, time-lapse photography of glacier motion, geophysical surveys of glacier ice, and topographic surveys (Evans, 2016). The results of this research are open to the public and can be found at the website[1]. Additionally, the University of Iceland has several current glacial research projects focused on Vatnajökull, including the recently launched research center (Research Center Hornafjorður), located in Breiaðmerkursandi with the goal of collecting information about the changes that occur over time in a land area that has only recently emerged from glaciation.

Radio-echo sounding (RES) surveys dating from 1978 to 2019 showed that ice caps' deepest ice, ranging from 600 m to 950 m deep, was generally located above deep valleys in the ice cap's interior and over large ice-filled calderas (Björnson et al., 2020). Additionally, RES

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[1] http://www.bgs.ac.uk/home.html

showed that, generally, only 10 to 20% of an Icelandic ice cap's bed lies above today's glaciation limit of 1100 to 1200 m in elevation. This suggests that if the ice caps were to disappear, they would be unable to re-establish themselves in today's climate conditions (Björnson et al., 2020).

Furthermore, RES data has allowed for bedrock mapping under Iceland's major ice caps, revealing that many of Iceland's biggest ice caps, including Langjökull, Hofsjökull, and Vatnajökull, are intertwined in a network of volcanoes (Björnson et al., 2020). Langjökull formed over a row of shield volcanoes, suggesting previous ice-free conditions, and has thus formed tuyas (flat-topped, steep-sided volcanic areas where previous eruptions are now covered by glacial ice). Hofsjökull rests above Iceland's largest volcano, Katla. Under Vatnajökull lies five central volcano complexes, Bárðarbunga, Háabunga, Grímsvötn, Kverkfjöll, and Esjufjöll (Björnson et al., 2020). RES surveys have also revealed the extent and shape of subglacial lakes (where meltwater accumulates underneath the glacier, usually from hydrothermal activity creating permanent depressions that then fill with meltwater) allowing for predictions of the locations of potential proglacial lakes (lakes that form in front of the glacier due to meltwater being trapped behind a moraine or ice dam) as glaciers retreat due to climate change (Björnsson et al., 2020; Björnsson et al., 2003; Jóhanesson et al., 2007).

Between 2008 and 2013, Light Detection and Ranging (Lidar) measurements of the glaciers' surfaces were conducted. Annual mass-balance measurements have also been regularly conducted on Hofsjökull since the geological year 1987/1988, Vatnajökull since the geological year 1991/1992, and Langsjökull since the geological year (1996/1997), making them some of the most well-studied glaciers in Iceland (Aðalgeirsdóttir, G. et al., 2020). Geodetic mass balance has also been estimated in several glaciers throughout the years and mass changes have been documented by using ICEsat (Nilsson et al., 2015), CryoSat2 (Foresta et al., 2016), and GRACE satellites (Ciraci et al., 2020; Aðalgeirsdóttir, G. et al., 2020).

3. LITERATURE REVIEW: ICELANDIC GLACIAL ADVANCES AND RETREATS

Global glacier mass loss first became a clear trend toward the end of the 20th century (Leclerq et al., 2011; Marzeion et al., 2015; Marzeion et al., 2012; Aðalgeirsdóttir, G. et al., 2020). Arctic glaciers and ice caps store 40% of global glaciers and ice caps (GIC) ice volume, corresponding to 144 mm of sea-level rise (Tepes et al., 2021). Between 2010 and 2017, Arctic glaciers and ice caps (GIC) have lost 609 +/- 7 Gt of ice per year, contributing to approximately 0.007 mm of sea-level rise per year (Tepes et al., 2021). According to Tepes et al. (2021), surface ablation is responsible for 87% of mass loss in Arctic glaciers.

Glaciological research has estimated that the earth's warming climate would have pronounced effects on glaciers and ice caps further leading to serious run-off changes in glacierized areas since as early as the 1990s (Jóhannesson et al., 1995). In fact, they have exhibited rapid rates of ice-marginal retreat and mass loss during the past decade (Chandler et al., 2016; Jóhannesson, 1986, Sigurðsson and Jónsson, 1995, Aðalgeirsdóttir et al., 2006, Sigurðsson et al., 2007, Björnsson and Pálsson, 2008, Björnsson et al., 2013, Bradwell et al., 2013, Mernild et al., 2014, Phillips et al., 2014, Hannesdóttir et al., 2015a, Hannesdóttir et al., 2015b).

Although short-term glacial studies only show various fluctuations with either short-term glacial advances or retreats, these studies are still important in order to observe any long-term patterns of glacial change. Glacial fluctuation studies can also be paired with climate studies in order to determine the influence of climate conditions on glacial fluctuations. One study looking at annual moraines as a proxy for annual ice-margin retreat rates (IMRR) on Skálafellsjökull (an outlet glacier of Vatnajökull), suggests that summer air temperature is not the only factor influencing glacial retreat, but also sea surface temperature, and the North Atlantic Oscillation

(Chandler et al., 2016). According to this study, these three factors work together to determine the glacier's IMRRs, with the glacier being most sensitive to summer air temperature, although it was hypothesized that sea surface temperatures may drive air temperature changes. The temperate glaciers in Iceland have thus been categorized as especially sensitive to climatic fluctuation on an annual to decadal scale due to their maritime setting (Chandler et al., 2016).

Additionally, by examining the annual moraine spacing of Skálafellsjökull, Chandler et al. (2016) identified that the glacier experienced ice-marginal retreat every year between 1936 and 1964, with an average of 25.6 ma^{-1}. Results showed that ice-front retreat was particularly strong during the late 1930s and early 1940s before slowing down, possibly due to cooler atmospheric air temperatures (Chandler et al., 2016). Prominent glacial recession occurred again in the mid-1950s before rates slowed once again in the 1960s. The study suggests that the glacier re-advanced between 1964 and 1969, a perceived common pattern between all non-surge glaciers in Iceland during the 1960s. Between 1969 and 1974, a short period of annual moraine formation occurred with the IMRRs averaging 9.9 m a^{-1} (Chandler et al., 2016). After this period, no annual moraine formation was observed and remote-sensing data indicated that the glacier was relatively stable between 1975 and 1989 (Chandler et al., 2016). While the absence of ice-front measurements and remote-sensing data from the 1990s did not allow Chandler et al., (2016) to definitively determine the fluctuation of the glacier during that time period, it was reported that other Icelandic non-surge type glaciers showed many of them readvancing during the 1990s (e.g. Sigurðsson and Jónsson, 1995; Sigurðsson, 1998; Sigurðsson et al., 2007). Chandler et al. (2016), reported that annual moraine formation along with ice-front recession recommenced during the winter of 2005/2006 and continued until June of 2012, the end of their imagery archive.

While this study evaluated glacier behavior on an annual basis, suggesting weather to be the primary driving factor for glacial retreats and advances, the multi-decadal timescale, as well as the corresponding observation of other Icelandic glaciers, would suggest glacier change forced by a common, regional mechanism (Chandler et al., 2016). In fact, Chandler et al. (2016), found a statistically significant relationship between IMRRs and summer atmospheric air temperatures (r^2=0.3464, p<0.0001), summer sea surface temperature (r^2=0.1623, p<0.0010), and summer North Atlantic Oscillation (r^2=1310, p<0.0201). While summer atmospheric air temperatures seem to be the primary driver in Skálafellsjökull's ice-marginal retreat, Iceland's complex climate makes it difficult to identify the influence of an individual climate variable on ice-frontal variations (Chandler et al., 2016). However, regardless of the difficulties in identifying the individual impacts of a climate variable on glacial change, atmospheric air temperature is still considered to be a major driver of glacial retreat in Iceland. Furthermore, the coincidence of glacial retreat periods in Iceland and Greenland would suggest the influence of a common mechanism in the North Atlantic Region (Chandler et al., 2016).

A study from Aðalgeirsdóttir et al. in 2020 used a combination of various data sets and methods, including glaciological observations, geodetic measurements, simulation with the HIRHAM5 snowpack model, estimates of non-surface mass balance, and results from empirical volume-area scaling that is used to extend the record back to the time of the maximum extent of Little Ice Age (LIA) glaciers recorded by geomorphological evidence. This study recorded the short-term glacial variability on a decadal timescale throughout a period of 129 years, including the time frame when climate change first became a salient issue to the general public in 1988 (Jackson, 2007). Throughout the 129-year period, researchers found the total mass change of Icelandic glaciers to be -240 +/- 20 Gt. The study further detailed decadal fluctuations in glacial mass balance with data resolution steadily increasing with the advance of remote-sensing and other technologies. Decadal fluctuations in glacial mass balance showed a period of nearly zero mass balance in the early stages of the global recognition of climate change (the 1980s and early 1990s) before showing continuous negative mass-balance measurements on the order of -1 m a^{-1} since then (Aðalgeirsdóttir, G. et al., 2020). Researchers found that nearly half of the total observed mass change (-240 +/- 20 Gt) during the studied period occurred from geological years 1994/1995 to 2018/2019 (Figure 1G, Aðalgeirsdóttir, G. et al., 2020). It was found that this time period, occurring shortly after the increase in the prevalence of climate change in international public debate (1994/1995 - 2018/2019), reflected higher temperatures than in previous years (Figure 3E, Aðalgeirsdóttir, G. et al., 2020) and that the observed negative mass-balance change is synchronous with glacier decline elsewhere in the world (Aðalgeirsdóttir, G. et al., 2020).

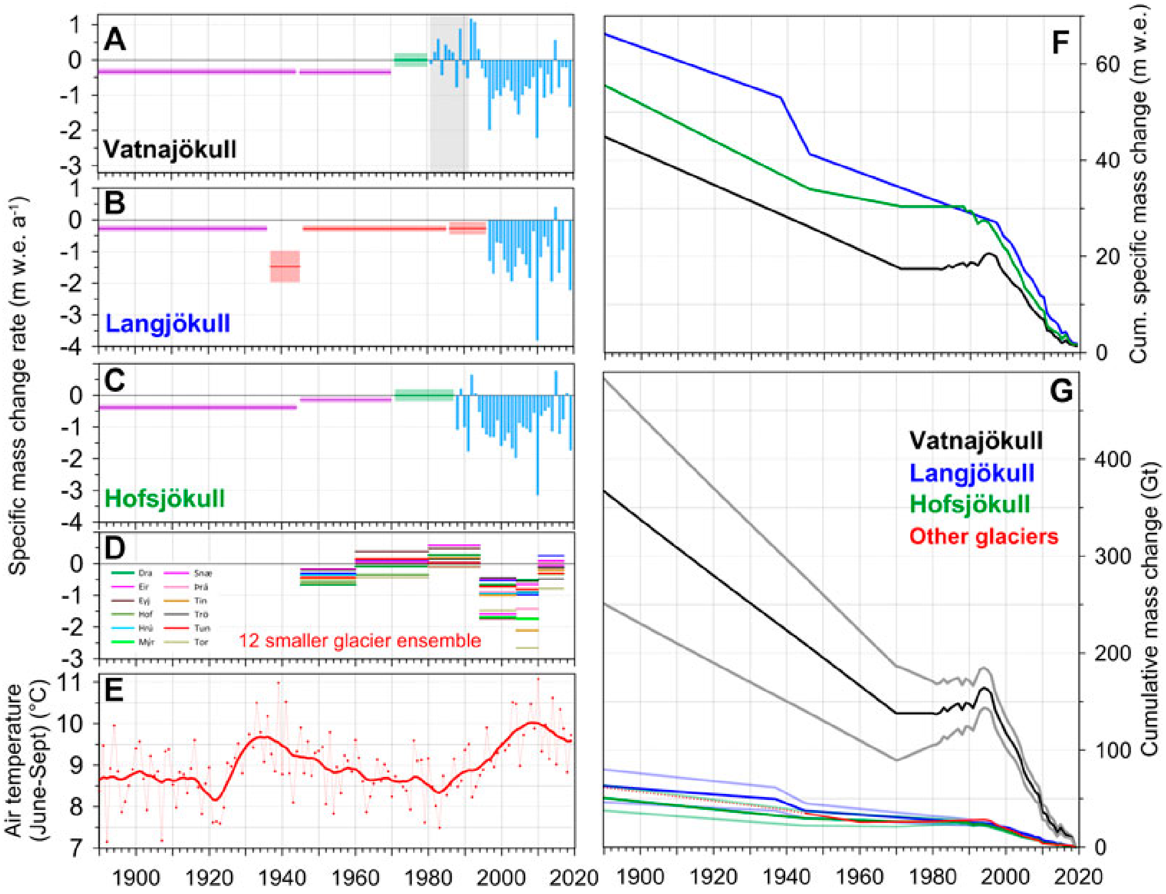

Figure 3: Left: The specific mass balance of glaciers in Iceland as observed, modeled, and estimated with various methods. The gray area in (A) indicates a period of modeled surface mass balance for Vatnajökull (Schmidt et al., 2019), green boxes in (A) and (C) are estimates from various sources, red boxes in (B) and lines in (D) are from geodetic mass balance (Pálsson et al., 2012; Belart et al., 2020) (heights of the boxes indicate uncertainty of measurements), and purple boxes in (A), (B), and (C) show estimated mass loss from volume–area scaling method. (E) The average summer (June through September) temperature at the meteorological station in Stykkishólmur; the thick line shows the 11-year running average with triangular weight, a 5-year filter. Right: (F) Cumulative specific mass balance (m w.e.) for Vatnajökull (black), Langjökull (blue), and Hofsjökull (green). (G) Cumulative mass change (Gt) of the same ice caps and the sum of other glaciers in Iceland assuming that the mass-balance records of the glaciers shown in (D) are representative of the unmeasured glaciers. The red dotted line shows the extension of this record for the years 1890/91 to 1944/4. [in (G) the mass change of Mýrdalsjökull for the years 1945/46–1959/60, not included in (Belart et al., 2020), is estimated from a linear fit (with R^2=0.98) between the mass balance of Mýrdalsjökull and the average mass balance of the neighboring glaciers, Eyjafjallajökull, Torfajökull, and Tindfjallajökull, during the other five periods shown in (D)]. Modified from Aðalgeirsdóttir, G. et al., 2020.

The computation of average mass rates for several selected periods corresponding with the reporting periods of the Intergovernmental Panel for Climate Change (IPCC) Sixth Assessment Report (AR6) estimates the average rate of mass change for the entire 129-year period to be -4.2 +/- 1.0 Gt a^{-1} (1900/01-1989/90: -3.1 +/- 1.1 Gt a^{-1}, 1970/71-2017/18: -4.3 +/- 1.0 Gt a^{-1}, 1992/93-2017/18: -8.3 +/- 0.8 Gt a^{-1}, 2005/06-2017/18: -7.6 +/- 0.8 Gt a^{-1}) and the rate during the rapid downwasting period (1994/95-2018/19) was found to be -9.6 +/- 0.8 Gt a^{-1} (Aðalgeirsdóttir, G. et al., 2020). The cumulation of the specific mass-balance values from 1890-2019 showed Vatnajökull losing the least with approximately 45-meter water equivalent (m w.e), Hofsjökull losing 56 m w.e, and Langjökull losing the most with 66 m w.e (Figure 4; Aðalgeirsdóttir, G. et al., 2020). However, while Vatnajökull had a less significant decrease in mass-balance values than the other two glaciers, the glacier was primarily responsible for the most cumulative mass change in Icelandic glaciers with 365 +/- 115 Gt, while Langjökull and Hofsjökull only accounted for 63 +/- 17 and 51 +/- 13 Gt, respectively (Figure 3F; Aðalgeirsdóttir, G. et al., 2020).

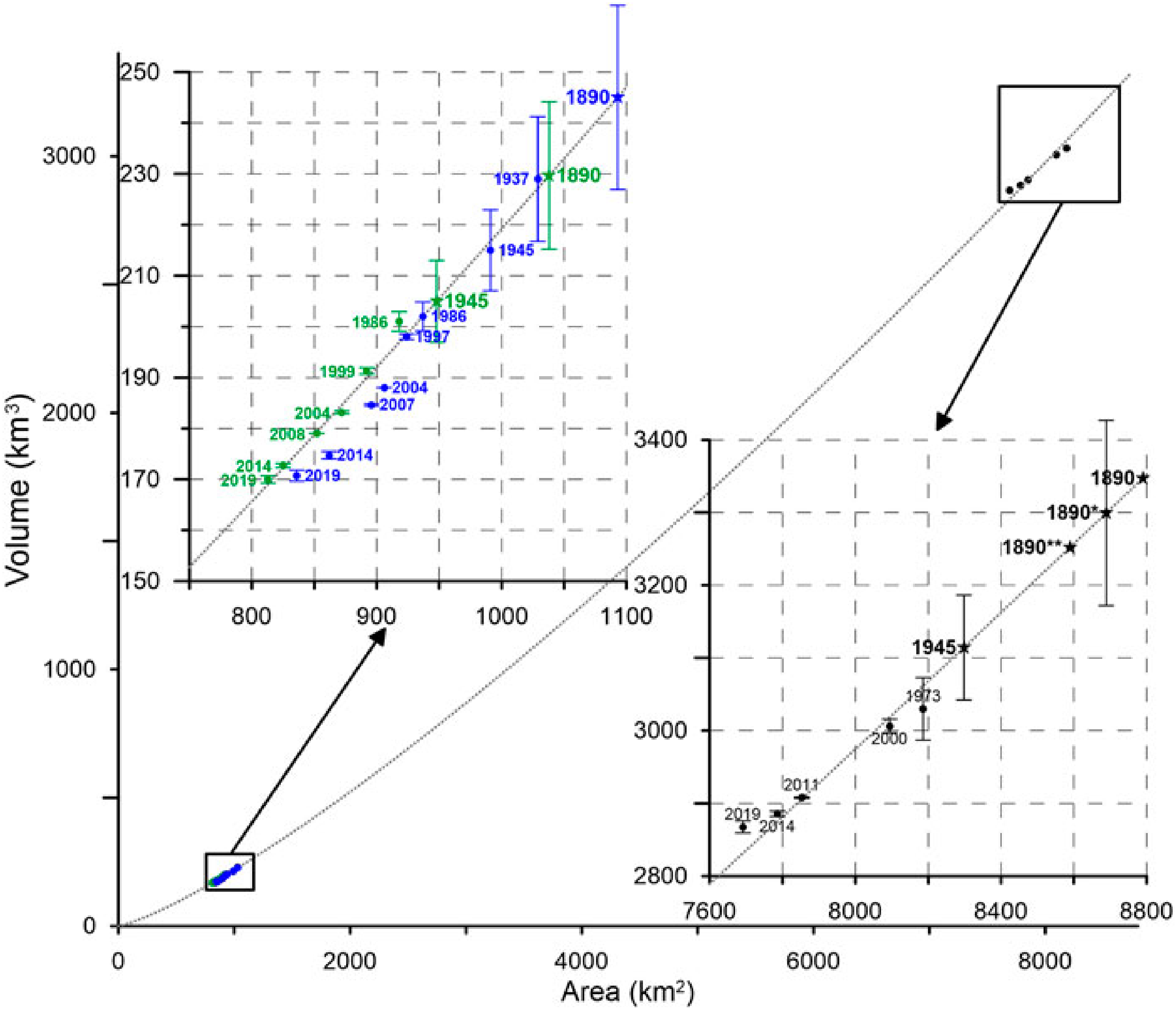

FIGURE 4. Volume–area scatter plot for the three largest ice caps in Iceland at various times since 1890. The blue markers are for Langjökull, the green markers for Hofsjökull, and the black for Vatnajökull. The dotted gray line shows the least square fit of volume area scaling ($V = cA^{\gamma}$) through all volume–area points for these ice caps. Inset figures show a zoom-in of the plot for the clusters with data from Hofsjökull and Langjökull (UPPER LEFT CORNER) and Vatnajökull (LOWER RIGHT CORNER). Labels by the filled circles indicate dates when both area (Hannesdóttir et al., 2020) and volume are well established, while labels beside stars indicate dates of well-known area, with volume estimated from the deduced volume–area relation (dotted gray line). The 1890 values are obtained using area based on geomorphological evidence of the Little Ice Age maximum extent (Hannesdóttir et al., 2020). The 1890* and 1890** for Vatnajökull show the volume estimates with the reduced area to compensate for the large portion of surging outlets from Vatnajökull. Modified from Aðalgeirsdóttir, G. et al., 2020.

An analysis of glacial activity on a decadal time scale showed large variability in mass balance. During the cold period, from 1980 to 1994, 9 of the 14 years indicated mass gain (Figure 3E; Aðalgeirsdóttir, G. et al., 2020). Mass gain was not observed again after the cold period, with the exception of the mass-balance year 2014/2015, which was characterized by a long sequence of continuous low-pressure systems throughout the winter, resulting in great amounts of precipitation and was followed by a cool summer with little melt. (Aðalgeirsdóttir, G. et al., 2020) During the study period, two high mass loss mass-balance years were observed, the first being 1996/97 and the second being 2009/10 (Aðalgeirsdóttir, G. et al., 2020). The mass loss observed in 1996/97 was due to the melting of approximately 3.7 Gt of ice due to the subglacial eruption of Gjálp, a hyaloclastite ridge that is most likely a part of the Grímsvötn volcanic system (Volcanoes of the World v.5.1.0, 2023). The eruption in October 1996 was followed by a warm and sunny summer with low surface albedo due to volcanic tephra and dust precipitating onto the glacier's surface (Volcanoes of the World v.5.1.0, 2023; Aðalgeirsdóttir, G. et al., 2020). The mass-balance year of 2009/10 also saw large mass loss as a result of the deposition of a thin layer of volcanic tephra on almost all Icelandic glaciers during the final phase of the Eyjafallajökull eruption from April to May 2010 (Aðalgeirsdóttir, G. et al., 2020). Similarly to the event in 1996/97, the deposition of the volcanic tephra in 2009/10 was followed by an unusually warm and sunny summer, where the deposited tephra greatly enhanced glacial melting, especially in the accumulation zones of glaciers (Aðalgeirsdóttir, G. et al., 2020; Gudmundsson et al., 2012; Gascoin et al., 2017; Möller et al., 2019; Björnsson et al., 2013; Belart et al., 2019).

Studies found that the glaciological year 2018/19 was observed to be one of the most negative mass-balance years on record due to persistent anticyclonic conditions throughout the summer of 2019 (Aðalgeirsdóttir, G. et al., 2020; Tedesco and Fettweis, 2020), leading to warm and sunny conditions starting in early spring. These warm and sunny conditions led to the early melting of an already thin winter snow layer, resulting in the early exposure of low-albedo regions in the ablation areas of glaciers (Aðalgeirsdóttir, G. et al., 2020; Gunnarsson et al., 2020).

The compilation of data from the study by Aðalgeirsdóttir, G. et al. (2020) suggests that a large proportion of the 20th-century mass loss observed in Icelandic glaciers occurred during the approximately 30-year period from the late 1920s to the late 1950s, which aligns with the findings of the 2016 study by Chandler et al.. During other periods throughout the 20th century, Aðalgeirsdóttir, G. et al. (2020) suggest that glaciers were most likely at or close to equilibrium on a decadal timescale. On this timescale, the studied glaciers did not show a substantially positive mass balance during any specific period. In fact, from 1980/81 to 1993/94, which is considered to be the period with the most positive mass balance since the early 1920s, the average mass gain only corresponded to 0.23 +/- 0.1 m w.e.a^{-1} for Vatnajökull, the glacier that was most responsible for the mass gain of Icelandic glaciers during that time period (Aðalgeirsdóttir, G. et al., 2020).

The estimates of the mass change rates of Icelandic glaciers from the study by Aðalgeirsdóttir, G. et al. (2020), were compared to estimates from other glaciological studies and were charted relative to sea-level change (Figure 5). This graph shows that from 2006 to 2020 (with the exception of 2015), Icelandic glaciers showed a consistent negative mass change, which correlated to a positive sea-level change (Figure 5; Aðalgeirsdóttir, G. et al.). The only year that does not fit with this trend is 2015, which instead saw a positive mass change rate with a negative sea level change (Aðalgeirsdóttir, G. et al.). Therefore, according to the relationship shown in Figure 5, negative glacial mass change rates are associated with a positive change in sea level whereas positive glacial mass change rates are associated with a negative change in sea level (Aðalgeirsdóttir, G. et al.).

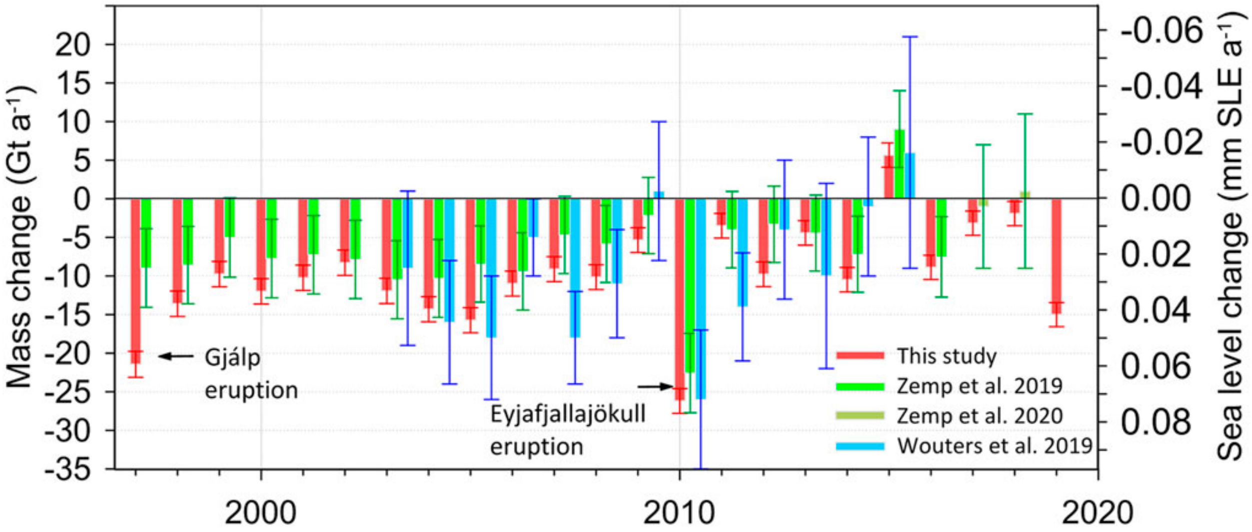

Figure 5: Comparison of mass change rates estimated in this study and studies based on glaciological observations provided to the World Glacier Monitoring Service (WGMS) database (Zemp et al., 2019; Zemp et al., 2020b) and the GRACE satellite observations (Wouters et al., 2019), with the respective estimated uncertainties. The figure shows only the period when Vatnajökull, Hofsjökull, and Langjökull have all been monitored with glaciological observations. The contribution of other glaciers is from geodetic results (Belart et al., 2020), including an estimated annual variability. Each line represents both mass-level change (Gt a^{-1}) and sea-level change (mm SLE a^{-1}). The mass change scale is on the left side of the graph with the numbers above the axis representing a positive change in mass (mass gain) and the numbers below the axis representing a negative mass change (decrease in mass). The sea-level change scale is on the right side of the graph with the numbers above the axis representing a negative change in sea-level (decrease in sea level) and the numbers below the axis representing a positive change in sea-level (increase in sea level). Modified from Aðalgeirsdóttir, G. et al., 2020.

4. METHODS

4.1 REPEAT PHOTOGRAPHY

Repeat photography is the practice of acquiring historical images and matching them to current images in order to document long-term ecological and geological changes in the landscape Webb et al., 2010). This technique originates from a Bavarian mathematician, Sebastian Finsterwalder, who in 1888 began using it to document changes in glaciers in the Tyrolean Alps. Repeat photography has since expanded to be used more broadly in both natural and social sciences (Webb et al., 2010).

In repeat photography, there must always be a baseline, an original image that can be used to compare later photographs. These images can be acquired through historical archives, museums, individuals, published sources, or by using the photographer's original image that can be replicated later (Webb et al., 2010). Although using your own original image as a baseline is usually the most ideal since it allows for more control over the project, this is not always possible due to various constraints such as time and resources. In this case, historical images are a good alternative, especially since they also allow for longer time intervals to occur between images. However, it is always important to check the actual location of an image before deciding to use it as a baseline as photographers have been known to rarely label their photographs, and even mislabel them in public archives (Webb et al., 2010). This can be especially dangerous when concerning glacial repeat photography as it may lead to the misidentification of a glacier. This misidentification may further lead to the incorrect conclusions about a particular glacier's stability and fluctuations. While this may be significant in and of itself, it's also possible that it could lead to dangerous situations regarding activities related to the glacier. Since glaciers are popular but dangerous destinations for hikes, climbing, and cave exploring, an incorrect identification may lead people to consider the glacier safe for activities despite the possibility of it being highly unstable.

Repeat photographs should always be as accurate and as precise as possible to allow for the best interpretation of the data (Webb et al., 2010). The most precise way to match a photograph is to position the camera over a previously established marker, use the same camera and lens, and adjust the camera position to the same height, tilt, and azimuth (Webb et al., 2010). However, although this technique may allow for the most precise results, it is not always possible, especially if you are working with historical photographs. Therefore, despite there being some extensive techniques to replicate photographs, most practitioners of repeat photography use simple foreground-background matching techniques to determine where to position their cameras (Webb et al., 2010). This is especially true when utilizing previously unmatched photographs. In fact, if the original photograph has not been labeled with a location, photographers must first locate roughly where the photo was taken. Using digital elevation modeling, like Google Earth, can help narrow down the possibilities. Only once the exact location has been identified can the photographer venture out into the field and replicate the photograph. Bringing high-quality copies of the original image can help with precise photographic matching (Wagner, 2011).

4.2 PHOTOGRAPHIC METHODS USED IN THIS STUDY

In this study, original photographs taken in the summer of 2013 by Professor Doug Thompson were used as baseline images. Once the location of these images had been confirmed through personal inquiry and through using Google Earth and Google Maps, the images were then replicated to the best of the photographer's abilities in March of 2023. Since the original images were not originally meant to be used as a baseline for repeat photographs, the exact location and camera position were unable to be replicated. Additionally, the original photographer used a variable zoom lens, in which the magnification of the glacier varied to an unknown degree. In order to replicate the original photos, the repeat photographer used a simple foreground-background matching technique to replicate the photographs. Several photographs were taken at varying distances, heights, and perspectives in order to find the best possible match for the angle of the original image. Once the repeat photographs were taken, the most accurate matches were selected to be used for the glacial outlines. If necessary, the selected images were cropped and were then layered with the original images using Adobe Photoshop in which the photographer outlined the key features of the glacier (rock formation, mountain, etc.) in order to align both photographs as accurately as possible (Figures 3c and 3d). Once both photographs were aligned, the outline of the original glacier was traced in red on the original image (Figures 8a, 9a, and 10a), and the outline of the 2023 glacier was outlined in blue on the 2023 image (Figures 8b, 9b, and 10b). When both glacial outlines were finished, they were both set to the 2023 image (Figures 8, 9, and 10). A chronological image timeline depicting this method is shown from Figure 6a to Figure 6g. Although the photographs were aligned as accurately as possible, the slight differences in perspective and magnification made it impossible for both images to be perfectly aligned. Additionally, the fact that the two sets of images were taken in different seasons impacted the location of the snowline in the two outlines.

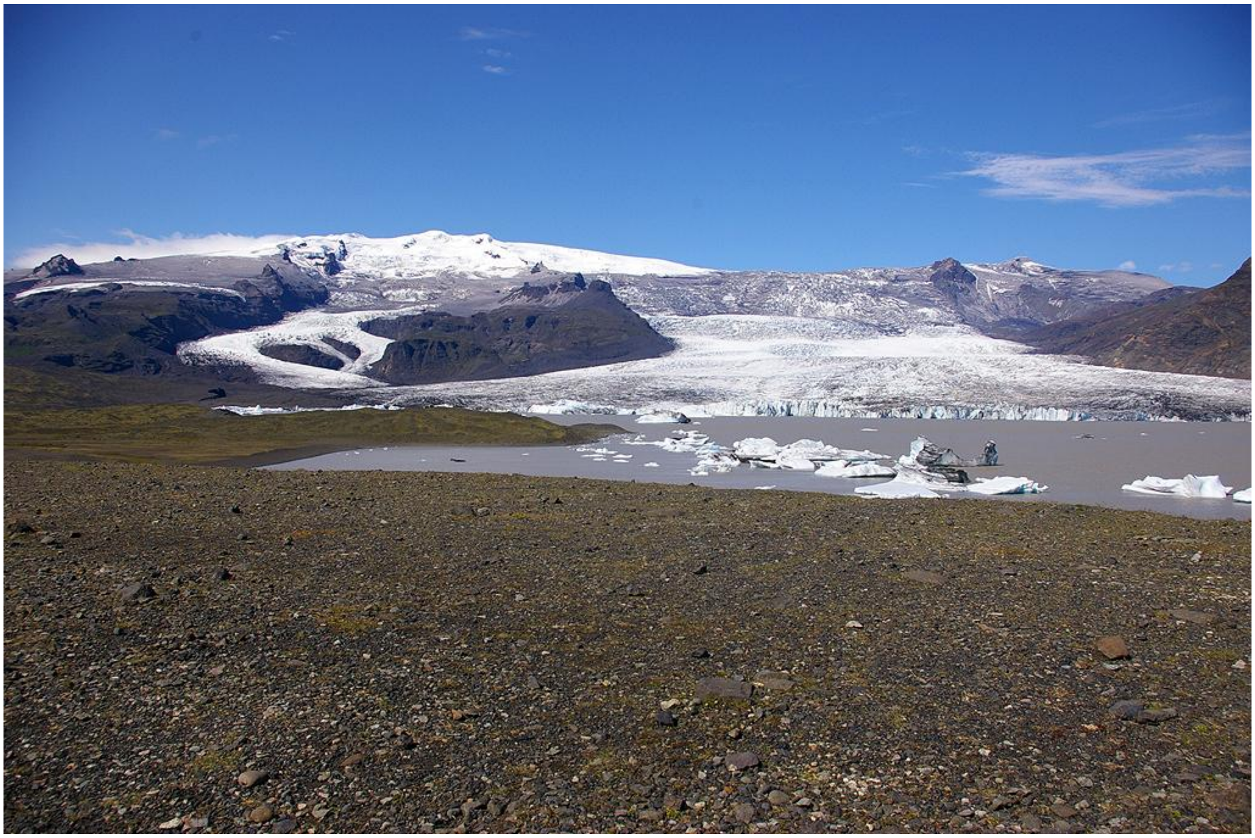

Figure 6a. Photograph of Fjallsjökull taken in the summer of 2013 by Professor Doug Thomspon

Figure 6b. Repeat photograph of Fjallsjökull taken in March of 2023 by Madeleine Gassin

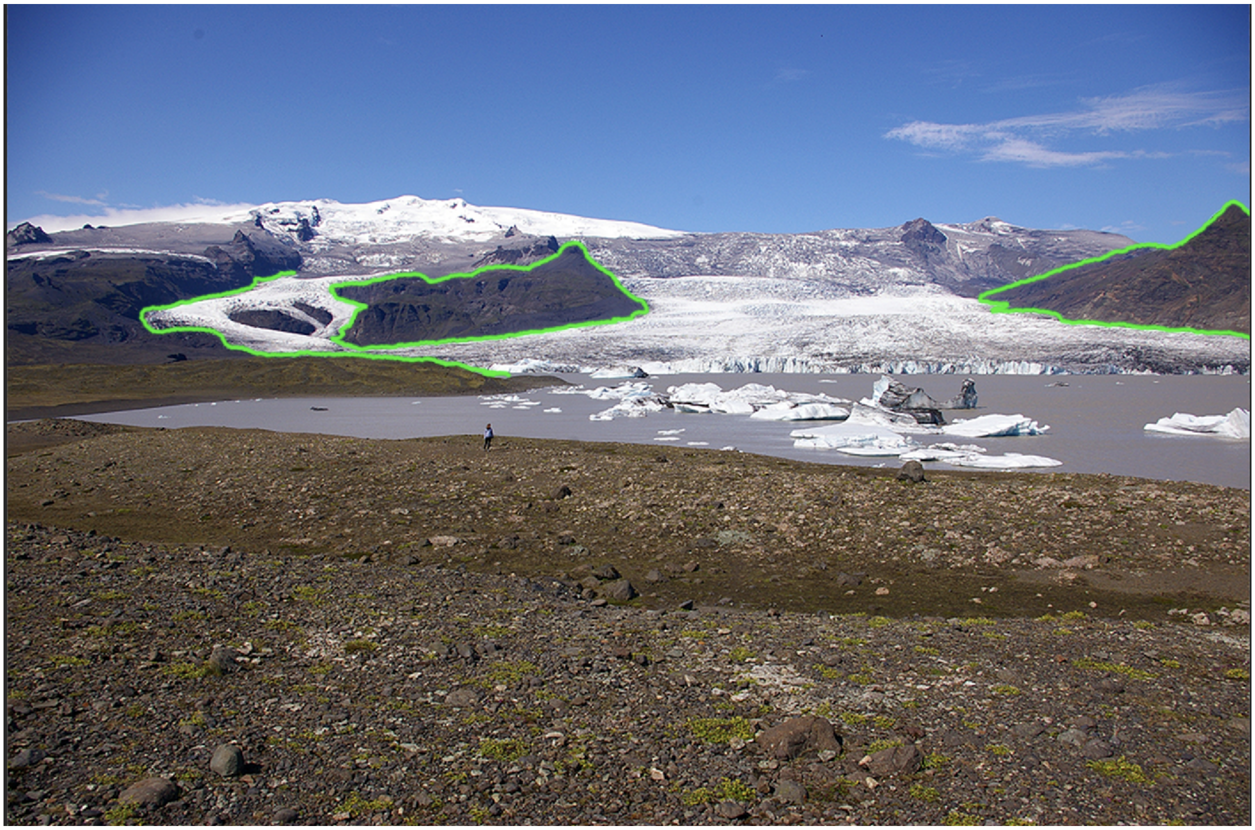

Figure 6c. Baseline photograph of Fjallsjökull with important landmarks (mountains, rock formations, etc.) outlined in green.

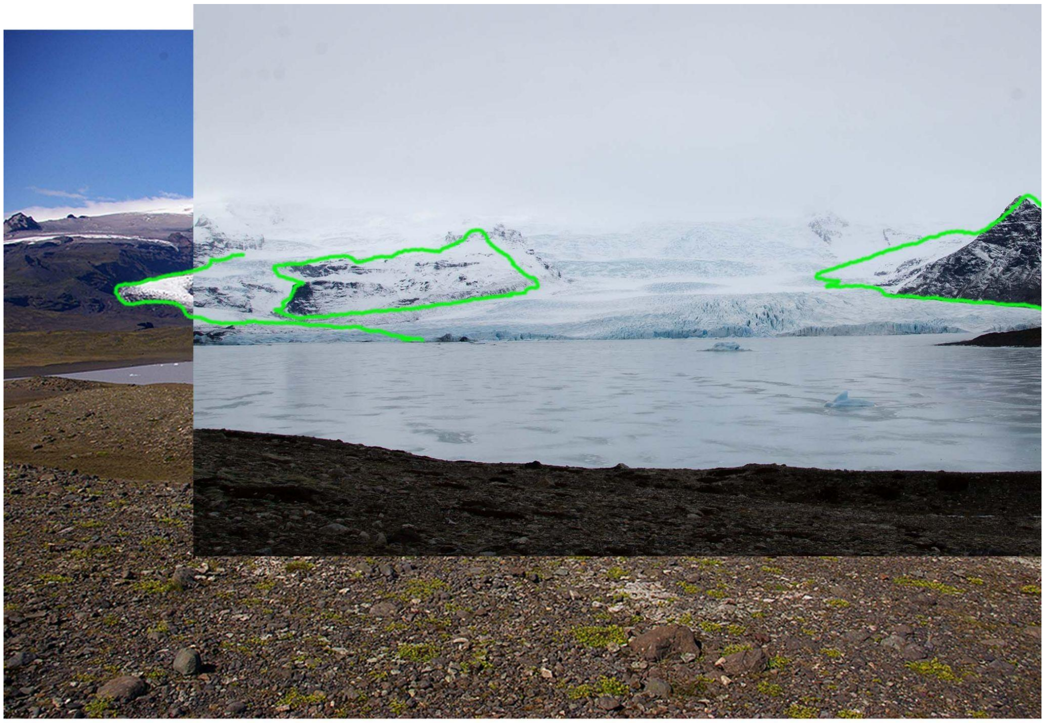

Figure 6d. Fjallsjökull work in progress. Both the original and the repeat photographs have been layered together following the outline of the important landmarks.

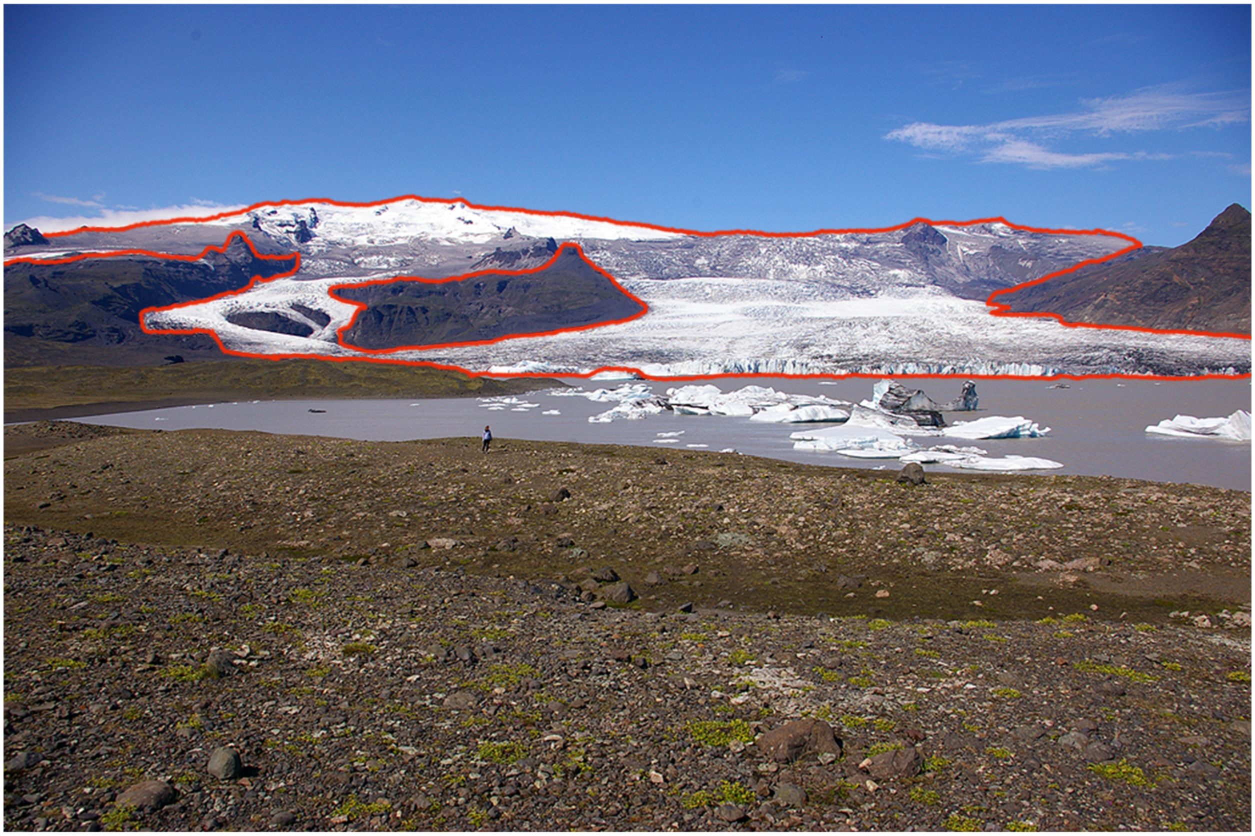

Figure 6e. Outline of Fjallsjökull from 2013 baseline image.

Figure 6f. Outline of Fjallsjökull from 2023 repeated photograph.

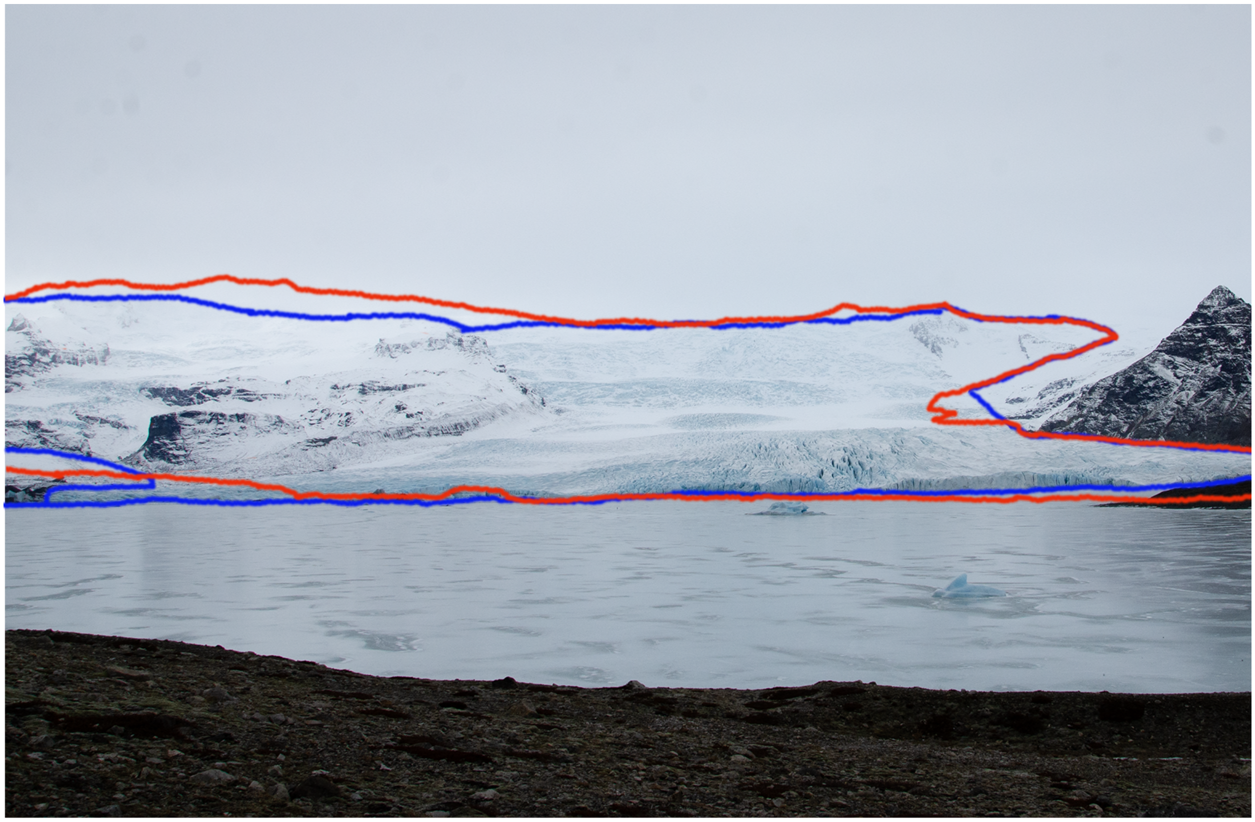

Figure 6g. Layered outlines of Fjallsjökull from the 2013 baseline photo and the 2023 repeated image displayed on the 2023 repeat photograph.

4.3 PHOTOGRAPHIC LOCATIONS

Five different glacial sites consisting of four different outlet glaciers of Vatnajökull were initially photographed for the purpose of a repeat photography glacial analysis. These four outlet glaciers included: Hoffelsjökull, Breiðamerkurjökull, Fjallsjökull, and Skaftafellsjökull (Figure 7). However, of the four outlet glaciers photographed, only three were photographed successfully enough to be used in the repeat photographic analysis (Fjallsjökull, Breiðamerkurjökull, and Hoffelsjökull; Figure 7) due to encountered difficulties in aligning the images with slightly different perspectives.

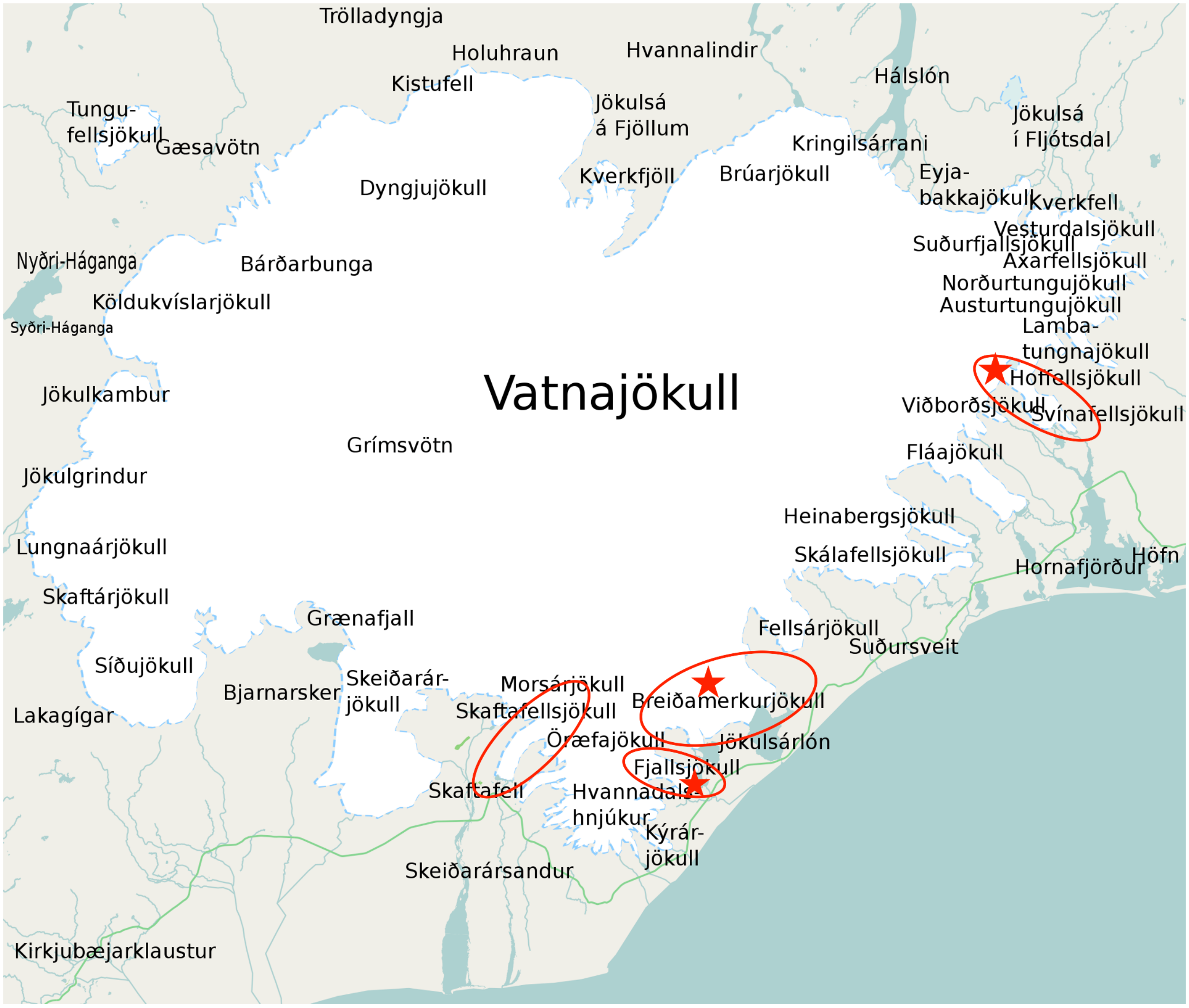

Figure 7. Map of Vatnajökull and its outlet glaciers. The outlet glaciers initially photographed for the repeat photographic analysis are circled in red (from left to right:Skaftfellsjökull, Fjallsjökull, Breiðamerkurjökull, and Hoffelsjökull). The outlet glaciers that were successfully repeat photographed and analyzed (Breiðamerkurjökull, Fjallsjökull, and Hoffellsjökull) are starred in red.

5. RESULTS

The photos of different Vatnajökull outlet glaciers all show a similar pattern of glacial volume loss throughout the ten-year period when the original photo was taken in 2013 and when the repeat photograph was taken in 2023. Upon analysis, two of the three successful repeated photographs (Figure 9-Fjallsjökull Glacier and Figure 10-Breiðamerkurjökull Glacier) showed evidence of more volume loss above the glacier's ELA, in the accumulation zone, than below the ELA, in the ablation zone. Hoffellsjökull Glacier (Figure 9) was the only glacier that showed evidence of more volume loss below the ELA, in the ablation zone than above the ELA, in the accumulation zone (although some volume loss was also seen above the ELA).

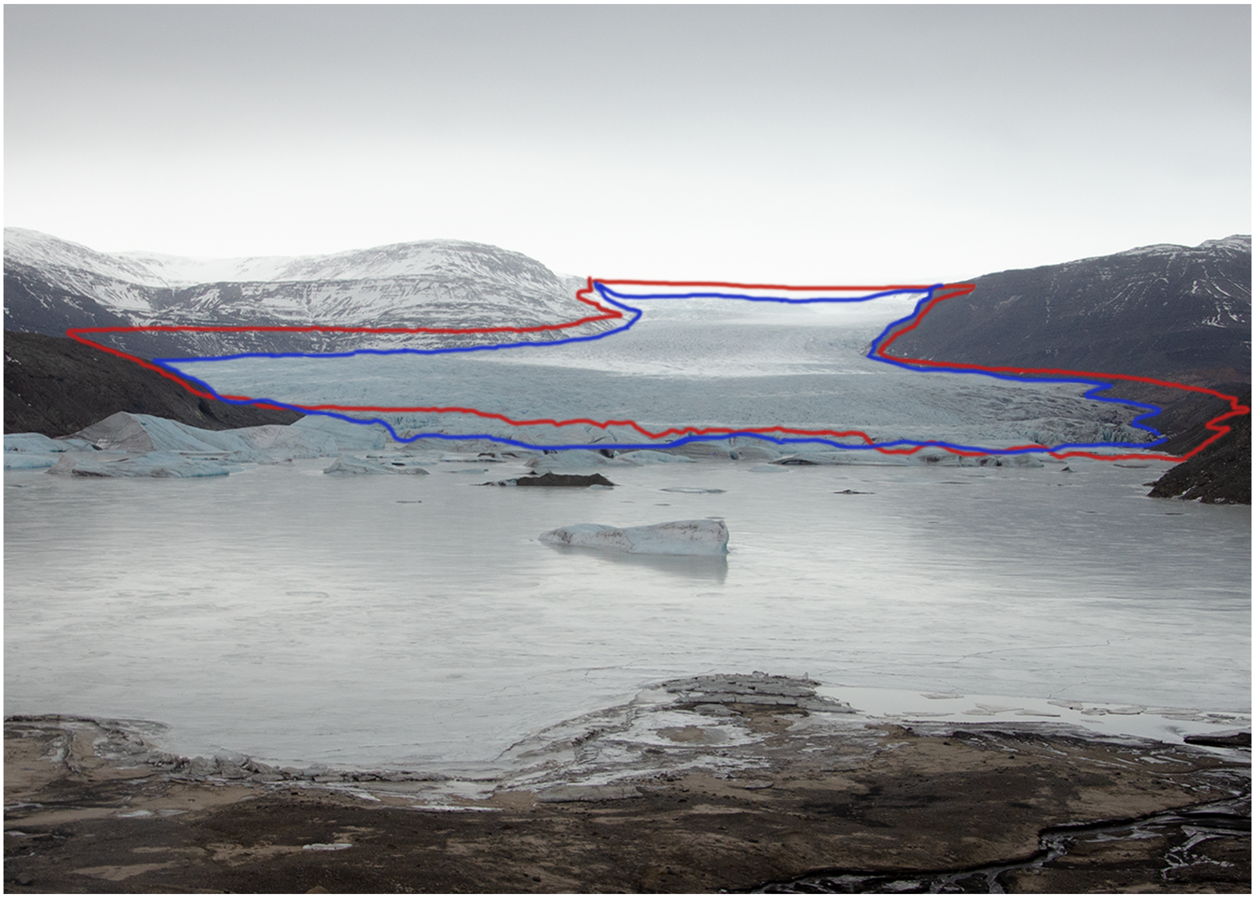

Figure 8. Hoffelsjökull outline
A layered image of the 2013 glacial outline and the 2023 glacial outline on the image taken in 2023. Red line: Outline of the glacier from Figure 8a, image taken in 2013 Blue line: Outline of the glacier from Figure 8b, image taken in 2023

As shown in Figure 8, the older outline of the glacier, taken from 2013, seems larger than the newer outline, taken from 2023, suggesting a loss of glacial volume occurring throughout the ten year period. Although some of the glacier's loss of volume seems to have occurred above the glacier's equilibrium line altitude (ELA), in the accumulation zone, the majority of the observed change seems to have primarily occurred below the glacier's ELA, as we can see from the ice-margin retreat focused at the foot of the glacier. From the photograph above (Figure 8), it seems like the ice-margin retreat is especially visible on the sides of the glacier towards the marginal moraines. This can further be seen in Figures 5a and 5b as more of the lateral moraine is visible in the 2023 photograph (Figure 8b) than in the 2013 photograph (Figure 8a).

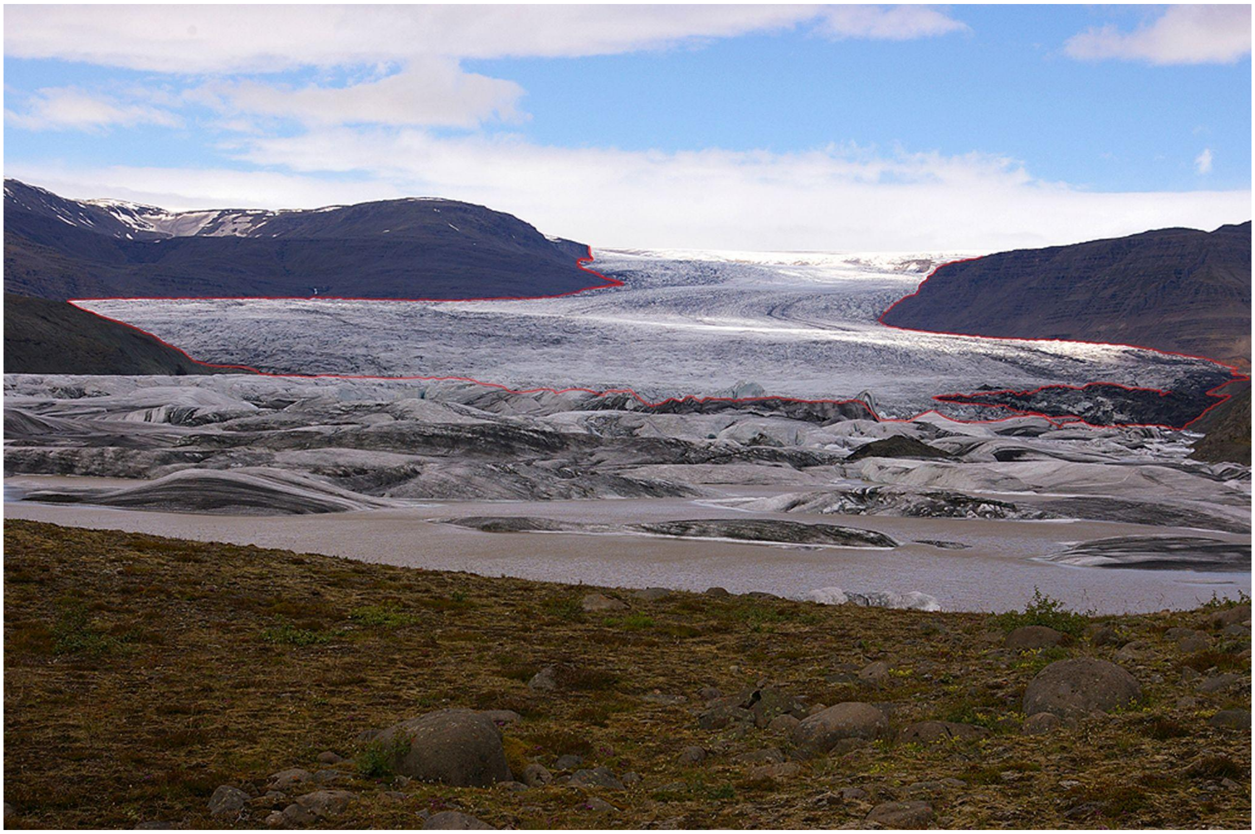

Figure 8a. Hoffelsjökull Glacial Outline 2013
Historical image used for Hoffelsjökull Glacier taken in the summer of 2013 by Doug Thompson. The glacier has been outlined in red.

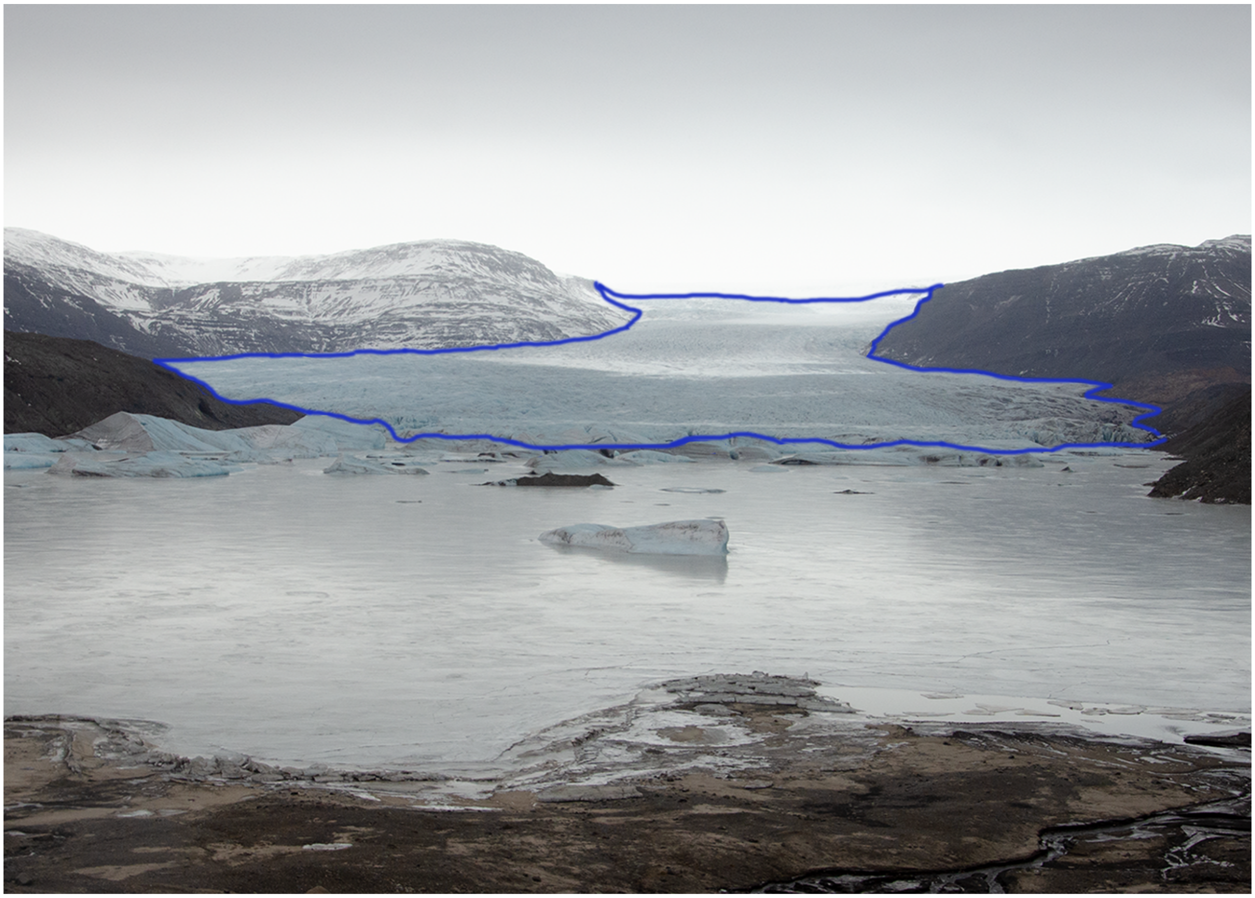

Figure 8b. Hoffelsjökull Glacial Outline 2023
Repeated photograph used for Hoffellsjökull Glacier taken in the winter of 2023 by Madeleine Gassin. The glacier has been outlined in blue.

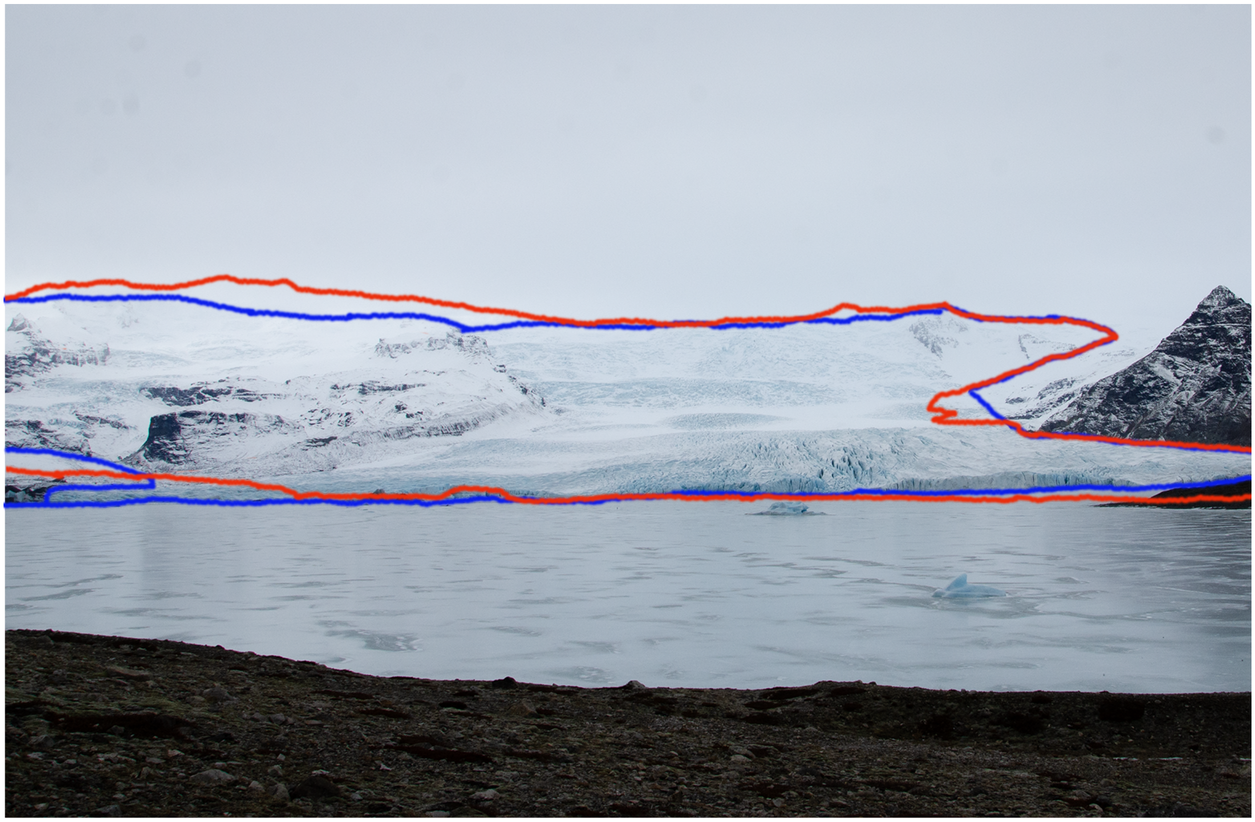

Figure 9. Fjallsjökull Glacial outline
A layered image of the 2013 glacial outline and the 2023 glacial outline on the image taken in 2023. Red line: Outline of the glacier from Figure 9a, image taken in 2013 Blue line: Outline of the glacier from Figure 9b, image taken in 2023

As can be seen from Figure 9, the outline of Fjallsjökull from an image from 2013 seems larger than the outline obtained from a 2023 image, suggesting the occurrence of glacial volume loss occurring during the ten year period in between photographs. Although some parts of the glacier seem to have advanced slightly compared to 2013, primarily on the lower left and on the right sides of the image, other sections show clear evidence of volume loss, especially on the upper left side of the image and on the lower right side. Although the volume loss occurring on the lower right section of the image is below the glacier's equilibrium line altitude (ELA), and therefore in the ablation zone, the volume loss focused at the upper left side of the image is above the glacier's ELA and is therefore in the accumulation zone. Additionally, in this image, we can see what appears to be the formation of a recessional moraine towards the middle of the right side of the image. However, while the formation of this recessional moraine indicates that the glacier has lost volume from the ablation zone, from the image and its outlines, the majority of the glacier's volume loss seems to have occurred above the ELA, in the accumulation zone.

Figure 9a. Fjallsjökull Glacial Outline 2013
The historical image used for Fjallsjökull Glacier taken in 2013 by Doug Thompson. The glacier has been outlined in red.

Figure 9b. Fjallsjökull Glacier outline 2023
Repeated photograph for Fjallsjökull Glacier taken in the winter of 2023 by Madeleine Gassin. The glacier has been outlined in blue. The recessional moraine can be seen towards the middle of the right side of the image.

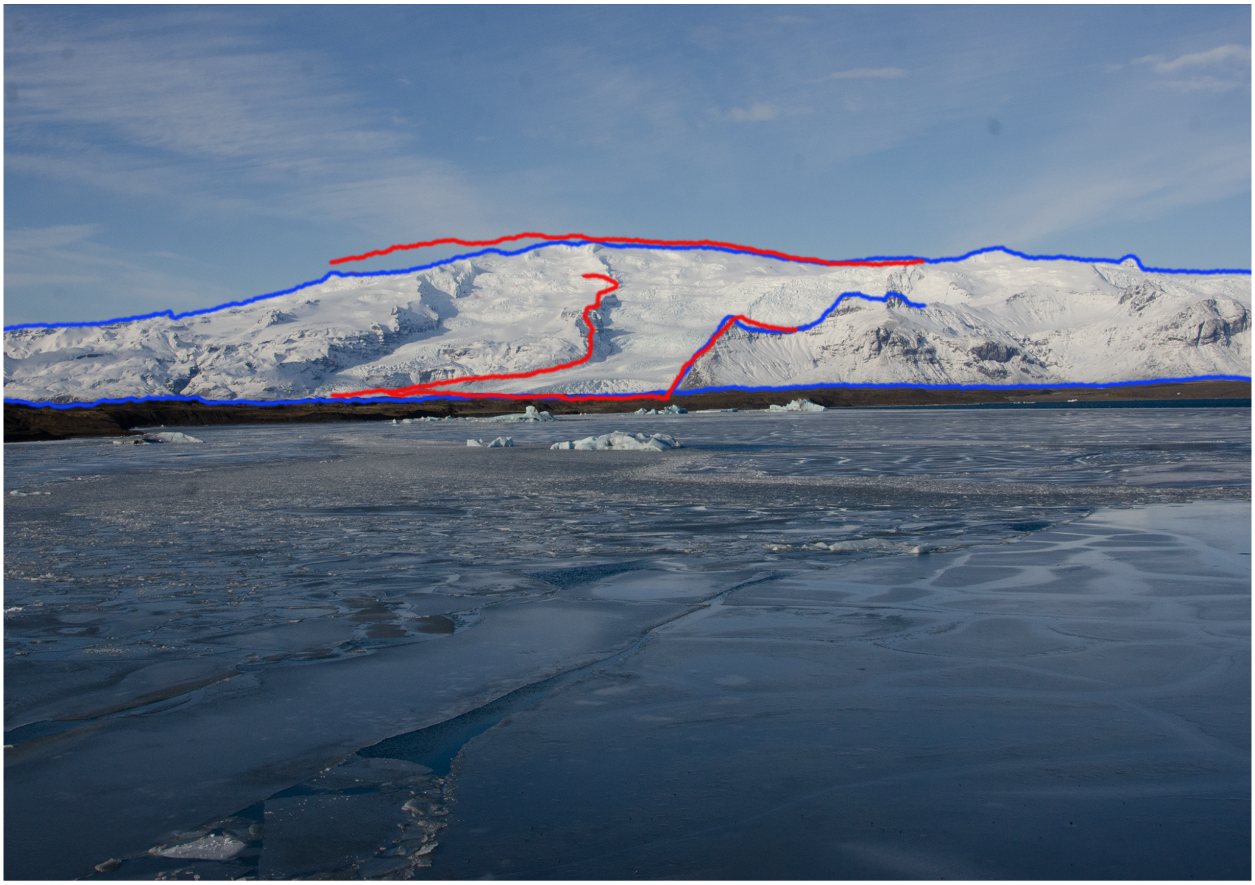

Figure 10. Breiðamerkurjökull Glacial Outline.
A layered image of the 2013 glacial outline and the 2023 glacial outline on the image taken in 2023. Red line: Outline of the glacier from Figure 10a, image taken in 2013 Blue line: Outline of the glacier from Figure 10b, image taken in 2023

Figure 9 compares the 2023 glacial outline to the 2013 glacial outline. While many parts of the outlines seem to overlap one another, there is a big divergence in the outline towards the left head of the glacier. The newer blue outline is much lower than the red outline from the 2013 image, thus suggesting that glacial volume loss occurred during the ten-year period. Some volume loss also seems to have occurred towards the left foot of the glacier, although the difference is subtle compared to the loss that occurred at the head of the glacier. The majority of the glacial volume loss, therefore, seems to have been focused on areas above the ELA, and therefore in the accumulation zone instead of the ablation zone (below the ELA).

Figure 10a. Breiðamerkurjökull Glacial outline 2013
The historical image used for Breiðamerkurjökull Glacier taken in the summer of 2013 by Doug Thompson. The glacier has been outlined in red.

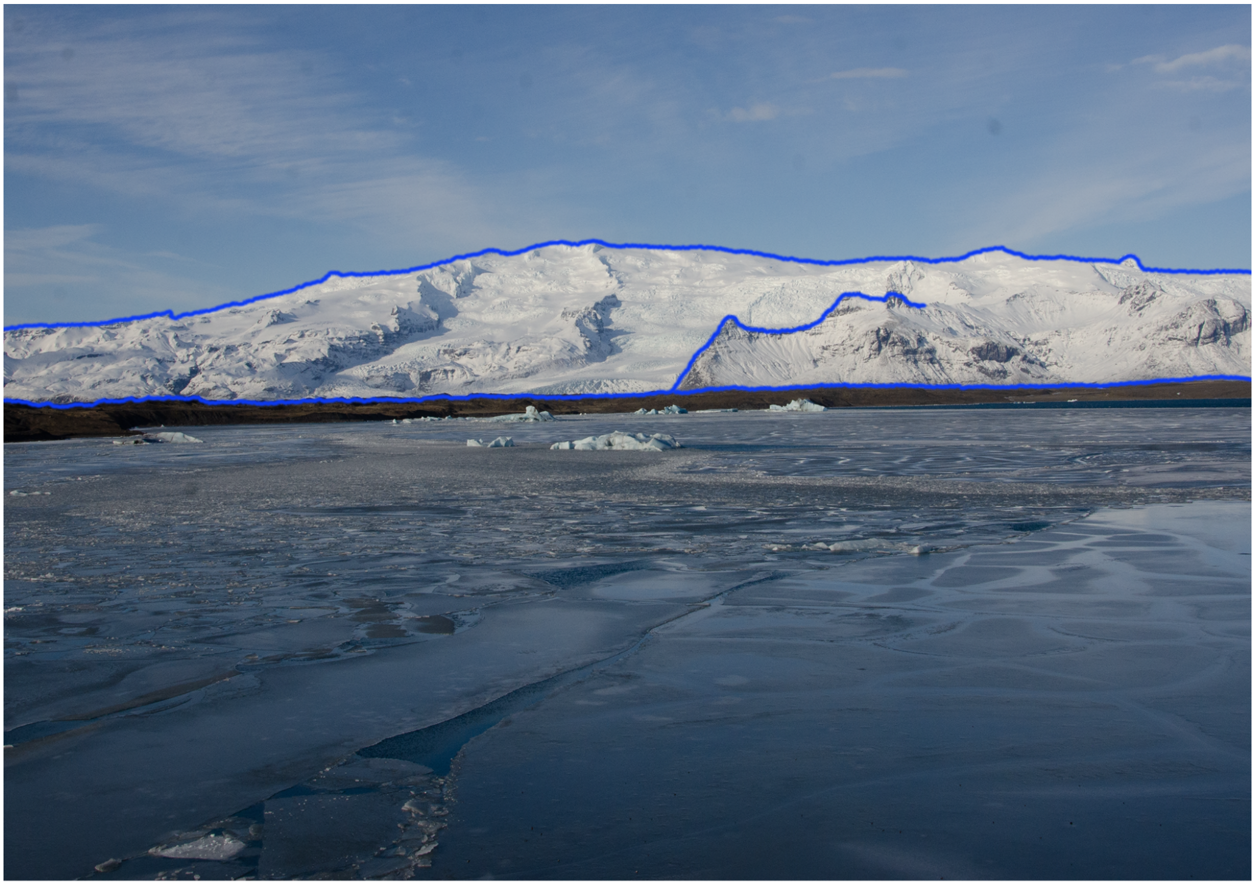

Figure 10b. Breiðamerkurjökull outline 2023.
Repeated photograph used for Breiðamerkurjökull Glacier taken in the winter of 2023 by Madeleine Gassin. The glacier has been outlined in blue.

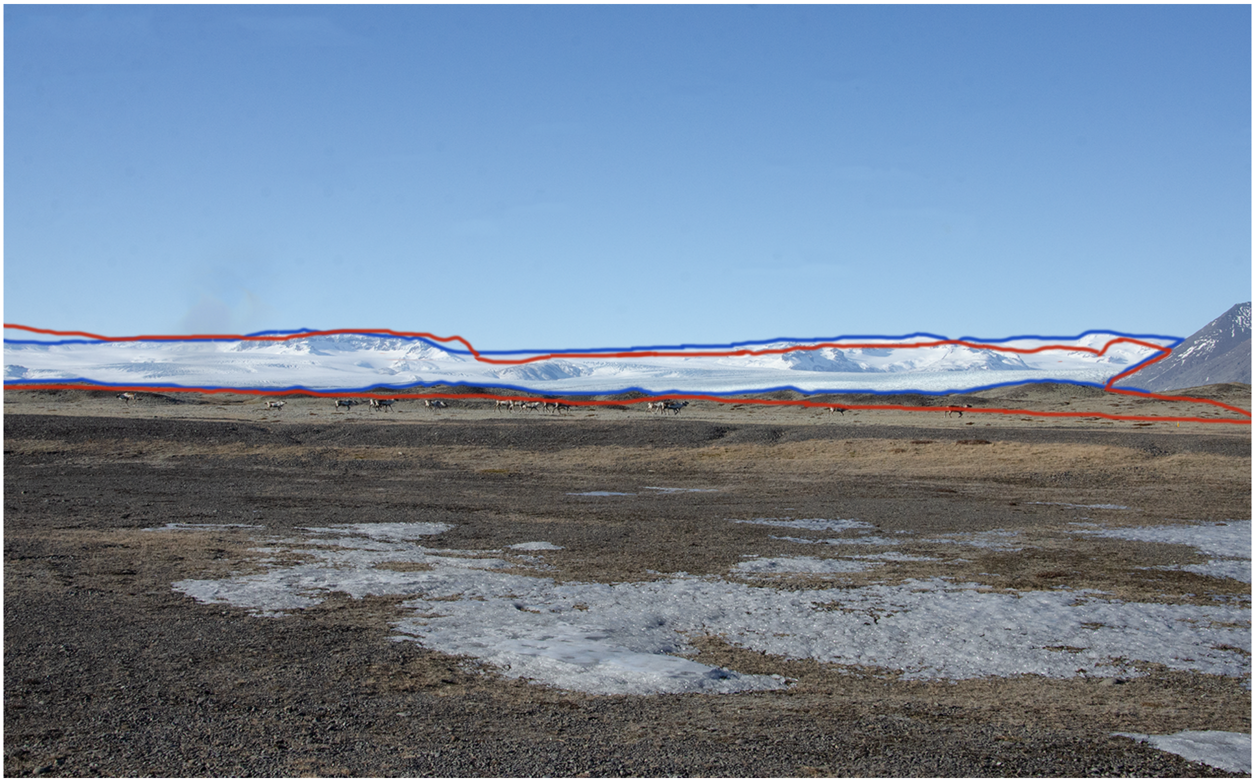

Figure 11. Breiðamerkurjökull glacial outline from a different perspective.
A layered image of the outline of Breiðamerkurjökull from the 2013 photograph and the outline of the 2023 photograph. Red line: Outline of the glacier from Figure 10a, image from 2013. Blue line: Outline of the glacier from Figure 10b, image from 2023.

Figure 11 shows the results of the outline for Breiðamerkurjökull from photographs taken from a different perspective than those from Figure 10. While the newer blue outline seems to perfectly represent the area covered by the glacier, the older red outline includes a large portion of land that seems far from the glacier and includes old recessional moraines in the area that should represent ice cover. From Figure 11, we can see that the moraines included in the red outline are older than ten years old as they are completely covered by vegetation and are extremely far away from the actual glacier. We can therefore see that the red outline is not representative of the glacier's position in 2013. We can further see this in separate 2013 and 2023 images (Figures 11a and 11b) as Figure 11a seems to have been taken from a higher perspective than Figure 11b, thus allowing us to see the foot of the glacier in Figure 11a.

Figure 11a. Breiðamerkurjökull Glacier 2013
A rejected historical image of Breiðamerkurjökull from a different perspective than in Figure 10 (the accepted repeat photograph).

Figure 11b. Breiðamerkurjökull Glacier 2023
A rejected repeated photograph of Breiðamerkurjökull from a different perspective than shown in Figure 10 (the accepted repeat photograph). Reindeer can be seen traversing the landscape towards the center of the image.

6. DISCUSSION:

6.1 METHODOLOGICAL REVIEW

In an attempt to demonstrate the effects of climate change on glaciers in Iceland in a visual manner, this study has used repeat photography as a tool to help visualize climate change-driven glacial decline in Iceland. While the use of repeat photography has allowed us to observe climate change-driven glacial changes described in previous glaciological studies (Chandler et al., 2016; Aðalgeirsdóttir, G. et al., 2020; Compagno et al., 2021), several factors surrounding the study's approach to repeat photography have limited this study's ability to quantify data from the photographs. Despite our best efforts to replicate the original images taken in 2013, slight differences in camera perspective, distance from the glacier, and lens variability made it impossible to perfectly replicate the historical images. These small differences not only made it difficult to align the photographs in order to outline the glaciers accurately but also led to some outlines being unusable (such is the case with Figure 11 of Breiðamerkurjökull). However, regardless of the difficulties encountered during the repeat photography analysis portion of the study, the repeat photographs themselves serve as excellent visual examples of the consequences of climate change.

In the case of Figure 11, although the 2013 and 2023 images were taken approximately in the same location with approximately the same orientation, a slight difference in the distance between the camera and the glacier in the 2023 image led the images to be impossible to properly align and outline. As seen in Figure 11a, the moraines covering the valley are not as prominent as they are in Figure 11b, most likely due to there being a shorter distance between the camera and the glacier as well as a small increase in elevation compared to the 2023 photo setup. As a result of these small differences, the moraines in the 2023 image cover a majority of the foot of the glacier, leading to unreliable alignment and outlines. However, while some small differences between the baseline and the repeated photographs were able to be worked with in order to create a representative outline comparison, other seemingly small differences made it impossible. One small difference that can be worked around is distance or zoom. If your replicated image is taken from a further distance from the glacier but the perspective and major landmarks are the same as the baseline image, then the replicated image can easily be enlarged, while still keeping the rations of the original image, and then cropped to match the baseline image. However, if the angle or perspective of the replicated photograph is different from the baseline image, such as in the case of Figure 11, then it is impossible to create a representative outline comparison. The misrepresentation of glacial changes through a non-reflective outline comparison could not only impact legislative decisions surrounding climate change but could also harm the relationship between the public and the science community. The misrepresentation of climate change-induced glacial changes could lead the public to lose trust in the scientific community, thus further widening the gap that we were trying to bridge through the use of repeat photography.

An additional complicating factor when it came to analyzing the differences between the repeat photographs and the historical photographs of the glaciers is the different seasons in which the two sets of photographs were taken. While the historical 2013 images were taken during the summer, a season that is characterized by ablation, the repeat photos were taken in the winter of 2023, a season that is characterized by accumulation. Therefore, the changes in glacial volume seen in the images and outlines may not reflect the true degree of change that occurred during the study period. Furthermore, different environmental conditions, such as cloud cover, fog, and sun glare, may have also affected this study's ability to accurately outline the glaciers. While some images, primarily the historical ones, were taken on days with exceptionally clear conditions (Figures 8a, 9a, and 10a), many of the repeat photographs were taken on days with non-negligible cloud cover and sometimes fog (Figures 8b and 9b). The white of the clouds and of the fog in these images complicated the distinction between the actual glacier and the sky, further affecting the reliability of the results observed in the glacial outline comparisons (Figures 8 and 9).

The combination of these difficulties demonstrates some of the limitations of using repeat photography as a quantifiable method for observing glacial change. While it is possible to obtain quantifiable results from repeat photography, the methodology for a project of this grandeur was beyond the scope of this study. Obtaining quantifiable repeat photographs would not only require a designated precise geographical shooting location, along with designated azimuths, cameras, lenses, and tripod height but would also require a certain length of time between each set of repeat photographs. The difficulty of meeting all of these conditions makes using repeat photography for quantifiable research somewhat unfavorable. This is one of the reasons why many researchers primarily use satellite imagery and remote sensing data instead of repeat photography.

Although repeat photography was historically used to study glacial change (Webb et al., 2010), as technology has developed, so have the ways in which we study glacial change. While in the past, the majority of studies documented glacial change from the ground, much glacial photography and data are now collected from space (Benningfield, 2023). For example, the Landsat series spacecraft (Landsat 8), which launched in 2013, goes over the same section of

Earth every 16 days and records visible and infrared wavelengths with a resolution of up to 15 meters (Benningfield, 2023). These images can help researchers gain a more historical perspective while also being able to observe and quantify how much ice has receded, the change in ice area, and the change in ice flow (Benningfield, 2023). Additionally, altimetry measurements coming from the Ice, Cloud, and Land-Elevation Satellite-2 (ICESat-2), in which a laser measures changes in elevation across Earth's surface, allows researchers to have access to continuous elevation data for ice sheets across the globe (Benningfield, 2023. However, while many different kinds of satellites allow for remarkable glaciological research, perhaps the most powerful one is the Synthetic Aperture Radar (SAR), which was deployed as a part of the European Space Agency's Sentinel program, a program that aims to replace older Earth observation systems that have retired or are nearing the end of their life-span (Benningfield, 2023; European Space Agency). The SAR satellite emits pulses of radio energy at wavelengths similar to those of a microwave and measures the returning signal from the ice (Benningfield, 2023). This allows scientists to measure ice velocities without needing to see defining landmarks such as crevasses by instead allowing them to measure a pixel-by-pixel change in ice flow (Benningfield, 2023).

The collaboration of these different technologies and satellites has allowed researchers to study glaciers in a more detailed way than is possible simply with repeat photography. However, despite the high-quality data that these new technologies have brought us, they may still contribute to the existing gap between scientists and public understanding of the effects of climate change. Repeat photography may act as a way to introduce the real-life effects of climate change to non-experts (Pope, 2022). As Ronald D. Karpilo, a research associate geologist at Colorado State University, has said before, "When you show a glacier that's just not there anymore, it's hard to dispute. It's disappearing… something is changing, and so that's what's made it such a great tool," (Pope, 2022). Used in parallel with supporting scientific data, repeat photography may be a powerhouse tool in bridging the gap between the scientific community and the general public's understanding of climate change.

6.2 DATA COMPARISON

A comparison of the outlines of the 2013 glaciers and the 2023 glaciers in the photographs shows a general trend of volume loss occurring during the ten-year period. However, while two of the glaciers, Breiðamerkurjökull and Fjallsjökull showed important signs of volume loss focusing in the accumulation zone, Hoffelsjökull was the only glacier that showed signs of volume loss being focused in the ablation zone. While the findings suggest that all of the glaciers are losing mass faster than they are accumulating it, the fact that volume loss is occurring more in the accumulation zones of two of the three glaciers was unexpected. It is possible that warmer summer atmospheric temperatures are increasing glacial melt, leading more glacial mass to flow downhill without enough accumulation of precipitation to replace the lost mass. In fact, a 2016 study by Chandler et al., found that summer atmospheric temperatures were the primary drivers of ice-marginal retreat for Skálafellsjökull, an outlet glacier of Vatnajökull.

Since Breiðamerkurjökull and Fjallsjökull are both outlet glaciers of Vatnajökull, not only are these glaciers likely to be similar in structure (temperate), but it is also very likely that they are subject to similar, if not the same, weather patterns. Therefore, the sensitivity to warm atmospheric air temperatures found regarding Skálafellsjökull could also be applied to Vatnajökull's other outlet glaciers, including Breiðamerkurjökull, Fjallsjökull, and Hoffelsjökull.

This would suggest that as summer atmospheric air temperatures have increased over time due to climate change, increased glacial melt has led more of these glaciers' masses to flow downhill without an adequate amount of precipitation accumulation to replenish the loss of mass. These results could further be explained by Breiðamerkurjökull's tidewater nature, in which the lack of resistance that occurs when tidewater glaciers float can lead the glacier to flow and calve rapidly, therefore leading to rapid ice loss (Bierman and Montgomery, 2014). Furthermore, the lack of resistance at the terminus of tidewater glaciers can facilitate basal sliding and can therefore lead to glacial surges (Bierman and Montgomery, 2014).

Despite Fjallsjökull and Hoffellsjökull not being tidewater glaciers, the sediment type of the region could also be producing a similar effect. It is largely believed that rapid ice-marginal advances during glacial surges occur due to fast ice flow being sustained by the deformation of water-saturated sediment that is strongly coupled to the glacier (Ingólfsson et al., 2016). This sub-glacial bed deformation, in which the bed surface is deformed by the weight of the glacial ice, occurs when the water pressure in the pore spaces between the sediment grains increases enough and allows them to move relative to one another (Hambrey and Glasser, 2005). This grain movement from water-saturated sediment, along with the meltwater, would therefore act as a lubricant that would then facilitate the movement of any present ice flow (Hambrey and Glassar, 2005; Ingólfsson et al., 2016). However, in order for grains of water-saturated sediments to be able to move relative to one another and thus deform, the sediment must be permeable enough to accommodate higher water pressures within the pore spaces between the sediment grains (Hambrey and Glassar, 2005; Ingólfddon et al., 2016). This phenomenon is therefore more common in environments with highly permeable sediment and poorly consolidated soils, such as Breiðamerkurjökull. In fact, it's been estimated that approximately 90% of Breiðamerkurjökull's velocity is due to subglacial bed deformation occurring due to the poorly consolidated sediments of the area (Hambrey and Glasser, 2005). Breiðamerkurjökull and Fjallsjökull's close proximity to each other could therefore point to similar soil composition of the surrounding area and could further accelerate downward glacial velocity, thus resulting in an imbalance between the accumulation and ablation zones.

As the snout of the glacier moves too quickly for the rest of the glacier, the balance between the accumulation and ablation zones is disrupted (Bierman and Montgomery, 2014). It is therefore possible that both Breiðdamerkurjökull and Fjallsjökull, both glaciers known to occasionally surge (Björnsson et al., 2003), are currently surging. Although surging glaciers do not usually alter their mass, the fact that the glaciers' overall current outlines are smaller than the older outlines despite the possible rapid frontal ice margin advance would not only further suggest an important ice volume loss occurring during the ten year period, but would even suggest the possibility of the volume loss being more significant than originally thought.

Hoffelsjökull was the only outlet glacier studied that showed the expected loss of volume presenting primarily in the ablation zone. Although the glacier did show signs of volume loss in the accumulation zone, it was predominantly present in the ablation zone and was concentrated at the foot of the glacier and towards the lateral margins. Therefore, although the glacier shows clear signs of ice volume loss, the glacier's accumulation and ablation zones appear to be more well-balanced than Breiðamerkurjökull and Fjallsjökull and may thus suggest that Hoffelsjökull is not currently surging. This may be due to the fact that Hoffelsjökull, unlike Breiðamerkurjökull is not a tidewater glacier and therefore has a stronger resistance to basal sliding as it relies entirely on meltwater as lubrication. It is also possible that due to the distance between Hoffelsjökull and Breiðamerkurjökull, the sediment in the area surrounding

Hoffelsjökull is composed of more consolidated sediments than those around Breiðamerkurjökull.

The results of the repeat photographic outline comparisons are further supported by the results found in the literature review, in which glacial decline was observed, not only in Iceland but also in other parts of the world (Aðalgeirsdóttir, G. et al., 2020; Chandler et al., 2016). In fact, in the study by Aðalgeirsdóttir, G. et al. (2020), researchers found that nearly half of the total observed mass change (-240 +/- 20 Gt) from 1890 to 2019 occurred from geological years 1994/1995 to 2018/2019 (Figure 3G, Aðalgeirsdóttir, G. et al., 2020), which reflected higher temperatures than previous years (Figure 3E, Aðalgeirsdóttir, G. et al., 2020). This is further supported by the findings of a study from 2016 by Chandler et al., which reported that annual moraine formation along with ice-front recession was seen from the winter of 2005/2006 until the end of their imagery archive in June of 2012. As annual air temperatures have started to rise, so have glacial retreats in Iceland. In addition to rising air temperatures, according to Chandler et al. (2016), rising ocean temperatures may also be contributing to glacial recession by driving air temperatures. As a result of these temperature increases, it has been projected that glaciers in Iceland will continue to retreat. In fact, a 2021 study by Compagno et al. (2021), projects the anticipated ice volume loss of Icelandic glaciers to be between 16 +/- 5% (RCP2.6) and 21 +/- 5% (RCP8.5) by 2050, and between 43 +/- 11% (RCP2.6) and 85 +/- 7% (RCP8.5) by 2100 (Figure 12)[2].

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[2] RCP: Representative Concentration Pathways climate model

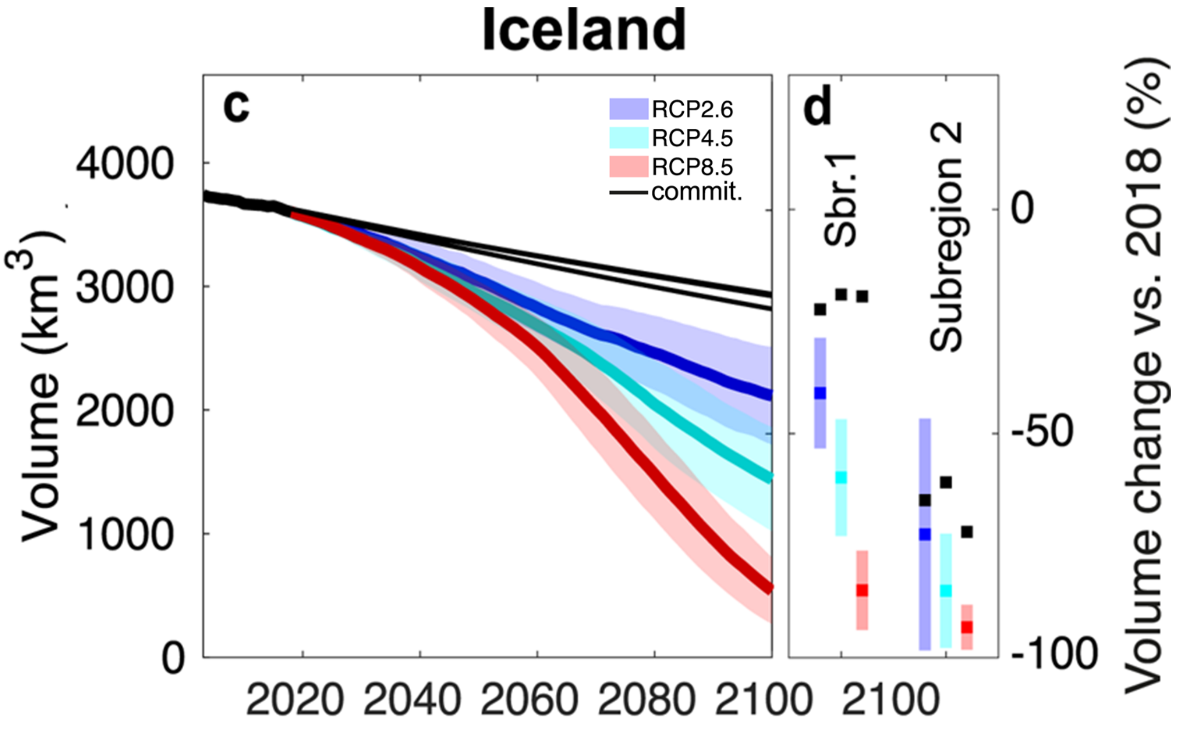

Figure 12: Modelled volume evolution of all glaciers in Iceland. For every RCP, the thick line represents the mean using all past climate data products and Regional Climate Models (RCM) as future climate projection. The transparent bands correspond to the standard deviation of all climate model members. The modeled ice volume fraction that remains in the subregions by 2100 is shown in panels and d. The percentages are relative to the volume in 2018. The black continuous lines in (c), and the black squares in (d), represent the committed loss under 1998–2018 climatic conditions. Note that there is one such line and square for each past climate data products. Modified from Compagno et al., 2021.

6.3 LONG-TERM IMPACTS OF CLIMATE CHANGE ON GLACIERS IN ICELAND

Understanding the full impacts of climate change on Icelandic glaciers is an integral part of raising awareness. As previously seen in Figure 5, a negative glacial mass change is directly linked to a positive sea-level change (Aðalgeirsdóttir, G. et al., 2020). In fact, according to Aðalgeirsdóttir et al. (2020), the total mass change in Icelandic glaciers from 1890 to 2019 was found to be 1.50 +/- 0.36 mm SLE per area. Although glacial mass changes can vary on a yearly basis, the continuous trend of glacial mass loss would thus also suggest a trend in increases in sea-level elevation per area. Aðalgeirsdóttir et al. (2020) suggest that from 1996 to 2019, with the exception of 2015, glaciers in Iceland saw a negative mass change, therefore indicating a positive change in sea-level elevation. However, while Iceland's melting glaciers may contribute to global sea-level rise, deglaciation in Iceland is leading to land in Iceland to rise. As glacial mass is lost, the overall weight of the ice mass decreases, thus causing less depression on the earth's lithosphere causing the surface to rise up compared to sea level in a process called isostatic rebound. As the weight continues to decrease with the loss of ice, the land surface's elevation will also continue to increase, thus causing a decrease in regional sea level (National Snow and Ice Data Center, 2023). The effects of this post-glacial isostatic rebound can already be seen in Iceland. Areas with large concentrations of glacial mass, like Vatnajökull, are already estimating 20 mm/yr in crustal uplift with nearby towns like Höfn estimating 10 mm/yr in uplift (Icelandic Met Office, 2018). With the projected continued glacial decline in Iceland (seen in Figure 12) more meltwater, and therefore mass, will continue to be added to the world's oceans thus continuing to cause global sea-level elevation increase in certain regions and a sea-level elevation decrease in regions that are actively losing glacial mass. Since crustal uplift is directly related to glacial recession, in addition to using repeat photography on the glacier, it may also be beneficial to conduct repeat photography on nearby shorelines in order to visually document the secondary effects of climate change-induced glacial recession.

The effects of glacial recession in Iceland are already being observed and as glacial ice is projected to continue to quickly retreat, their impacts can only be expected to worsen. Although the 20 mm/yr increase in crustal uplift near Vatnajökull may seem like a small impact, it has larger implications for Iceland and its community. Fishing boats are already struggling to come in and go out of harbors and are already experiencing increased risks of grounding and therefore also increasing the risk of shipwreck, leaking hulls, and financial loss (Kottasovà and Doran, 2022). In fact, in some areas, navigation in and out of the harbor has become entirely tide-dependent leading ships to be increasingly vulnerable to storms (Alderman, 2019). According to a 2019 article from *The New York Times*, Mr. Ingólfsson, a fisherman from Höfn, had already experienced two of his trawlers being stuck in the harbor as a storm hit and needing to offload their catch at a factory further up the coast (Alderman, 2019). Unfortunately, as glacial decline worsens, these experiences can be projected to not only continue, but also worsen in severity, ultimately increasing the overall human danger surrounding the fishing industry. For countries like Iceland whose economy heavily relies on the fishing industry, the overall increase in human risk and the possibility of financial loss due to climate change-induced glacial changes could have devastating consequences.

Unfortunately, the impacts of climate change-induced glacial retreat do not end with sea-level elevation. As previously mentioned, glacial retreats can also impact water availability and distribution, hydropower production, natural hazards, and tourism. As glaciers continue to recede due to rising atmospheric air temperatures, one of the most important drivers of glacial change (Chandler et al., 2016), glaciers release higher amounts of meltwater than usual, thus altering the course of glacial rivers (Icelandic Met Office, 2018). As high amounts of meltwater continue to be emitted as the glaciers recede, its meltwater “reservoir” also shrinks, leading glacial meltwater output to not only decrease over time but also stop completely once the glacier disappears. This affects river flow further downstream and can further lead to more seasonal water availability and distribution as well as impact hydropower production (Davies, 2022; Icelandic Met Office, 2018; Schaefli et al., 2019).

Glacial recession in Iceland has also been directly linked to increased risk of both landslides and volcanic activity (Icelandic Met Office, 2018). While the thawing of permafrost initially destabilizes existing slopes, this effect is reinforced by the loss of stabilization coming from a previously supporting retreating glacier (Icelandic Met Office, 2018). This climate change-induced destabilization of slopes is expected to increase Iceland's risk of landslide frequency and possibly intensity (Icelandic Met Office, 2018). Additionally, as many Icelandic volcanoes are located underneath glacial ice, the loss of glacial mass is expected to decrease lithostatic pressures on subglacial magma chambers, thus leading to an increase in magma production (Icelandic Met Office, 2018). This increase in magma production underneath glacial ice may not only result in more frequent and longer-lasting volcanic eruptions, but may also promote volcanically generated jökulhlaups, possibly leading to catastrophic consequences on the Icelandic landscape including flattened landscapes, destruction of vegetation and wildlife, and possibly even the loss of human life (Icelandic Met Office, 2018; Bierman and Montgomery, 2014).

The loss of Icelandic glaciers would additionally result in the loss of some of Iceland's most attractive landmarks and would further lead to the loss of some of Iceland's most famous tourist attractions associated with glaciers, including ice cave exploring, ice climbing, glacier hiking, etc. (Vargas, 2017). The loss of these tourist attractions could further negatively impact Iceland's economy, 39% of which relies on tourism (Welling et al., 2020). As glaciers in Iceland are projected continue to quickly retreat (Figure 12) and may even disappear completely by 2200 (Kottasovà and Doran, 2022), the negative impacts of glacial retreat can only be expected to worsen.

However, while people in Iceland struggle with the local impacts of climate change-induced glacial retreat and its subsequent impacts on Iceland's economy and culture, the impacts of the consequential rise in sea level in other parts of the world are felt disproportionately. Island nations with low ground elevation are the most at risk from the effects of global sea-level rise and are usually the least responsible for driving climate change (Kottasovà and Doran, 2022). The reality of the climate change-induced glacial decline is that despite glaciers often being considered a very local phenomenon, it is important to understand their impacts on the rest of the world. Although glacial retreats will affect local communities in important ways, either through changes in water availability and distribution, hydropower, sea-level elevation, natural hazards, or tourism, changes in glacial systems also affect communities beyond the local region. It is therefore not only important to understand the global nature of climate change-induced glacial retreat despite only studying a small glaciated region but also important to work on minimizing our climate impact.

6.4 POSSIBLE CLIMATE ACTIONS

Actions to minimize climate impacts can range from individual actions, community programs, to nationwide initiatives. Individual actions such as switching to LED light bulbs and energy-saving appliances, changing your home's source of energy to a more renewable one, using public transportation, eating more plant-based foods, and limiting your purchases of consumer goods can be great ways to reduce your individual carbon footprint. Although individual actions may differ depending on a person's ability to make certain changes, each individual action can help limit climate change impacts. Community-based projects and initiatives are also great ways to have a more widespread impact than acting as an individual. These can vary from installing solar panels in communities without access to electricity to community, city, or state environmental policies and restrictions. For example, the New York State Environmental Quality Review Act (SEQR) requires all local, regional, and state government agencies to equally examine the environmental impacts, as well as the social and economic considerations of any project or action during a required discretionary review (New York State Department of Environmental Conservation, 2023). Although community-based initiatives may act on smaller regions than a nationwide policy would, several community-based initiatives with similar policies and projects could eventually form a significant part of a country and therefore have a significant impact. This is especially true if these community-based policies include cities or areas with large populations or significant environmental impacts.

Whereas community-based initiatives focus on certain communities or regions, nationwide initiatives allow for a uniform change across a nation. As these initiatives usually include nationwide climate policies that limit a nation's environmental impact through climate action plans, they can sometimes be motivated by global international treaties, such as the Paris Agreement. Countries that sign such a treaty are legally bound to comply and must therefore ensure that their climate action plans fulfill the requirements of the treaty. For example, Iceland's updated 2020 Climate Action Plan includes 48 actions aimed at reducing carbon emissions and increasing carbon uptake from the atmosphere (Government of Iceland, Ministry for the Environment and Natural Resources, 2020). This plan aims to cut Iceland's greenhouse gas emissions by 40% by 2030, thus abiding by the Paris Agreement, while also helping Iceland achieve carbon neutrality before 2040 (Government of Iceland, Ministry for the Environment and Natural Resources, 2020). Nationwide climate initiatives can therefore be a great way to enforce standardized climate action and regulations on the public.

However, although these widespread climate policies may be effective in limiting a nation’s climate impact, they can sometimes be difficult to enforce as they need to be legislated by each participating country’s governments. As a result, some countries may try to enact ambitious climate legislation but be unable to put it into effect. Therefore, while ambitious nationwide climate initiatives may be more effective in theory, community-based policies and initiatives can sometimes be easier to enforce. This is especially true in countries, like the United States, where climate change has become a politically divisive topic. In cases like this, it may be more advantageous to put more focus into large amounts of community-based projects and initiatives that may eventually be supplemented by nationwide policies.

7. CONCLUSION

Anthropogenic climate change is a phenomenon that affects regions of the world disproportionately. The Arctic region has been documented to experience more intense climate change-induced warming due to a phenomenon known as the Arctic Amplification Effect (Icelandic Met Office, 2018). This phenomenon has led to the rapid glacial retreat of Arctic glaciers, including glaciers in Iceland. A literature review of previous Icelandic glaciological research revealed that Icelandic glaciers have been rapidly declining since the geological year 1995/1995 (Aðalgeirsdóttir, G. et al., 2020). This glacial retreat has been shown to impact local communities in several different ways, including sea-level elevation, water availability and distribution, hydropower production, natural hazards, and tourism. Glaciers in Iceland are also projected to continue their decline with at least 16+/- 5% (RCP2.6) of ice volume being lost by 2050 and at least 43 +/- 11% (RCP2.5) of ice volume being lost by 2100 (Compagno et al., 2021), thus leading the negative impacts of glacial retreat to continue to worsen. However, while some issues may predominantly affect local Icelandic communities, others may contribute to more global problems. In fact, the resulting loss of glacial mass in Iceland has been observed to contribute to both sea-level rise and crustal uplift depending on the region of the world. As Iceland loses glacial mass, the earth’s surface rises due to decreased weight, thus lowering the sea level around Iceland. This lowering of sea level is further intensified by the mass lost from Greenland’s nearby ice sheet, which decreases the ice sheet’s gravitational pull, thus resulting in a decrease in water level (Kottasová and Doran, 2022). Contrastingly, the addition of glacial runoff into ocean systems is increasing sea-level elevations in other parts of the world, disproportionately affecting small island nations (Kottasová and Doran, 2022).

The results of the repeat photography comparison of Vatnajökull's outlet glaciers were shown to align with the results from the literary review despite the possible flaws found in the photographic method. The consensus between the literature review and the repeat photography in this study thus was able to visually represent the scientific effects of climate change on Icelandic glaciers in a simple and direct manner. Repeat photography visually demonstrates the effects of the slow and somewhat abstract concept of climate change, in a clearly visible way and highlights any climate change-induced landscape changes for the general public. It is therefore possible that repeat photography may not only be a helpful tool in bridging the gap between scientific discourse surrounding climate change and the consumption of the general public but may also be a helpful tool in raising awareness for climate change.

Although this study addressed the use of repeat photography in order to document the effects of climate change on Icelandic glaciers, possibly through long-term repeat photography projects with more extensive protocols, it is important to continue to monitor glacial change in Iceland. Studies like these may not only help our understanding of glacial decline but the visibility of glacial decline may also help portray the effects of climate change to the general public in order to raise awareness. This study has shown that glacial decline is already occurring. It is therefore important for us, as a society, to prioritize minimizing our impact, not only in order to help preserve famous natural Icelandic features belonging to the country's culture, but also to help minimize the increase of human risk due to sea level elevation changes, natural hazards, changes in water availability and distribution, and changes in country economics. Efforts to minimize our environmental impacts through individual or community action as well as nationwide policies and initiatives should further be applied to the preservation of all glaciers around the world.

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APPENDIX

This appendix consists of various glacial photographs taken in Iceland in March 2023. Several photos depict glacial ice of different forms that can only be seen from walking on or below the glacier. Images 1 through 9 were all taken on Breidamerkurjökull and depict the texture, color, and lighting of glacial ice. Image 10 was taken at the snout of Skaftafellsjökull as it terminates in a glacially scoured valley. All photos were taken by Madeleine Gassin.

Image 1. Breidamerkurjökull ice cave explorers

Image 2. Luminous turquoise ice in a Breidamerkurjökull ice cave

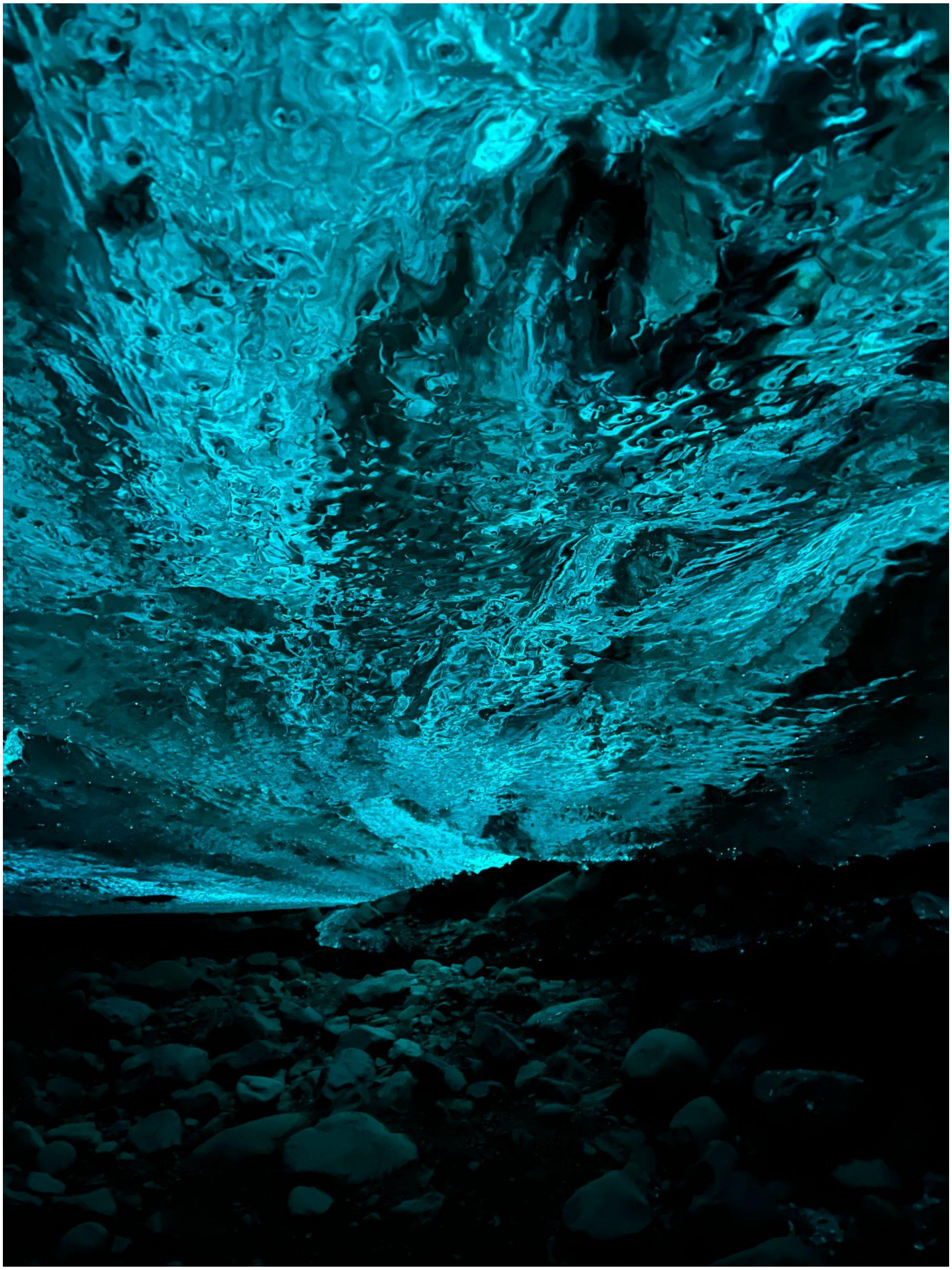

Image 3. Textured turquoise luminous ice in Breidamerkurjökull ice cave

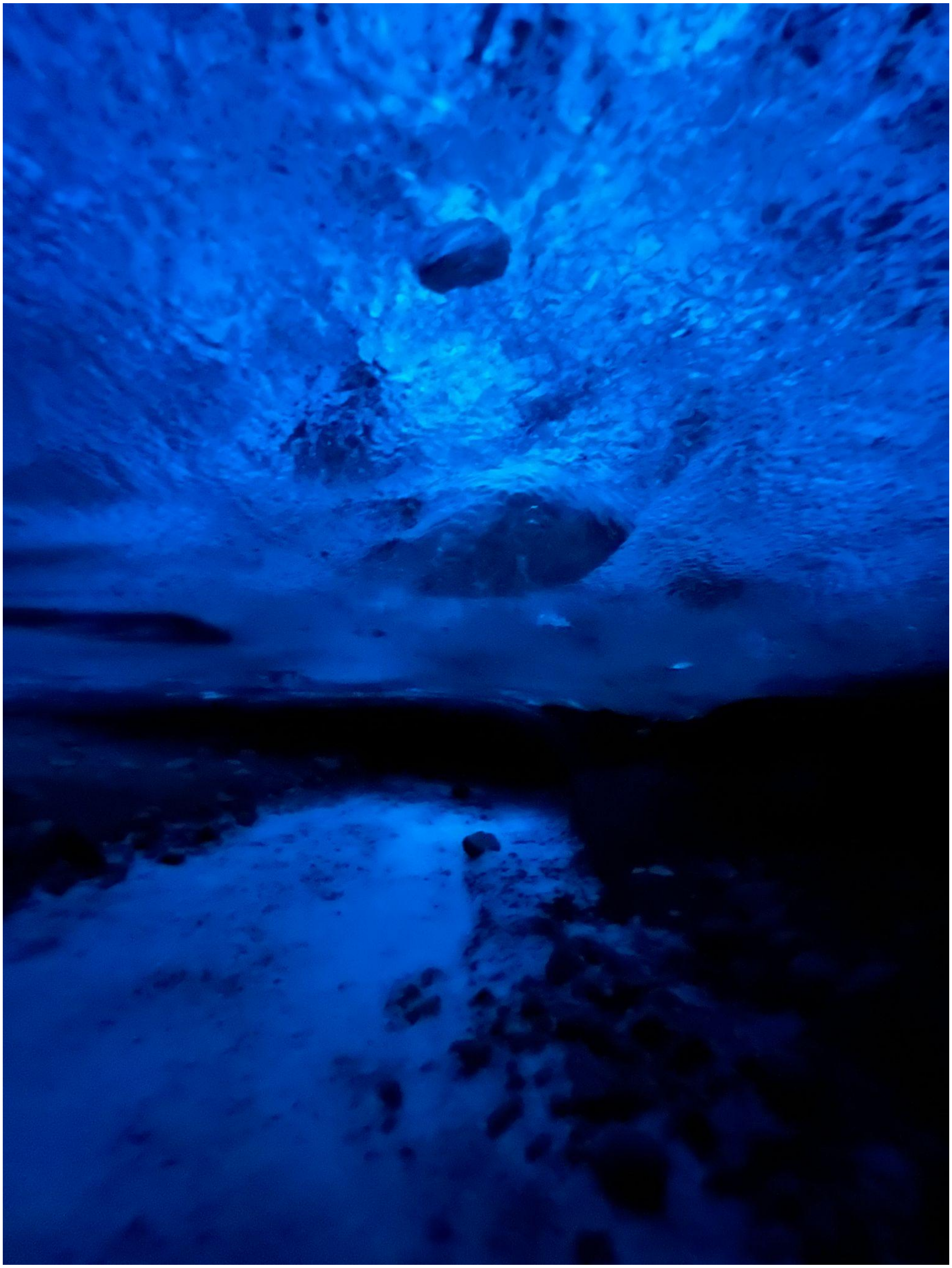

Image 4. Blue ice cave overlooking icy boulders in Breidamerkurjökull

Image 5. Ice cave entrance at Breidamerkurjökull

Image 6. Glacial meltwater-gouged ice on Breidamerkurjökull

Image 7. Meltwater-gouged ice walls on Breidamerkurjökull

Image 8. Meltwater-gouged ice canyon on Breidamerkurjökull

Image 9. Meltwater-gouged ice peak on Breidamerkurjökull

Image 10. Skaftafellsjökull Glacier snout in glacially carved valley