Climate and guidance

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1. Introduction

The project *Climate and guidance* of the Nýheimar Knowledge Centre in Höfn and Vatnajökull National Park is a part of a larger cooperative undertaking of the park and the Icelandic Meteorological Office, which again is a part of the Icelandic government's climate agenda, to enhance people's awareness and understanding of the impacts of climate change, not least on Icelandic glaciers. The specific purpose of *Climate and guidance* is to provide comprehensive and reliable information about the impacts of climate change to personnel in the travel industry, and specifically tour guides in Vatnajökull national park and vicinity. Tour guides utilise these breath-taking landscapes as an educational platform and have a unique opportunity to increase public knowledge about climate change and its effect on nature and society.

2. Climate change–what and why?

Since the industrial revolution, late in the 18th century, massive changes in human activities have led to greatly increased emissions of carbon dioxide (CO_2) and other so-called greenhouse gases (GHGs) into the atmosphere. This is the main cause of the current observed global warming. The rapid increase in the concentration of CO_2 and other GHGs in the atmosphere, on the other hand, is due to combustion of fossil fuels, such as coal and oil, in electric power plants, transportation and industry and a decrease in the uptake of carbon dioxide, mainly due to deforestation, soil erosion, agriculture and expanding cities.

Earth's climate is largely determined by the planet's energy budget, *i.e.* the balance of incoming short-wave radiation from the Sun and the outgoing long-wave radiation of the Earth back into outer space. The atmosphere absorbs a small portion of the suns incoming warming rays, a larger portion is reflected by the atmosphere and cloud coverage but approximately half of the incoming solar radiation reaches the Earth and warms its surface.

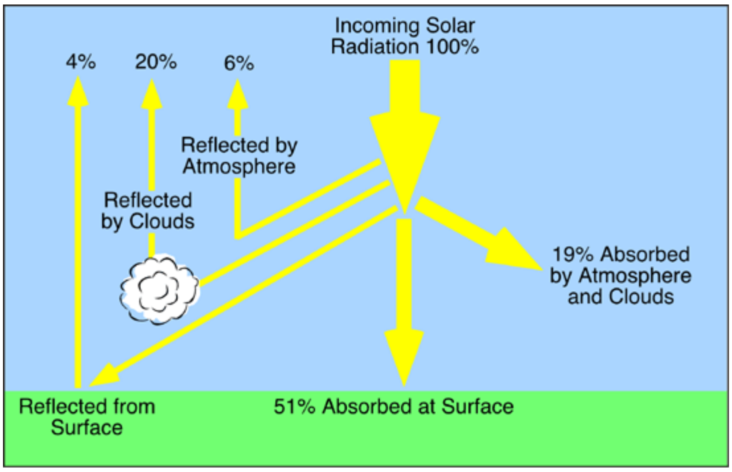

Figure 1. Reflection and absorption of solar radiation. Of all the sunlight that passes through the atmosphere annually, only 51% is available at the Earth's surface to do work. This energy is used to heat the Earth's surface and lower atmosphere, melt and evaporate water, and drive photosynthesis in plants. Of the other 49%, 4% is reflected back to space by the Earth's surface, 26% is scattered or reflected to space by clouds and atmospheric particles, and 19% is absorbed by atmospheric gases, particles and clouds. Source: physicalgeography.net.

The nature of GHGs in the atmosphere has been known for decades. Both the Sun and the Earth emit electromagnetic rays. GHGs in the atmosphere allow the majority of the high energy radiation (short-wave radiation) from the Sun to easily pass through and reach the Earth’s surface – fortunately though the ozone layer (O_3) blocks most of the harmful ultraviolet rays from reaching the surface. The Earth warms up as a result of the incoming radiation and reflects heat rays (long-wave infrared rays) back into the atmosphere. However, the atmosphere prevents this infrared radiation to pass through into space, but rather absorbs them or reflects back to Earth, thus functioning like a blanket. Hence, the mean temperature of the Earth is at present around 15°C, not -18°C as it would be without the atmosphere.

Many greenhouse gases, such as carbon dioxide, methane, water vapor, and nitrous oxide, occur naturally while others are synthetic. However, humans are altering their balance and especially the concentration of CO_2 through interference with the carbon cycle (burning forests, mining and burning coal). These activities artificially remove carbon from solid storage and convert it into its gaseous state, thereby increasing atmospheric concentrations of CO_2. As a result, they are higher now than ever during the last 650.000 years according to scientific studies on ice cores from Antarctica.

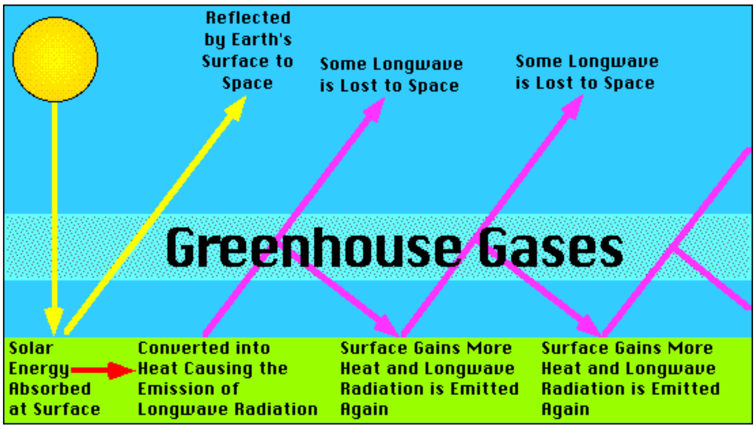

Figure 2. Atmospheric gases absorb long-wave radiation very strongly. This causes a warming of planetary surfaces by a process called the greenhouse effect. The greenhouse effect is said to "trap heat" like a blanket making the planet's surface warmer than it would be without it. The yellow arrows refer to solar (shortwave) radiation and pink arrows refer to terrestrial (long-wave) radiation. Source: laulima.hawaii.edu.

The fifth scientific report of the Intergovernmental Panel on Climate Change (IPCC) of the United Nations was published in 2014. IPCC's reports are based upon research of thousands of scientists and are the most comprehensive syntheses about climate change ever compiled. The results of the latest report confirmed and strengthened the findings of the 4th IPCC report from 2007, which marked a turning point in the world debate on climate change. Ever since, the vast majority of climate scientists have recognised it as a fact that the current global warming is mainly due to anthropogenic emissions of CO_2.

Natural climate fluctuations are well known in geological history. The glacial periods of the Ice Age that began some 2.7 million years ago have been punctuated repeatedly by interglacial periods of warmer global average temperature, lasting thousands of years. Changes in the earth's orbit and the tilt of its axis cause systematic variations in the amount and distribution of solar radiation. Cyclical variations in three elements of earth-sun geometry combine to produce these variations:

1. Variations in the shape of the Earths's orbit around the sun; every 100.000 years the orbit changes from being oval to circular.
2. Changes in obliquity; i.e. in the angle that the Earth's axis makes with the plane of the orbit, with 41.000 years passing between the least and most tilt of the axis.
3. Precession, or the change in the direction of the Earth's axis of rotation, with a cyclus of 22.000 years.

The difference in globally averaged temperatures between glacials and interglacials is about 5°C. The current Holocene interglacial began at the end of the Pleistocene, about 11,700 years ago. Indicators of past climate can be found within the stratum of the ancient ice sheets in Greenland and Antarctica that preserve information about the chemical composition of the atmosphere and the air temperature during its formation. Sedimentary layers on the bottom of the ocean also preserve details of the climate history of the Earth.

Solar energy reaching the Earth began to increase some 18.000 years ago and reached a maximum 9000 years ago. This increasing solar energy warmed up the atmosphere and the oceans and marked the end of the last glacial period. Approximately 5000 to 7000 years ago average temperatures where higher in the northern hemisphere than ever during the Holocene, due to a change in the Earth´s orbital eccentricity and obliquity, a period called the Holocene Thermal Maximum. Some 3000 years ago, the climate cooled again, and glaciers started to form on the highest mountains in Iceland, called the Neoglacial period. In addition to amount of solar radiation changing over tens of thousands of years, there are also seasonal and annual anomalies in climate, especially due to variations in atmospheric and ocean currents.

Although, similar temperatures as today are acknowledged during earlier interglacial periods, scientists believe that the current warming has occurred ten times faster than the median rate of earlier warming periods before and that the rate of warming is getting even faster during the last two decades. Global surface temperatures increased by 0.8°C on average during the 20th century and considerably more in the Arctic and in sub-polar areas. This rapid warming is traced to increased anthropogenic GHG emissions. The temperature increase in Iceland during the same time period is close to 1.5°C.

The above mentioned numbers do not appear high considering day-to-day or seasonal temperature fluctuations, but as a change in global mean annual temperature it has substantial consequences, resulting in sea-ice and glacier melting, rising sea levels, increased vegetation growth and changes in migratory routes of birds and animals. The year 2016 was the warmest on record since the beginning of measurements, and 2017 was the second warmest year on record.

The burning of fossil fuels is estimated to have contributed to a 78% increase, above natural levels, in CO_2 emissions between 1970 and 2010. Approximately 40% of this "extra" CO_2 is still circulating in the atmosphere, while the oceans have absorbed approximately 30%, and vegetation and soil have bound some 30%. Obviously, increasing concentrations of GHGs upset the natural balance in the atmosphere and as a result the IPCC forecasts a warming of 0.3-4.8°C over the next 100 years depending on different scenarios of human behaviour and efforts put into reducing emissions and implementing countermeasures.

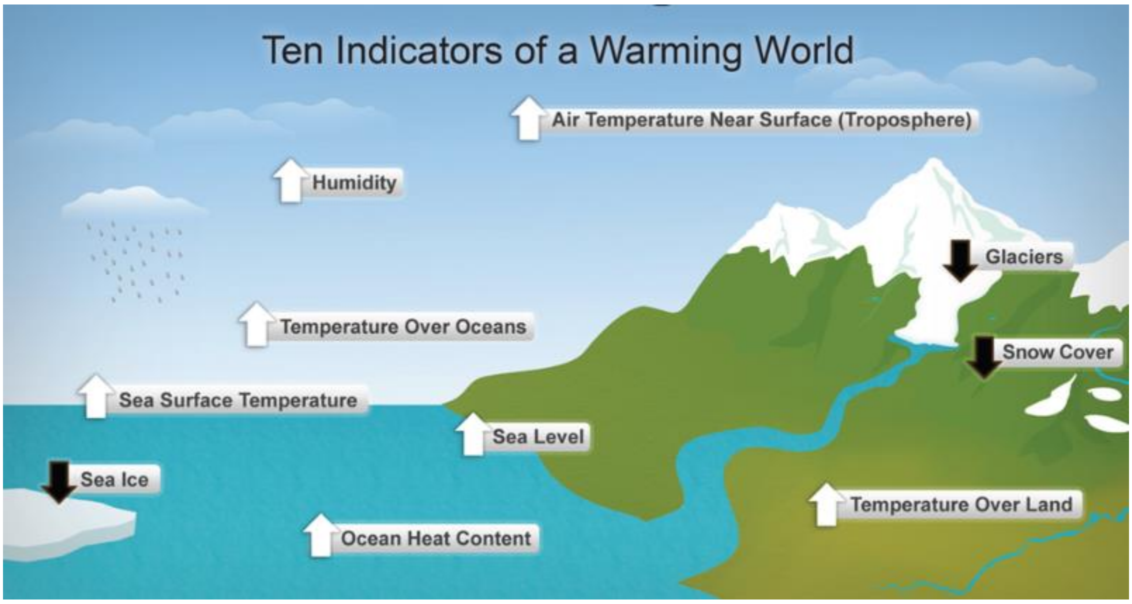

Figure 3. Ten key climate indicators that all point to a warming world.
Source: http://cpo.noaa.gov/warmingworld

Figure 4. Comparison of atmospheric samples contained in ice cores and more recent direct measurements, provides evidence that atmospheric CO_2 has increased since the Industrial Revolution. (Credit: Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO_2 record). Source: https://climate.nasa.gov/evidence/

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2.1 Greenhouse Gases

Some 78% of Earth's atmosphere is made up of nitrogen (N_2) and another 21% of oxygen (O_2). Hence, GHGs, such as carbon dioxide (CO_2), methane (CH_4), water vapour (H_2O), ozone (O_3), nitrogen oxide (N_2O), sulphur hexafluoride (SF_6) and various halocarbons, are a vast minority in the Earth's atmosphere:

- **Carbon dioxide** (CO_2) is one of the most influential GHG. It is an essential molecule for life as plants create their nourishment from it through the process of photosynthesis where the CO_2 molecule is broken up into its elementary particles. The oxygen (O_2) is immediately released into the atmosphere again, while the carbon (C) is built into carbohydrates, utilised both as an energy source and in the development of the plant's organic structure. When plants are eaten by herbivores the carbon is carried over to the animal food chain. Eventually, the carbon is released again as CO_2 through the process of respiration or through decomposition of living tissues at the death of an animal. Decomposition is assisted by a myriad of microorganisms that release carbon dioxide into the atmosphere through their own respiration. Thus, the carbon rotates constantly between living organisms and the atmosphere. In anaerobic environments, such as ocean or lake sediments, decomposition does not take place and the carbon compounds will be trapped in the sediments and, with time, converted into fossil fuels.
- **Methane (CH_4)** develops in the stomachs of ruminants but also forms when organic materials decompose anaerobically, e.g. in wetlands, scrap heaps and, during rice production. Methane is also released during incomplete burning of fossil fuels.

- **Ozone (O_3)** builds a layer high up in the atmosphere that shields the Earth from ultraviolet rays of the Sun. Ozone dissolves easily when it reacts with other pollutants such as halocarbons (see below).
- **Nitrogen Oxide (N_2O)** forms in small amounts during the burning of fossil fuels, both in industry and agriculture.
- **Sulphur Hexafluoride (SF_6)** perfluorocarbons and halocarbons are man-made elements that contain halogen (bromine, chlorine, and/or fluorine) and have been used, among other things, in cooling mechanisms and fire suppression systems, and are known to damage the ozone layer.
- **Water Vapour (H_2O)** is the most common type of greenhouse gas. Unlike the other GHGs its concentration in the atmosphere is highly variable both in time and space. Humans do not have a direct effect on its concentration. Generally speaking, however, evaporation of water will increase with rising temperatures, especially from the world oceans.

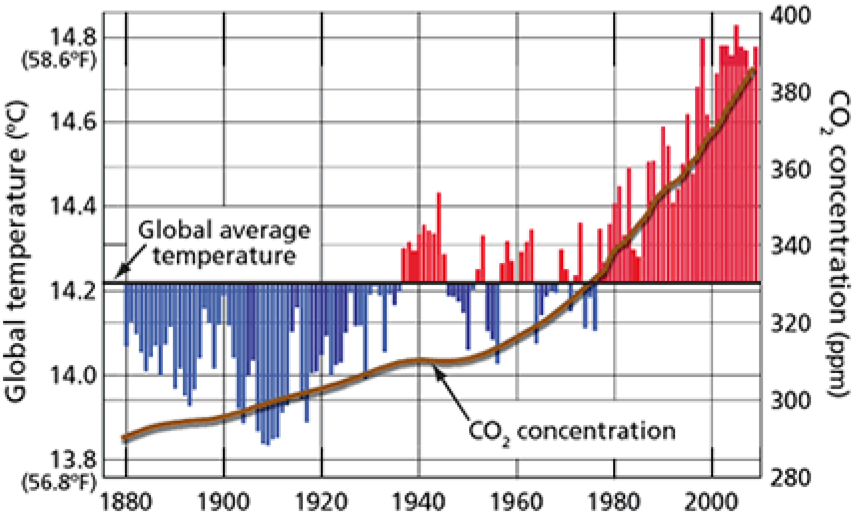

Figure 5. Global average temperatures and carbon dioxide. The red bars signify temperature above the median for the years 1901-2000 and, the blue bar signifies temperatures below. The brown bar signifies carbon dioxide in the air (measured in ppm). Source: Source: NOAA/NCDC.

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3. The effects and manifestations of climate change

Climate change is affecting societies and natural systems worldwide, including human health, infrastructure, and transportation systems, energy, food, and water supplies. Melting glaciers, rising sea levels, disruptions of ecosystems and climate extremes are examples of the consequences of climate change. Even seemingly minor temperature and precipitation anomalies can have profound impacts on natural ecosystems, agricultural production and the earth's freshwater supplies. Examples of observed changes include:

- Increasing numbers of and enlarging proglacial lakes
- Unstable surface layers in areas with permafrost and increasing rock avalanches
- Changes in sea ice ecosystems, including marine organisms and animals high up in the food chain
- Increase in glacial runoff and snow melting
- Shifting seasons, for example spring comes earlier which effects timing of greening and flowering, nesting time of birds and timing of river spring floods and migration
- Satellite data indicate increased vegetation cover and yield
- Shifting habitats of many species, migrating north or south towards the poles and to higher elevations in mountains
- Warming of lakes and rivers affecting water quality and ecosystems
- As permafrost thaws, large quantities of methane may be released into the atmosphere, amplifying the greenhouse effect

As areas with sea ice and snow cover shrink, the oceans and soils absorb large quantities of the radiation that otherwise would have been reflected. The albedo of snow is very high, 80–90% of the incoming sunlight. By contrast, vegetation and soil reflects only 10–30% of sunlight. About 98% of the Earth's snow cover is located in the Northern Hemisphere. On such a large scale, snow cover helps to regulate the exchange of heat between the Earth's surface and the atmosphere, i.e. the Earth's energy balance.

Regions are affected differently by increasing temperatures, changes in weather patterns and rising sea levels. Climate change will hit developing and poor countries the hardest, islands in the Indian and Pacific Oceans and other low-lying areas such as Bangladesh are particularly vulnerable. As sea level continues to rise, flooding and storm surges will threaten freshwater sources, as well as coastal homes and buildings. Coastal facilities and barrier islands in many parts of the world are gradually submerging, and some low-lying islands have already had to be evacuated such as some of the Solomon islands. Societies in Asia and Africa will experience increased crop failures and melting glaciers reduce the freshwater reservoir that many countries are dependent on. Climate change will also affect infectious disease occurrence, as with rising temperatures, the disease carriers will spread into new areas.

3.1 Climate and weather

Climate is the average of weather conditions (temperature, precipitation, wind) in a certain region over a long period of time (months, years or thousands of years). In contrast, weather is measured in hours or days and is ever changing. Weather can be forecast a few days into the future, whereas climate is determined retrospectively from the prevailing weather conditions of a region. The weather must have been measured for several decades for meteorologists to detect true changes in the climate.

Observed trends, theoretical understanding and numerical modelling demonstrates that climate change is increasing the risk of extreme weather events such as heat waves, heavy precipitation, droughts and wildfires. In some regions, increased temperatures have resulted in decreased mean precipitation, although downpours and floods have become more common. In other areas, droughts are becoming more frequent with dry periods lasting longer than before. Commonly, wet areas have become wetter and arid areas have become drier. Heat waves are now more frequent and extreme in most regions of the world while the number of cold days has decreased.

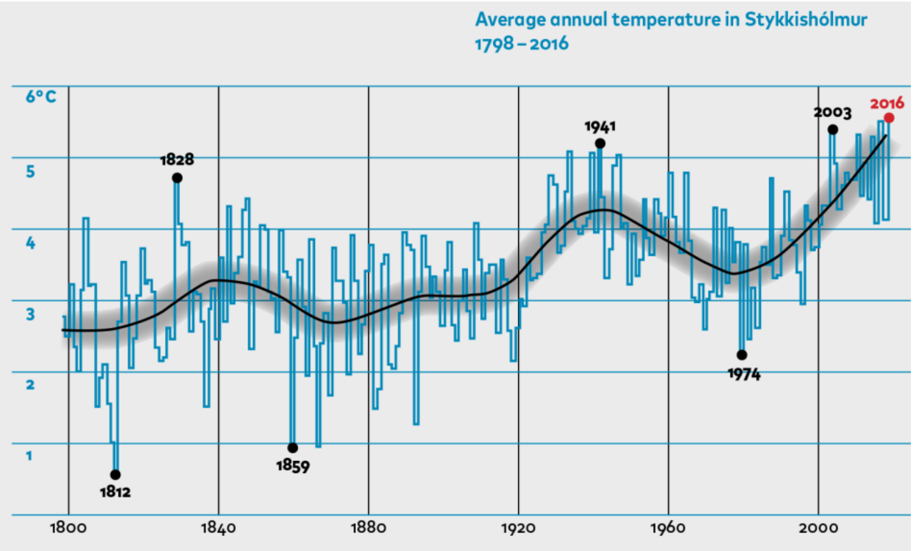

Figure 6. Annual mean temperature in Stykkishólmur 1798-2016. Source: Icelandic Meteorological Office, published in Hannesdóttir and Baldursson, 2017.

Iceland lies in the North Atlantic, just south of the Arctic Circle. The country is at the border of two main climate zones, polar and temperate, and the climate can thus be classified as cold-temperate. A warm ocean current from the south, the North Atlantic Current, results in a milder climate than expected considering the latitude of the country. The average annual temperature in lowland areas in Iceland is in the range of 2–5°C. Southerly winds deliver high amounts of precipitation to the south coast and the average annual precipitation in the wettest parts of the lowland is 2000–3000 mm, up to 4000–5000 mm on Vatnajökull (and Mýrdalsjökull). In the rain shadow north of the Vatnajökull ice cap, the precipitation is much less or 400–800 mm per year.

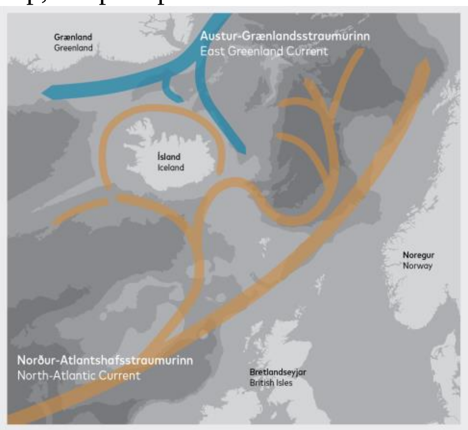

Figure 7. Main ocean surface currents in the North Atlantic. Published in Hannesdóttir and Baldursson, 2017.

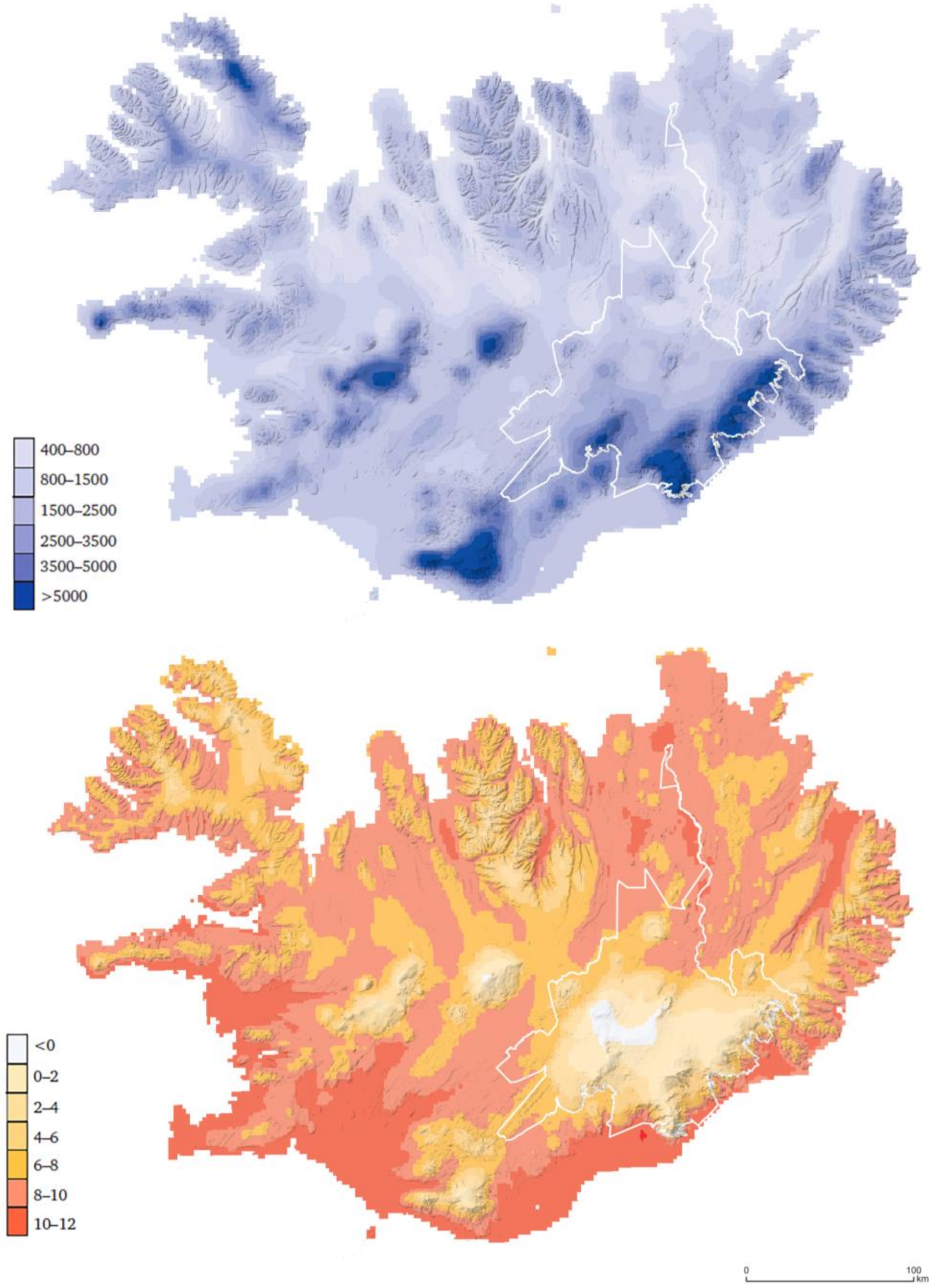

Figure 8. Mean annual precipitation in mm (top) and mean July temperatures in °C (bottom) across Iceland. Source: Icelandic Meteorological Office. Published in Baldursson et al., 2018.

- In the lowlands of Iceland, like in other northern regions, more precipitation falls now as rain rather than snow.
- In Iceland, temperatures in winter have risen notably more than in summer.
- It is expected that precipitation will increase approximately 2–3% for every 1°C rise in temperature and that there will be fewer days without any precipitation.

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3.2 Glaciers

Glaciers cover 10% of Iceland and contain 3600 km^3 of ice, which if melted would raise the global sea level by 1 cm. The largest glacier in Iceland, and in Europe by volume, is Vatnajökull which covers approximately 8% of Iceland (7800 km^2). The location of the country's main glaciers is controlled by topography and high amounts of precipitation that are delivered to the south coast. The glaciers are on average 350 m thick, which amounts to a 35 m thick ice layer distributed over the whole country. The water contained in glacial ice equals 20 years of annual precipitation. The Icelandic glaciers are temperate, which means that they are maintained above freezing point (at 0°C) from top to bottom, unlike the polar ice sheet, which are frozen throughout. The thermal characteristics of the glaciers affect their movements, erosion potential and runoff. Most of earths fresh water is stored in Glaciers around the world. Glaciers preserve important information about Earth's history, which is stored in ice layers of the polar ice caps. We therefore have knowledge about volcanic eruptions, climate, vegetation and wildlife from previous interglacial and glacial periods.

Repeated eruptions and glacially eroded strata, including deep valleys and fjords, peaks and mountain passes, characterise Icelandic geology. The most spectacular glacial erosion is traced back to the glacials of the Ice Age. However, Icelandic glaciers are still active today and a great tourist attraction throughout the year. The proximity to glaciers and glacier rivers is an important part of Icelandic identity and culture but nowhere in Iceland has this proximity been more intimate or difficult than in the Hornafjörður municipality. Vatnajökull is the most important tourist magnet in Hornafjörður municipality, where the southernmost outlet glaciers of Vatnajökull dominate the landscape and most of them are easily accessible. These glaciers are retreating fast, and the area is considered to be a natural laboratory for the study of glaciers and climate change. Glacial geomorphological evidence witnesses their previously larger extent and freshly eroded glacial landforms are highly visible and accessible in their forelands. The sandur outwash plains south of Vatnajökull, which are a mixture of glacially eroded material and volcanic ash, are among the largest active sandur plains on Earth (Skeiðarársandur 1300 km^2).

3.2.1 Glacier ice

Glaciers form where more snow accumulates over the year than melts during summer. As layers of snow accumulate, the buried snow grains become more and more tightly packed and are converted to firn, which subsequently metamorphoses to glacial ice. This process takes place in the accumulation zone at the higher altitudes. Air becomes trapped in bubbles within the ice. At that point the snow has transformed into glacier ice, which has a density of approximately 900 kg/m^3. For Icelandic glaciers, this process only takes about 5–6 years at a depth of 20–30 m. However, in the polar regions, this process takes up to 100 years and occurs at a depth of 60–100 m. Ice crystals grow as they travel down glacier and can reach the size of a person's head at the termini of some Icelandic outlet glaciers. However, in Antarctica the ice crystals can become one meter in diameter, as the ice is thousand times older than in Icelandic glaciers.

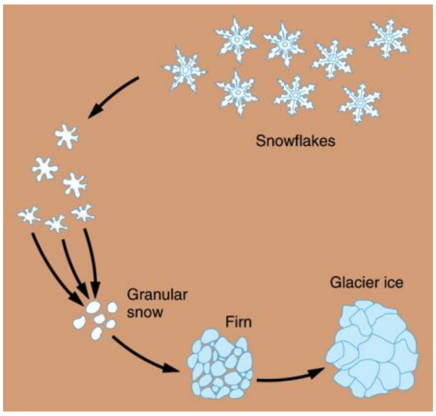

Figure 9. Conversion of snow to glacial ice. Source: geographyalltheway.com

The area where more snow accumulates than melts over the year is called the accumulation zone, and the area below, the ablation zone. The line that separates the accumulation and ablation zones is called the equilibrium line. The elevation of the equilibrium line depends on temperature, precipitation and the surrounding landscape. If the climate conditions remained constant, neither the equilibrium line nor the glacier margin would change. The equilibrium line is easily seen in late summer or fall from satellite images or aerial photographs, with a clear boundary between the darker glacial ice and the white snowy accumulation area.

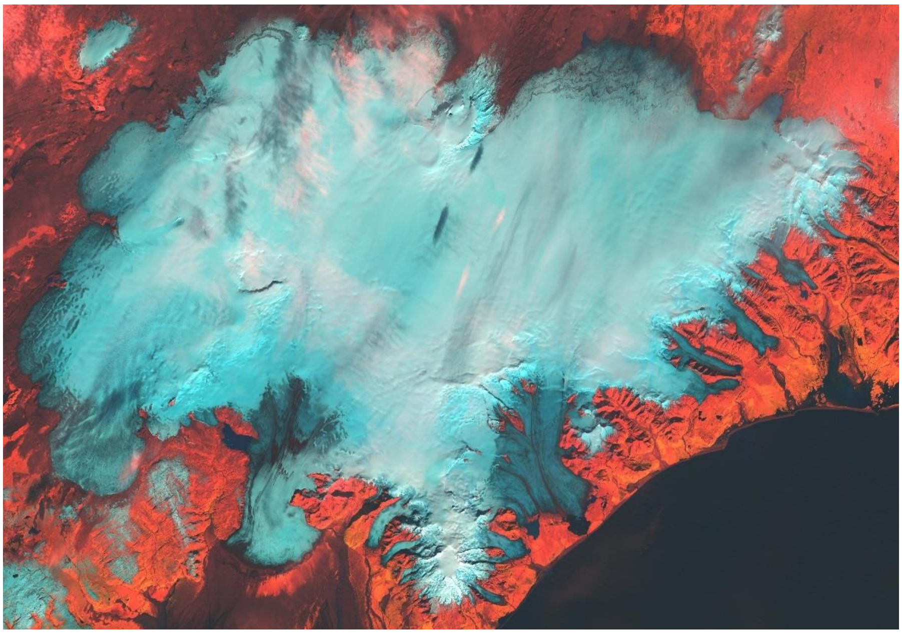

Figure 10. Landsat satellite image from autumn of 1994 of Vatnajökull ice cap. The location of the snowline is visible, separating the snowy accumulation area and the barren darker ablation area. Source: https://landsat.usgs.gov/

In Iceland, the elevation of the equilibrium line ranges from 800 m on Drangajökull glacier in the Westfjords to 1700 m on Mt. Herðubreið in the rain shadow north of Vatnajökull ice cap. The elevation of the equilibrium line is 1000–1200 m on the southern outlet glaciers of Vatnajökull. These glaciers descend well below the equilibrium line, or down to 10–100 m above sea level. At the end of the Little Ice Age (a period of cooler and more variable climate from 1450–1900) the equilibrium line altitude on southeast Vatnajökull was probably some 300 m lower than today. The accumulation areas of the glaciers were thus much larger. Due to lower temperatures and a shorter melting season, there was less ablation and the outlet glaciers advanced down the valleys and reached far out onto the lowland.

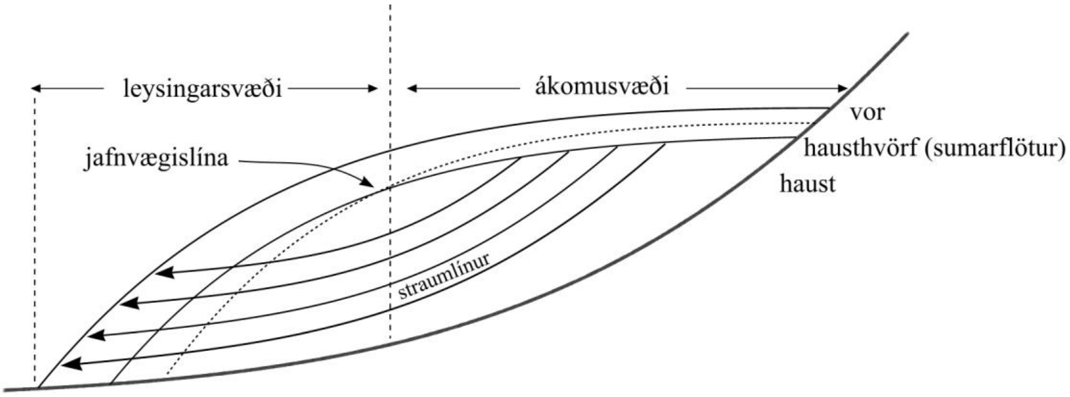

Figure 11. Cross section of a glacier showing the accumulation and ablation areas, snowline or equilibrium line, and flowlines.

The thick mass of ice deforms under its own weight in the accumulation area and flows downstream like dough or molten metal. The ice flows downhill towards the ablation zone where higher temperatures intensify the melting of snow and ice and melting exceeds the accumulation of snow over the year. Crevasses form in the surface of the glacier as it flows over an uneven bed or are dragged along the sides of mountains. Outlet glaciers are typically heavily crevassed, the upper part of the glacier is brittle and when changes in velocity occur, extensional forces cause the ice to fracture.

- The depth of crevasses in glaciers in Iceland is seldom more than 30 meters; however, larger ones can be found in polar glaciers
- The main types of glacier crevasses are longitudinal, transverse, and marginal
- Crevasses are hidden under the snow, but many become prominent in late summer
- In the ablation area crevasses are often visible and some have transformed into moulins

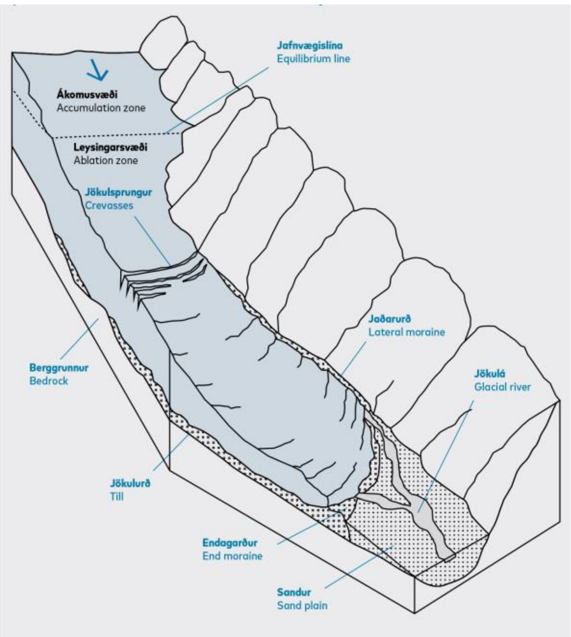

Figure 12. A typical outlet glacier. The ice deforms under its own weight and flows from the accumulation zone to the ablation zone like a dough. Crevasses form when the glacier flows over an uneven bed or is dragged along the sides of mountains. Source: modified by Hannesdóttir and Baldursson, 2017.

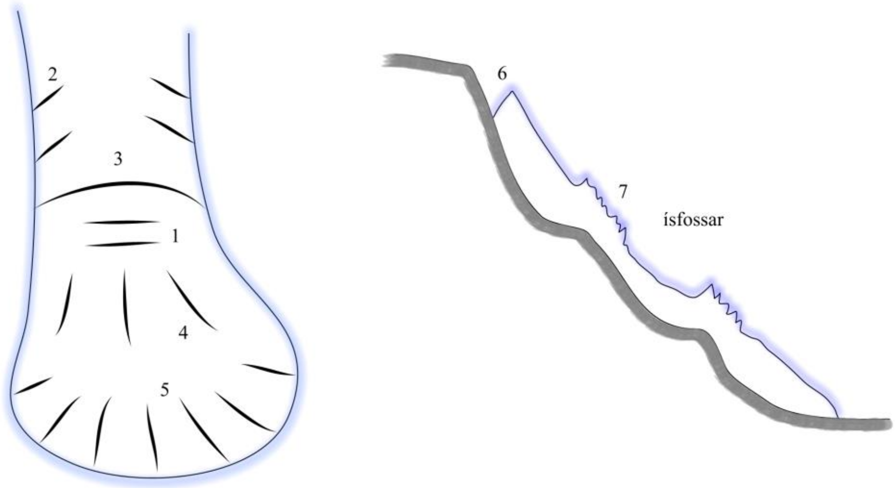

Figure 13. Main types of glacier crevasses, 1) transverse, 2) marginal 3) horse shoe shaped, 4) longitudinal, 5) radial, 6) bergschrund, 7) icefall.

The ice velocity is dependent on the temperature of the ice, the slope of the bed, and even the weather, as increase in ice velocities have been measured during heavy rainfall. The larger outlet glaciers flow approximately 1 m/day, as monitored by GPS and satellite data. Some of the outlet glaciers of Vatnajökull surge. Then the glacier suddenly flows faster, and the snout can advance some hundreds of meters in a few months. Water is distributed at the base of the glacier and lifts it slightly, such that the flow is increased approximately hundred times. Most surge type glaciers are relatively flat (between 1.5° and 4°) and move too slowly to keep up with the snow accumulation in the accumulation area. In order to keep regain their equilibrium, they surge. Surge-type glaciers cover 75% of the surface area of Vatnajökull and many of them surge regularly. However, no surges have been recorded since the 1990s.

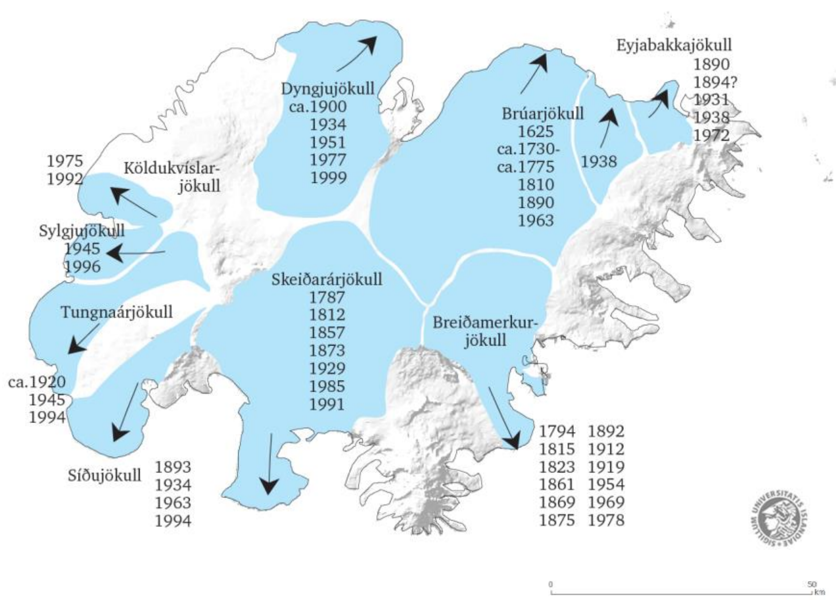

Figure 14. Surges in Vatnajökull. Source: Björnsson et al., 2003.

Variations in glacier mass balance often give reliable indications of changes in climate. The mass balance is positive if the glacier gains more than it loses. The accumulation of snow is measured in the spring by drilling cores through the winter snowpack and the ablation of snow and ice by measuring changes in the height of the stakes left in the boreholes or drilled into the glacier ice. In general, snow accumulates during winter and snow and ice are removed by ablation during the summer months. However, snow may accumulate during summer at high elevations and ablation may win over accumulation during winter at low elevations.

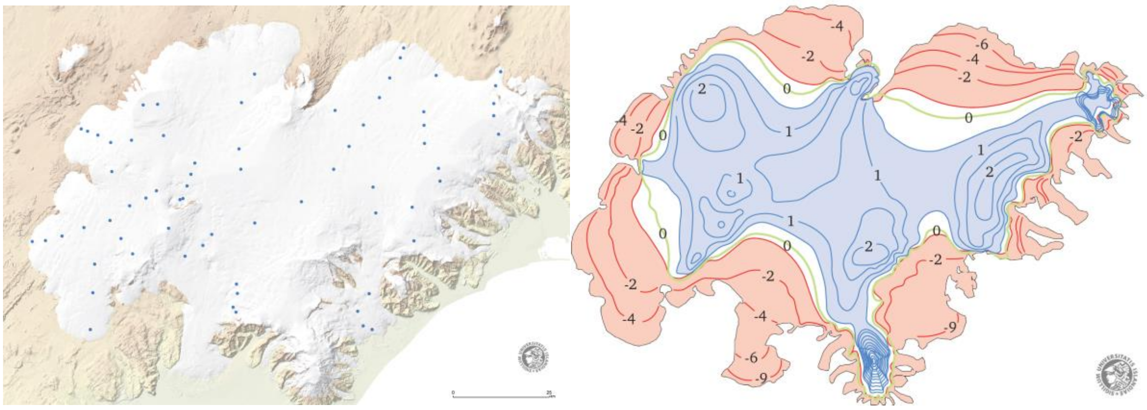

Figure 15. The location of mass balance meausrements sites of the Institute of Earth Sciences at the University of Iceland (left), and the mass balance of the ice cap during the glaciological year 2015-2016. Source: Pálsson et al., 2016.

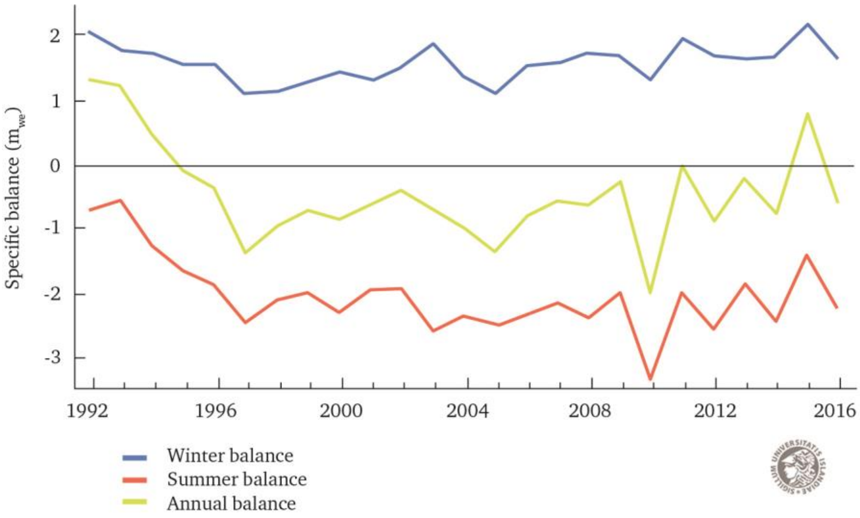

Figure 16. Annual, winter and summer mass balance of Vatnajökull since the start of the measurement series. Source: Pálsson et al., 2016.

The response of glaciers to climate change depends on their size and shape, but most of them react to a change in mass balance within a few years by adjusting the position of their snout. The glacier will then continue to retreat or advance for many years or decades before completely adjusting to a change in climate. Short and steep valley glaciers adjust in a decade or two, but larger and less steep glaciers have a much longer respond time.

Warming climate effects glaciers as fallowing:

- The higher the temperature exceeds 0°C, the faster the ice melts.
- As more days are expected to exceed, the longer the ablation of the glaciers will last.
- Glaciers will advance more rapidly and calve faster into lakes or oceans.

3.2.2 Glacier dynamics and landscaping

Glaciers and glacial rivers reshape the landscape in many ways. The ice itself is too soft to erode the bedrock, but rocks and gravel embedded in the ice carve the bed, creating so-called glacial striations. Glacial debris is carried on top of the glacier, within the ice, and at the interface of the bed and ice. The debris is finally deposited at the margin of the glacier as moraines. Outlet glaciers can erode over-deepened troughs, and as they retreat, water accumulates in the depressions evacuated by the ice, and glacial lakes form. Landscapes are ever changing in the vicinity of glaciers and in the last one or two decades, enormous changes have been observed. New lakes form, the glaciers deposit huge amounts of material, rivers change their course etc. All around the periphery of Vatnajökull ice cap are textbook examples of glacial geomorphological processes and landforms and the outlet glaciers of Vatnajökull have been central to the study of these landforms and processes. As the glaciers retreat freshly deposited features and landforms are uncovered that are easily accessible for study and repeat measurements. Extensive mapping of the forelands of receding glacier snouts have been carried out in the last few decades by several research teams.

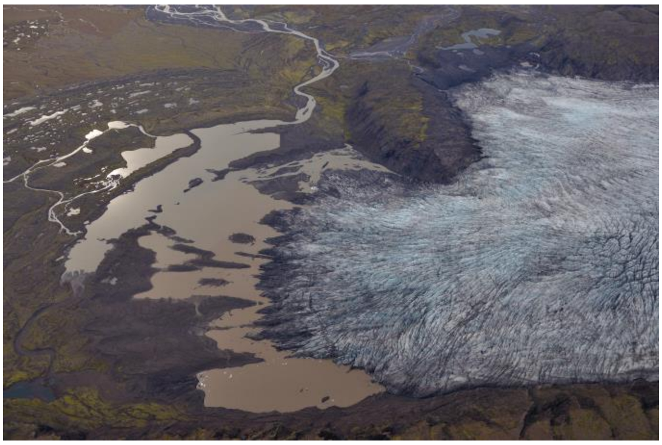

Figure 17. Glacial lakes in front of Fláajökull outlet glacier. Photo: Snævarr Guðmundsson.

Figure 18. Fjallsárlón glacial lake, Fjallsjökull outlet glacier and mt. Breiðamerkurfjall. Photo: Snævarr Guðmundsson.

Figure 19. Glacial lakes in front of Skaftafellsjökull and Svínafellsjökull outlet glaciers. Photo: Snævarr Guðmundsson.

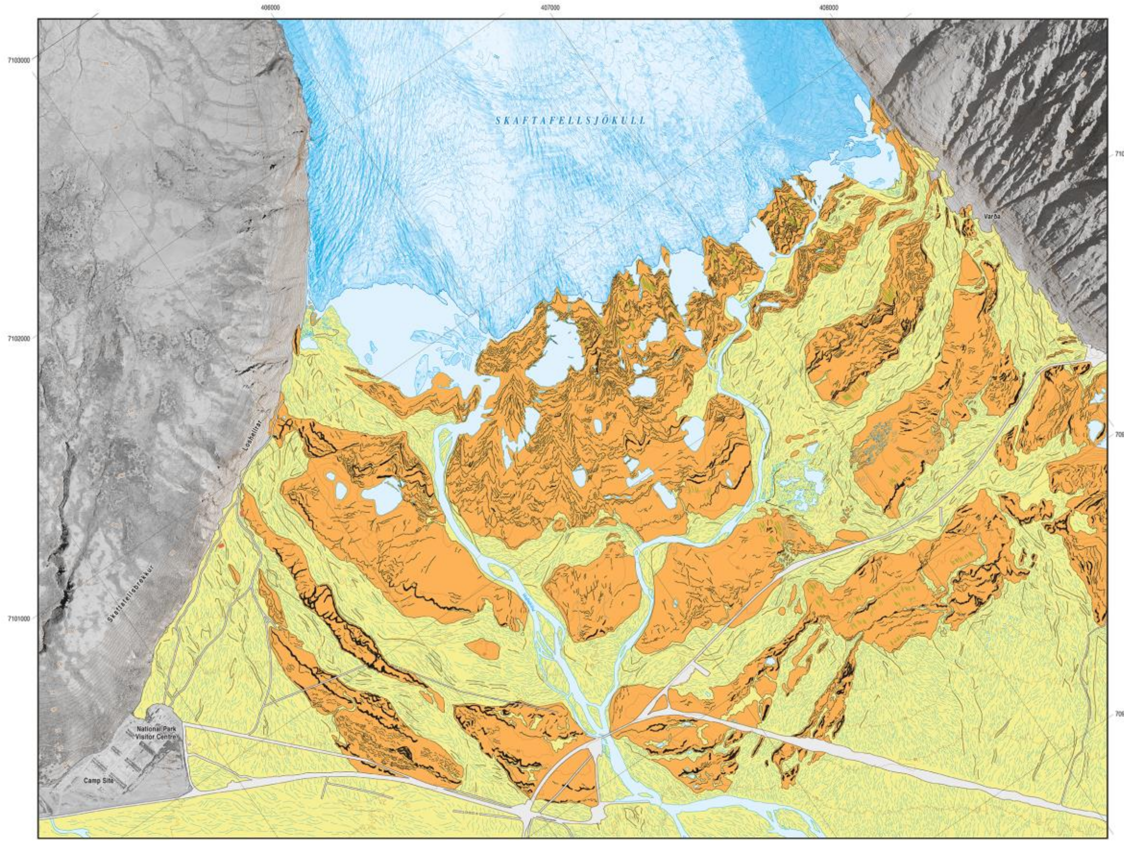

Figure 20. The foreland of Skaftafellsjökull outlet glacier. Glacial geomorphology recording the retreat of the glacier since the Little Ice Age maximum. Source: Evans et al., 2017.

Advancing glaciers may override vegetated land and destroy habitats of many species. Glacial rivers form sinuous branches and intricate braided patterns in flat areas because sedimentation of suspended material raises the riverbed and leads to frequent changes in the river path. Due to ever changing landscapes at glacier margins, rivers can easily change their course, leaving dry riverbeds and old bridges that have outlived their use. There is for example almost no water running underneath the longest bridge in Iceland, over the Skeiðará river, as most of the river changed course into Gígjukvísl in 2009. A new, shorter bridge opened in the fall of 2017.

Figure 21. In the 1940s a bridge was built over river Heinabergsvötn, but shortly after the river changed course, and merged with river Kolgríma. Photo: Snævarr Guðmundsson.

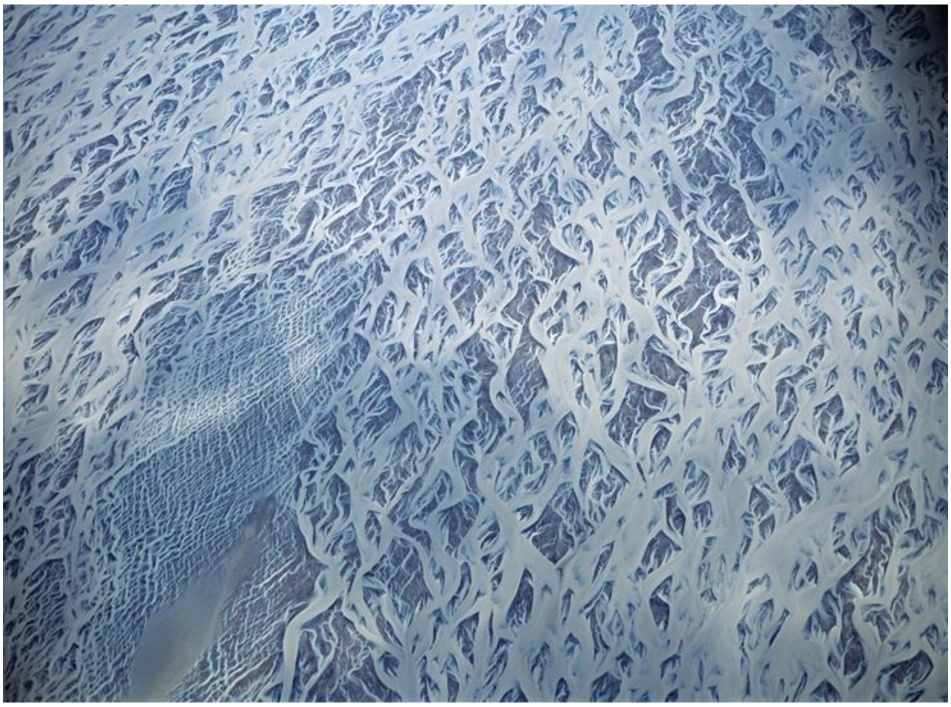

Figure 22. The course of the river Djúpá southwest of Vatnajökull after it converges with the river Hverfisfljót. Photo: Oddur Sigurðsson.

When the first settlers came to Iceland, the glaciers were much smaller than today. The glaciers advanced significantly during the Little Ice Age (ca. 1450–1900). In the 17th and 18th centuries, the southeast outlet glaciers of Vatnajökull reached far out onto the lowlands. They retreated slightly during the first decades of the 19th century and then re-advanced. Around 1890 nearly all of Vatnajökull's outlet glaciers had reached their maximum size in historical times.

A few historical mountain routes between farms and settlements became impassable during the Little Ice Age, due to advancing glaciers. One of those routes, the so-called Norðlingavegur from Fljótsdalur to Lón, was named after farmers who lived on the north side of the ice cap but travelled to the southeast coast to fish. Prior to 1700, there is also thought to have been a route between Morsárdalur valley south of the ice cap to Möðrudalur á Fjöllum in the northern highlands.

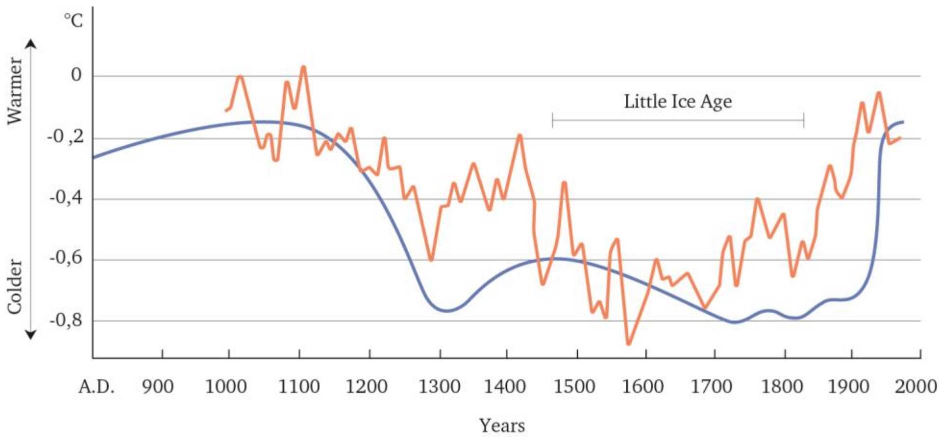

Figure 23. Annual mean temperatures in Iceland for the last 1100 years. The Little Ice Age (ca. 1450– 1900) is clearly indicated. Iceland enjoyed a warm climate in the first centuries after settlement (870–1262) and again during the last century or so (1918–2017). Orange line, temperature proxies based on oxygen isotopes in ice cores from the Greenland ice sheet. Blue line, estimate from Þórarinsson (1974). Modified after Björnsson (2017) and published in Baldursson et al., 2018.

The southeast outlet glaciers of Vatnajökull are in the warmest and wettest area in Iceland and respond quickly to changes in temperature and precipitation. Hence the area provides unique opportunities for

research on the relationship between glacier and climate change. Their former size has been traced from well-preserved glacial moraines and from descriptions in written historical accounts. The local accounts and writings of naturalists and travellers also provide valuable information about the extent of the glaciers. Descriptions of damaged pastures, hayfields and houses due to glacial rivers and advancing glaciers, along with difficult access to grazing areas are prominent in the written records.
By using maps from the early 20th century and onwards along with aerial and satellite images, lidar measurements, and GPS measurements the surface of the glacier has been reconstructed at various times and areal, elevation and volume changes estimated.

After 1890 most southeast outlet glaciers of Vatnajökull started retreating. They receded fast in the 1930s–1940s and continued retreating, albeit more slowly, until the 1960s. During the 1970s and 1990s, the glacier retreat slowed further or stopped and some of the glaciers even advanced. From 1995, the glacier retreat has been exceptionally fast. Research indicates that glacier variations since the 1930s are mostly related to changes in temperature, since long-term variations in precipitation during this period are negligible.

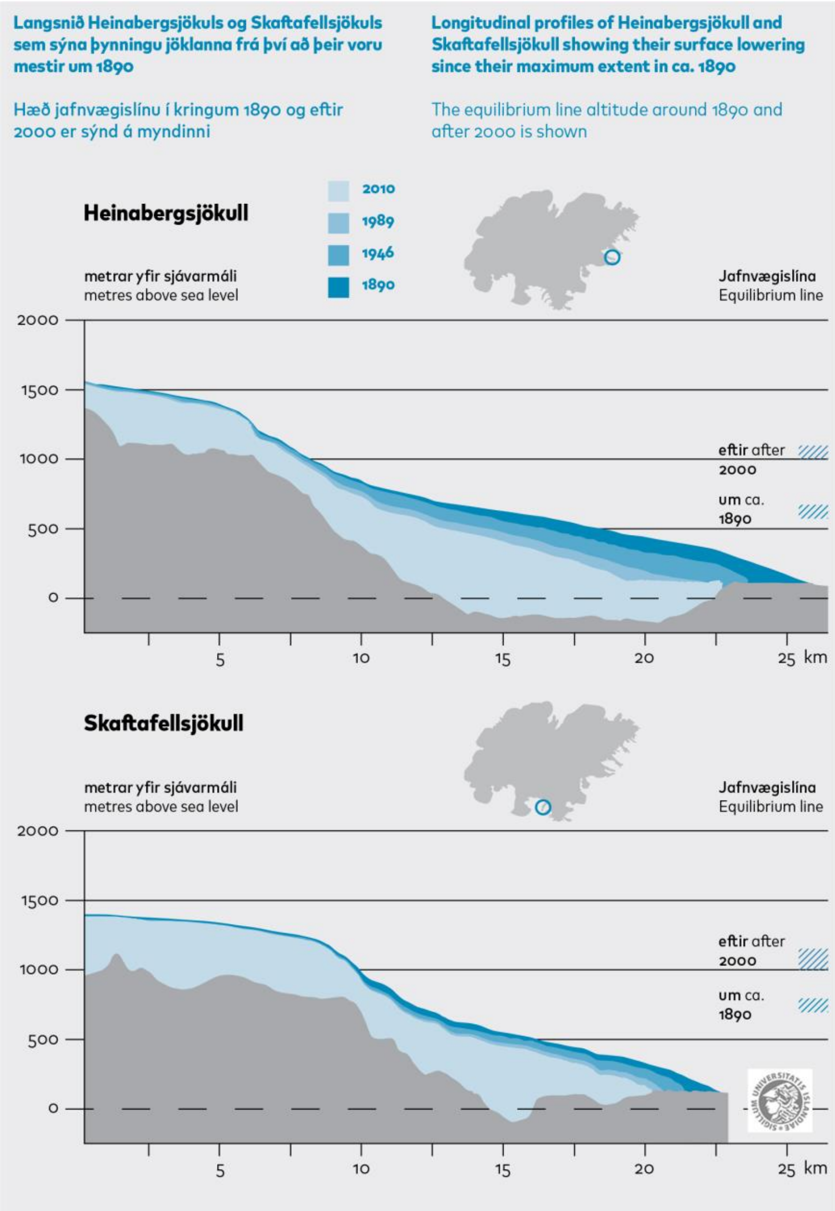

Figure 24. Longitudinal profiles of Heinabergsjökull and Skaftafellsjökull, showing their retreat and thinning since their maximum size around 1890. Source: Hannesdóttir et al., 2015, modified by Hannesdóttir and Baldursson, 2017.

Since the end of the Little Ice Age, the glaciers have retreated 1–8 km depending on location. They have also undergone significant surface lowering, amounting up to 300 m at their snouts; this equals to approximately four towers of the famous Hallgrímskirkja in Reykjavík.

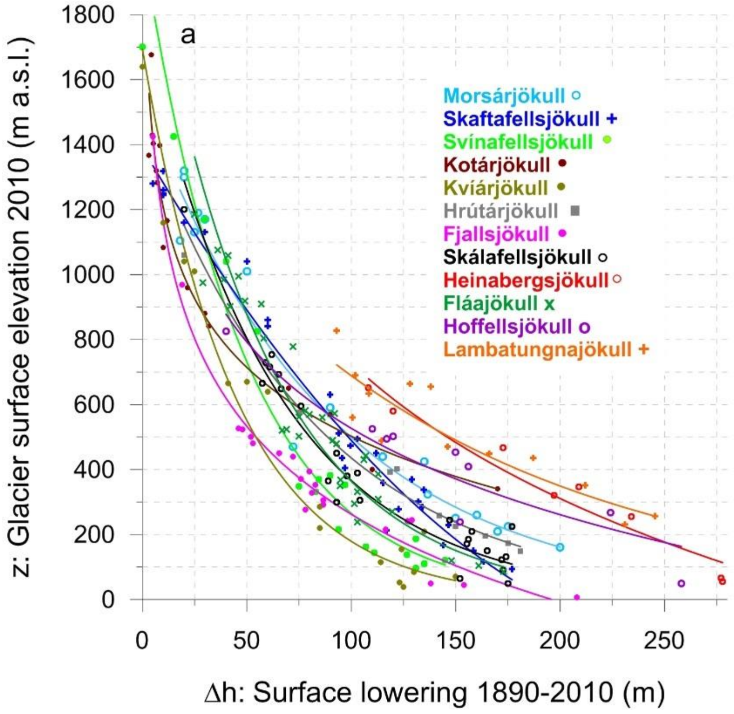

Figure 25. Surface lowering of a few outlet glaciers in southeast Iceland, during the time period 1890-2010. It is evident that at higher elevations, surface lowering is negligible, but close to the terminus the lowering is close to 250 m. Source: Hannesdóttir et al., 2015.

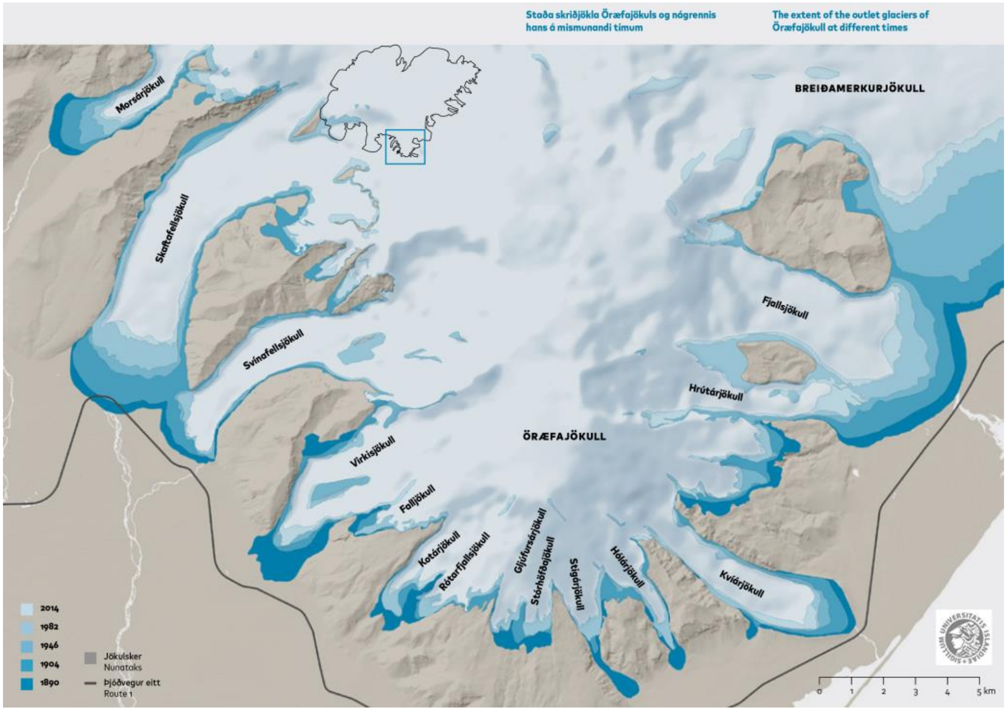

Figure 26. The extent of the outlet glaciers of Öræfajökull at different times. Source: Hannesdóttir et al., 2015, Guðmundsson, 2014, unpublished data from Snævarr Guðmundsson, Joaquin Belart, Daði Björnsson 2015. Modified by Hannesdóttir and Baldursson, 2017.

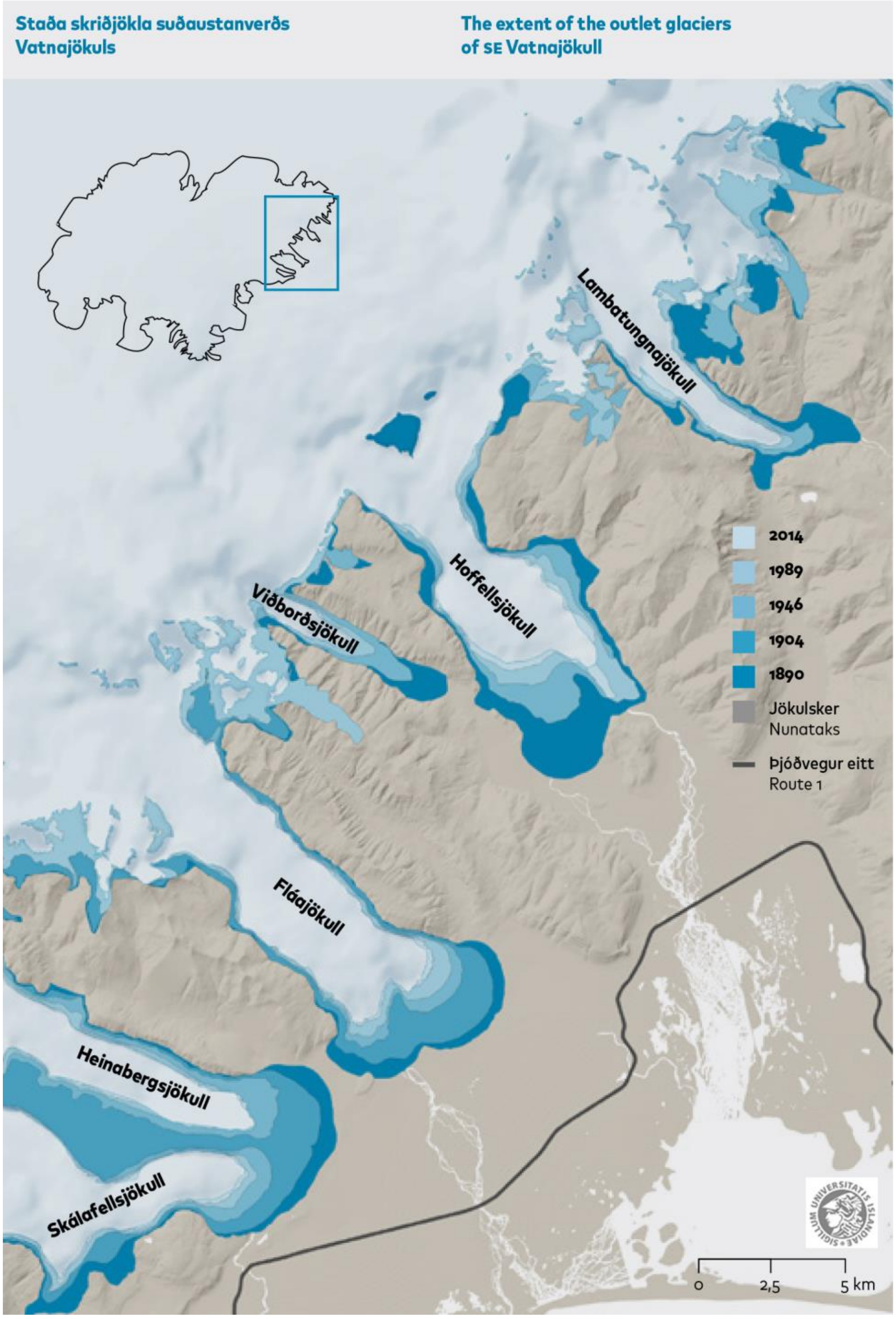

Figure 27. The extent of the outlet glaciers of SE Vatnajökull at different times. Source: Hannesdóttir et al., 2015, Aðalgeirsdóttir et al., 2011. Modified by Hannesdóttir and Baldursson, 2017.

The southeast glaciers have since the end of the 19th century shrunk by some 300 km^2; Breiðamerkurjökull alone has withered by 115 km^2. For comparison, the Reykjavík capital region covers an area of 275 km^2 and the small peninsula of Höfn in Hornafjörður is only ca. 4 km^2. The ice volume lost since the end of the Little Ice Age, calculated from maps of the surface lowering and the reduction in area of the glaciers, amounts to 130 km^3, which is equal to 13 billion truckloads of ice (given that each truck holds 10 m^3). Individual outlet glaciers have lost 15–50% of the ice volume during the same period. The actual loss depends on the size of their accumulation area, bed slope and whether they terminate in a glacial lake. Since the year 2000 the glaciers have retreated extremely fast, and their mass loss per unit area is among the highest in the world.

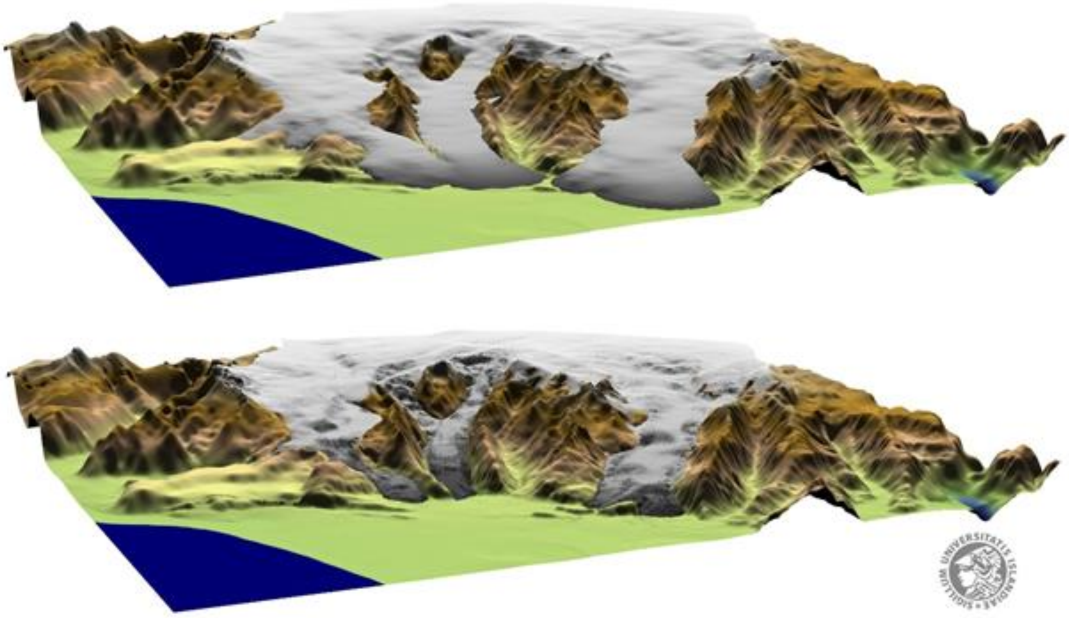

Figure 28. Top: Reconstructed surface geometry of Skálafellsjökull, Heinabergsjökull and Fláajökull around 1890, based on glacial geomorphological data, and oldest maps. Bottom: The same glaciers in 2010, based on lidar DEM. Source: Hrafnhildur Hannesdóttir, unpublished data.

To put the changes of the southeast outlet glaciers into context, the Greenland Ice Sheet has in recent years *annually* lost double the amount of ice that these glaciers have lost in 120 years (1890–2010). The total ice volume loss of the southeast outlets corresponds to a 0.33 mm rise in global sea level, while melting of the polar ice sheets (Greenland and Antarctica) contributes to 3–4 mm rise in sea level, annually, whereof only some 20%, or 0.6–0.8 mm, are attributed to melting of the Greenland Ice Sheet.

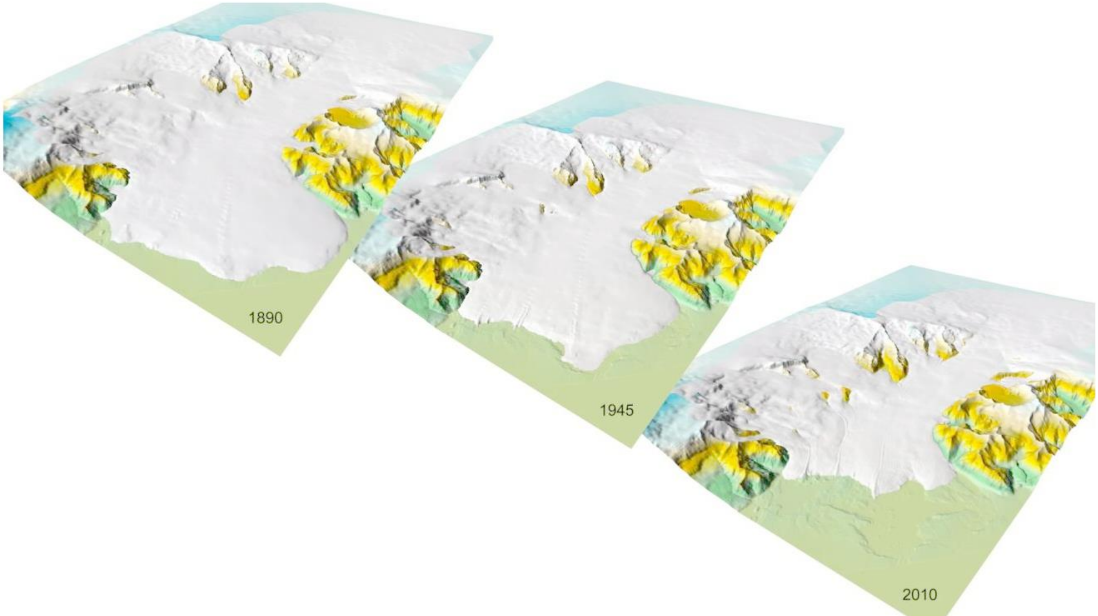

Figure 29. Evolution of Breiðamerkurjökull outlet glacier in 1890, 1945 and 2010. Source: Snævarr Guðmundsson, 2014.

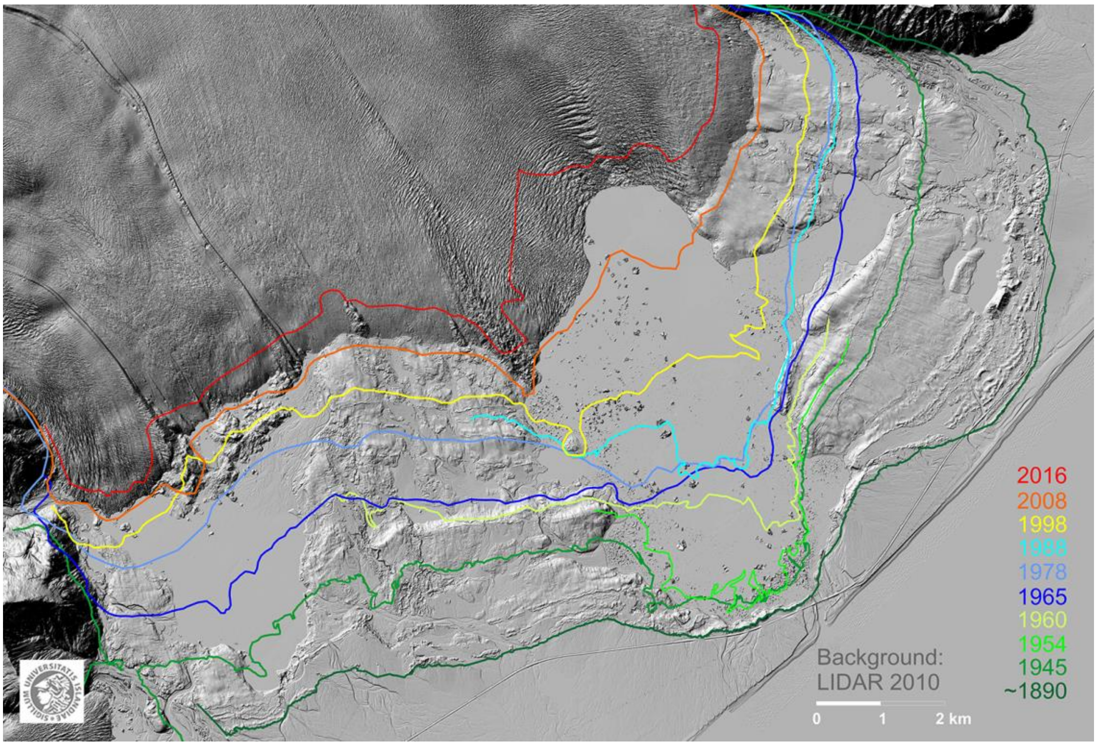

Figure 30. The retreat of Breiðamerkurjökull and growth of the Jökulsárlón glacial lake over the last century. The 3-D topography is based on lidar measurements from 2010. Image: Glaciology Group, Institute of Earth Sciences, University of Iceland.

Breiðamerkurjökull outlet glacier reached its maximum in 1890. At that time, when the glacier snout was only 250 m away from the shore, people worried that it would extend to the sea and close the main route connecting southeast and south Iceland. Instead, however, the terminus began to retreat, and a glacial lake began to form in 1934–1935. In 2015, the Jökulsárlón glacial lagoon had grown to become 8 km long and the deepest lake in Iceland, 248 m. The lagoon is really the mouth of a 200–300 m deep and 25 km long trough that the glacier has carved out. It is renowned for its beauty and one of the most popular tourist destinations in the country.

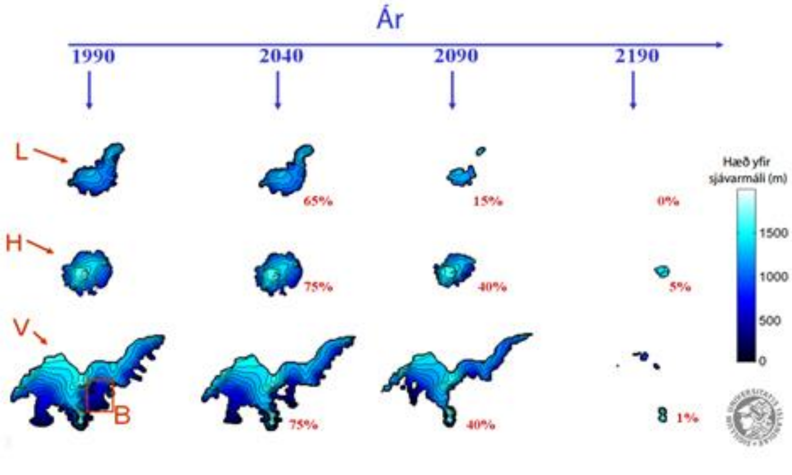

Figure 31. Response of Langjökull (L), Hofsjökull (H) and southern Vatnajökull (V) to the CE/VO-climate change scenarios. The volume numbers in red are the percentage of the ice volume in 1990. Source: Tómas Jóhannesson et al., 2007.

The subglacial topography is known from radio-echo sounding measurements of the Institute of Earth Sciences at the University of Iceland, which began in the 1950s and are still ongoing. These measurements have "lifted" the ice cap and uncovered previously unknown landscapes and formations, including some of the largest volcanoes in Iceland.

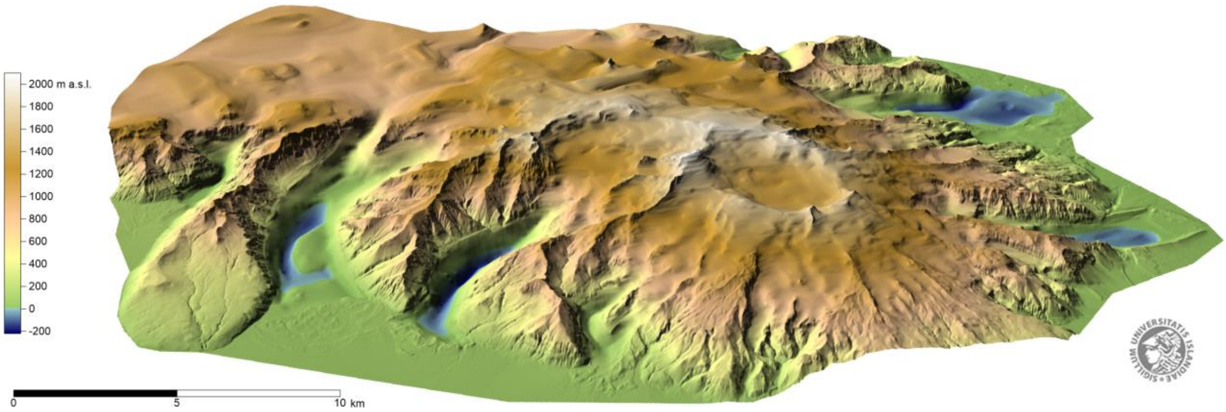

Figure 32. Perspective view from the southwest of the ice-capped Öræfajökull stratovolcano, showing the bedrock below the ice, including large depressions filled with lakes. From Eyjólfur Magnússon et al. 2012.

As the outlet glaciers retreat, glacial lagoons form in front of them. Initially several small pools form between the glacier moraine and the terminus, but they soon merge into an elongated lake. The lake grows rapidly when the front of the glacier thins, floats up and breaks into pieces. In the end, a large lagoon may be formed, into which the glacier calves, i.e. ice chunks break off the glacier tongue, along a steep front. The glacial lagoons in front of Svínafellsjökull and Skaftafellsjökull in Öræfi, illustrate well the development of such lagoons.

Icebergs float around in the lagoons. About 90% of an iceberg is below the surface of the water. They are very unstable, and their random shape and non-uniform melting can cause them to tip or roll suddenly and people should not try to stand on them. Glacial ice is a mixture of ice, sand, gravel, ash and air bubbles, and the composition is clearly seen in the icebergs that break off the glacier snout. Sometimes smaller icebergs and chunks are carried out of the lagoons by glacial rivers and can be found scattered on the shore, as e.g. on the shore of Breiðamerkursandur south of Jökulsárlón.

Figure 33. Floating icebergs on Jökulsárlón glacial lake, Öræfajökull in the background. Photo: Hrafnhildur Hannesdóttir.

Glacial ice has a different colour from regular ice. It is blue because the dense ice of the glacier absorbs all colours of the spectrum except blue. If there are many air pockets in the ice, the bluish tone is not as prominent, making it appear whiter.

A number of landslides and rock avalanches have occurred in southeast Iceland. In spring 2007, a large rock avalanche descended onto the Morsárjökull glacier, leaving one fifth of the glacier buried. This is one of the largest rock avalanches to occur in Iceland during the last decades. The insulating effect of the deposit on the ice is evident and it moves along the glacier by some 80–90 cm per year. Undercutting of the mountain slope by glacial erosion and the retreat of the glacier are the main contributing factors for the rock avalanches, along with thawing permafrost and weaknesses in the bedrock. Landslides falling into glacial lakes may cause floods and thus pose hazard for people.

Figure 34. View towards Morsárdalur, Morsárjökull and Skaftafellsjökull, with Skaftafellsheiði, Kristínartindar and Skarðatindur between the outlet glacies.A large rock avalanche fell on Morsárjökull in March 2007, one of the largest in Iceland for decades. Photo: Snævarr Guðmundsson. Published in Hannesdóttir and Baldursson, 2017.

Glacier models indicate that after 200 years there will only be small ice caps on the highest mountains of Vatnajökull, i.e. on Öræfajökull and Bárðarbunga, and the highlands between Grímsvötn, Bárðarbunga and Kverkfjöll mountains. Vatnajökull could lose ca. 25% of its current volume within the next 50 years. Simultaneously, the runoff from the ice cap will increase and remain higher than today well into the 22nd century, until the ice reservoir has been substantially depleted.

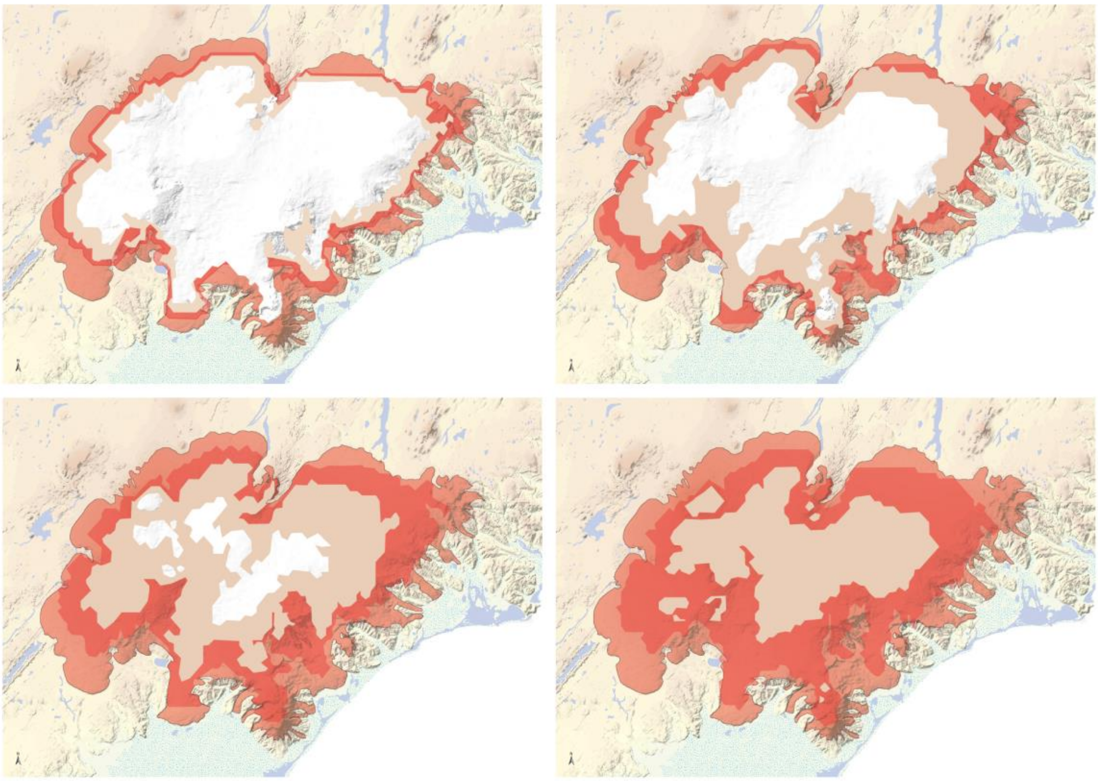

Figure 35. Simulated areal extent of Vatnajökull at present, as well as after 100, 150, and 200 years of warming, with no change in precipitation. Per century warming rates are as follows: (a) 1°C; (b) 2°C; (c) 3°C; and (d) 4°C. Modified after Flowers et al. (2005) and Björnsson 2017, published in Baldursson et al., 2018.

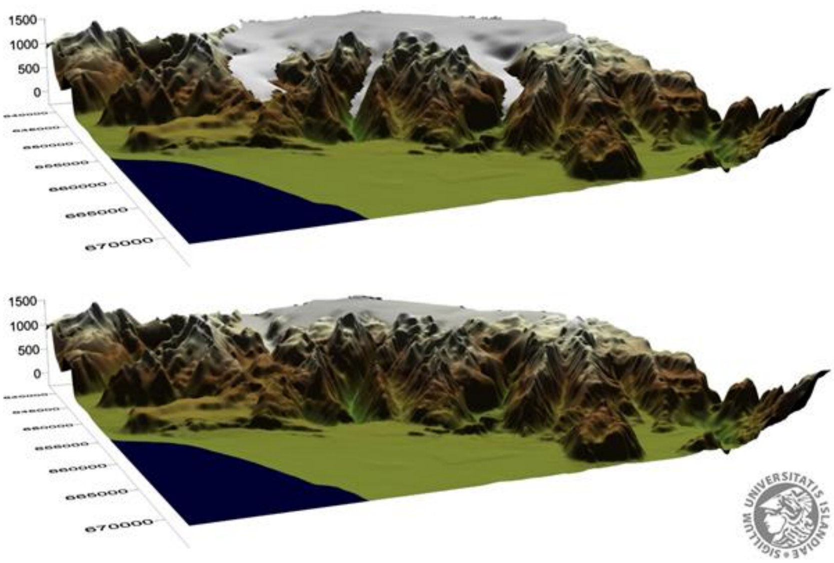

Figure 36. Surface geometry of Skálafellsjökull, Heinabergsjökull and Fláajökull according to model calculations; top: if temperatures were 2°C higher than the average of the time period 1980-2000 (when most glaciers in Iceland were in balance, neither retreating nor advancing), bottom: 3°C higher than the average of 1980-2000. Source: unpublished data from Hrafnhildur Hannesdóttir.

3.2.3 Glacier frontal measures

Jón Eyþórsson, meteorologist at the Icelandic Meteorological Office, initiated a monitoring programme of glacier termini in Iceland in 1930. These measurements have continued to this day and have been managed by the Iceland Glaciological Society since its foundation around the middle of the 20th century. The monitoring involves measuring year-to-year variations of the terminus position relative to a reference point. The measurements, published annually in the journal Jökull, are a remarkable source of information about glacier variations in Iceland for almost 100 years. The measurements document terminus retreat and advance, and in some cases dramatic surges, of a majority of outlet and valley glaciers in Iceland. The results are submitted to the international database World Glacier Monitoring Service about glacier variations.

Currently, the monitoring program involves 50 termini with 64 measurement sites. The location of the sites as well as all the annual reports on terminus variations, published in Jökull, are available at the projects website, http://spordakost.jorfi.is. The web also shows information about the people who carry out the measurements and displays photographs of the glaciers monitored. Historical photographs of particular termini at different points in time are provided in some cases. Graphs showing the variations of many different termini on the same plot are also provided

These measurements are an important contribution to monitoring of climate change and a good example of how the public can participate in scientific exploration. Since 1990 students taking a geology course at the local highschool in Austur-Skaftafellssýsla (FAS,) at Höfn have carried out terminus measurements. A co-operation between the school and the South East Iceland Nature Research Centre started in 2016 and involved measuring changes of Fláajökull glacier. The glacier edge is measured with a GPS device and the ata imported to GIS software, and the current position of the terminus portrayed on a satellite image. Information regarding the FAS glacier measurements can be found at the website https://nattura.fas.is/index.php/joklamaelingar. As the glaciers retreat and formation of terminal lakes advances, access to the termini for volunteers conducting the measurements becomes more difficult.

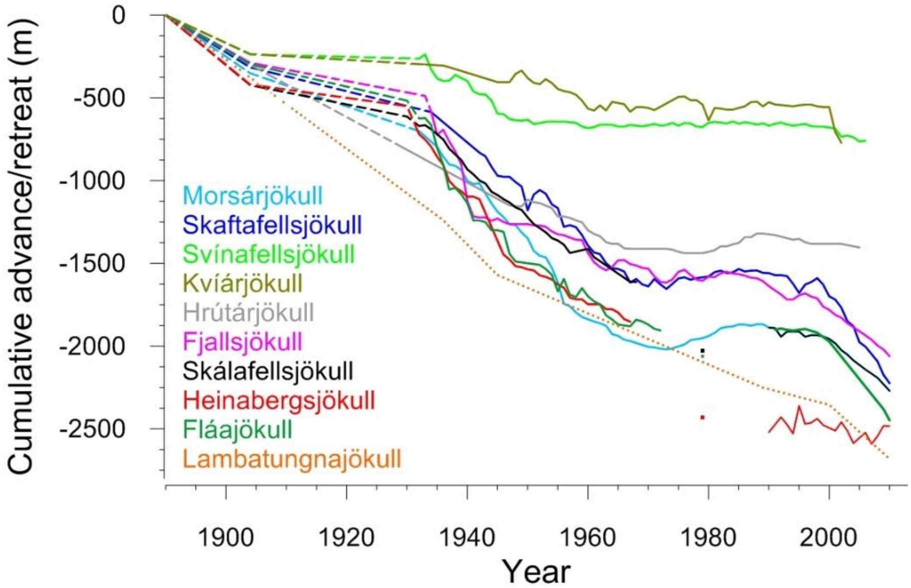

Figure 37. Cumulative frontal variations of a few south-flowing outlet glaciers relative to the ca. 1890 terminus position determined from the terminal Little Ice Age moraines. Source: Hannesdóttir et al. 2015.

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3.3 Uplift

As glaciers grow and advance the ice loading causes crustal depression displacing the mantle below the ice, forming a crustal bulge beyond the ice cap. With the crustal depression sea levels move higher and coastlines and shells can be found many meters above sea level since the last glacier period During the Little Ice Age Icelandic glaciers grew causing crustal depression. As the glaciers retreated and thinned again during the 20th century the underlying crust rebounds at an accelerated rate. Vatnajökull glaciers weight is approximately 3000 million tons and since the ending of 19th century (Little Ice Age peak) the glacier has lost about 10% of its volume.

Satellite data and GPS measurements have revealed the pattern of uplift around the periphery of the Icelandic ice caps. The rate of uplift is highest closest to the margin and on nunataks where the greatest mass loss takes place. High-resolution GPS measurements have shown extensive uplift around Iceland’s main glaciers and the central highlands which is associated with the crusts isostasy. The highest peak in Iceland, Hvannadalshnúkur in Öræfajökull is rising as is the land south of the ice cap. The uplift is especially evident in the shallow fjords, marshes and wetlands around Höfn in Hornafjörður.

GPS measurements devices are located all around the ice cap, but also on Grímsfjall and temporary on nunataks and mountains during scientific expeditions of the Earth Science Institute of the University of Iceland and the Icelandic Meteorological Office. Vertical and horizontal movements have been recorded, and on average the horizontal displacement is 3-4 mm per year, but the uplift is very variable, depending on location. Measurements indicate an uplift rate of 40 mm per year at Jökulheimar at the western margin of the ice cap, compared to 15 mm per year at Höfn in Hornafjörður, southeast of the glacier. If the ice cap would melt completely, uplift would be approximately 100 m at the centre of the ice cap and 50 m at the margin over a longer period of time.

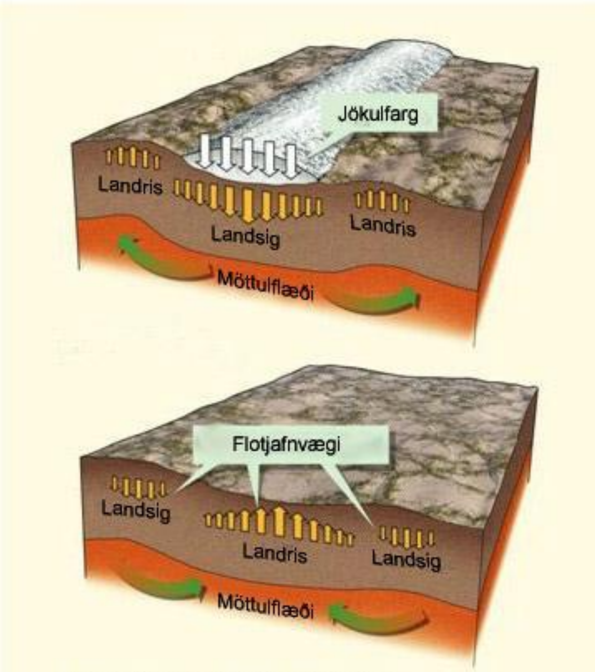

Figure 38. Uplift and isostasy. The weight of the glacier pushes the earth's crust down, so that it pushes up at the sides. When the glacier melts the earth's crust rebounds back. Source: http://www.loftslag.is/?p=6738

The National Land Survey of Iceland has since 1998 measured uplift at Hornafjörður. The GPS station is located at Fjárhúsahóll, at the edge of the town of in Höfn. This is the longest continuous GPS survey of uplift and horizontal movements in Iceland and the data is published in real-time at the following website: http://brunnur.vedur.is/pub/gps/timeseries/HOFN-plate-full.png .

The removal of the ice load as the glaciers retreat can lead to enhanced magma generation and increased volcanic activity and there are some indications that these effects are already causing increased volcanic unrest. The effect can thus be seen in increased activity in Grímsvötn, Bárðabunga, Öræfajökull and Kverkfjöll in Vatnajökull glacier.
This increases the risk of jökulhlaups (e. glacial outburst flood) to the south, west and north, threatening settlements and infrastructure.

These landscape changes have been evident to the residents of Hornafjörður municipality for years. The future of shipping through the inlet of Hornafjarðarós is uncertain due to the rapid uplift in this area. However, rising sea level due to warming climate and melting glaciers counteracts that process to some degree. Evidence of uplift in the area in recent decades are e.g. the following:

- Between the years 1910 and 1954 a pilot boat from Hornafjörður bay was docked in the fjord. Initially located at Lækjarnes at the eastern end of the Hornafjörður airport. As it became more difficult to sail to Lækjarnes, the boat was docked to Dilksnesskjól and people rowed to and from Lækjarnes to get to the boat. After 1954, when the fjord became too shallow to navigate, the pilot boat has been located at the harbour in Höfn.
- In 1912 a new cemetery was established at the shores of Laxá in Nes, replacing the older one at Bjarnarnes. At that time the latter had become impossible to use due to high ground water levels. When graves were dug, the caskets needed to be weighted with rocks for them to sink. The old cemetery at Bjarnarnes become functional again around 1980 and has been used ever since.
- North of the stables at Nes, there were "bottomless" and impassable marsh called *Rot.* Now the *Rot* is dry, utilisable grassland that does not submerge unless there is considerable swelling of the rivers.

- Traces of marine life, such as shells and walrus teeth, have been found in the moraines in front of Hoffellsjökull glacier, indicating a much higher sea level at that time. These remains have been dated approximately 7000 years old.
- Many islands are now in Hornafjörður fjord but from old photographs they are only seen during low tides and then only as small islets. Nowadays, most of these islands are covered in grass and many of them have eider nests. It is even possible during low tide to walk to the ones nearest the shore.

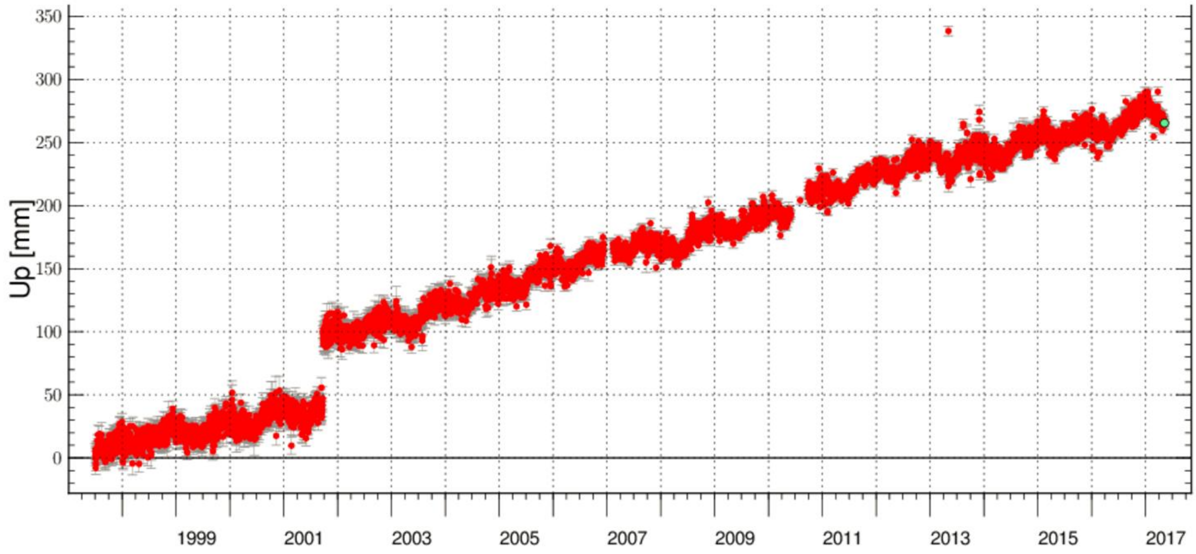

Figure 39. Uplift at Hornafjörður from 1998–2017 measured by GPS devices in mm.Source:http://brunnur.vedur.is/pub/gps/timeseries/HOFN-plate-full.png.

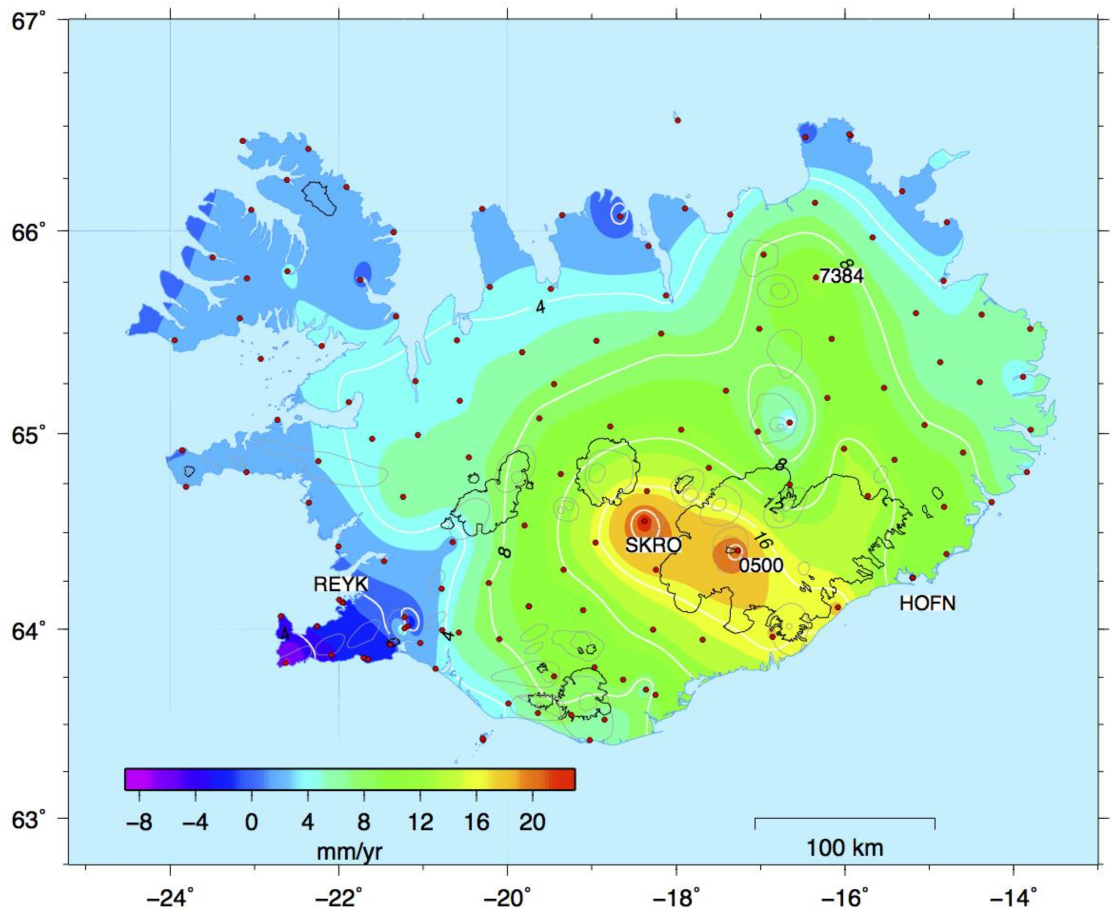

Figure 40. Vertical uplift in Iceland 1999–2004 from GPS measurements. Source: Þóra Árnadóttir et al., 2009.

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3.4 The ocean

The ocean is the largest ecosystem in the world containing over 97% of all of Earth's water and producing some 50% of the atmosphere's oxygen. The ocean plays an important role in the natural carbon cycle, but increased greenhouse gas emissions have created an imbalance in the cycle.

3.4.1 Ocean acidification

The ocean absorbs carbon dioxide (CO_2) from the atmosphere and its increased levels in the atmosphere results in equivalent increase in the ocean. Chemical reactions in the ocean result in acidification of the ocean and less dissolved calcium compounds, i.e. the acidity of the water, and conversely reduce the amount of carbonate ions, the building blocks in calcium carbonate skeletons. Acidification affects shell-building animals like bivalves, molluscs and corals. With less carbonate ions available, their shells end up being thinner and more fragile. It is feared that increasing ocean acidity will lead to species extinctions and affect the overall structure of marine ecosystems.
With current carbon dioxide emission rates, ocean acidification might reach critical levels already by 2030. The ocean north of Iceland acidifies considerably faster than further south, due to the mixing of warm and cold currents. Over the past 300 million years, ocean pH has been slightly basic, averaging about 8.2. But since 1750 the oceans pH units have dropped about 0.1.

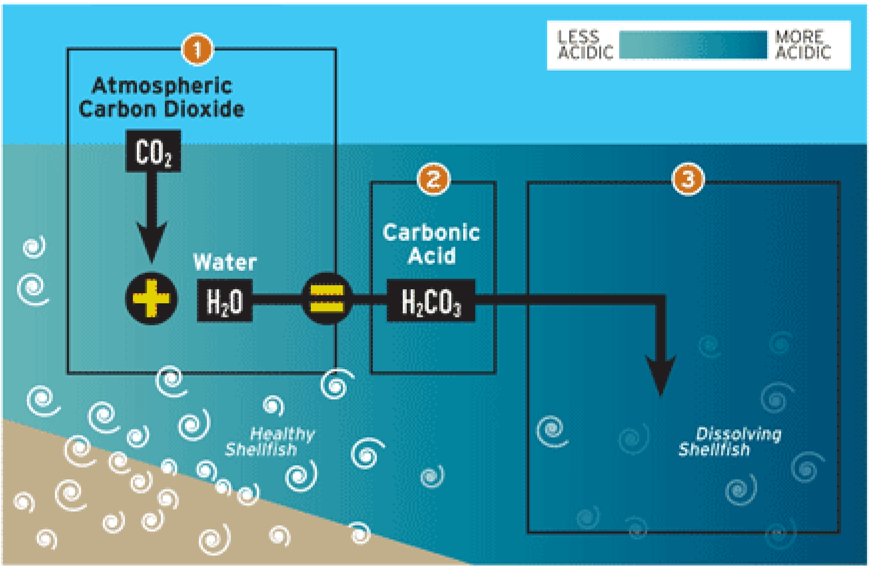

Figure 41. Ocean acidification. Increased levels of CO_2 in the atmosphere leads to increased uptake of CO_2 in the ocean, decreasing the pH of the ocean water. Source: http://seattlemag.com/sites/default/files/newfiles/article/Mar2011/0311_water_graphic.gif

3.4.2 Warming of the oceans

Warming of the ocean occurs mostly in the uppermost 70 m, which have warmed by approximately 0.11°C/decade since 1971. It is only last few decades that the warming has penetrated to depths below about 700 meters. The warming alters the physical properties of the ocean and reduces water mixing. Hence the oceans become more stratified. Nutrients, which are found mostly deep in the ocean or on the ocean floor, are less likely to move up to the surface where photosynthesis takes place. This reduction in upwelling and down welling makes it more difficult for water rich in nutrients, such as nitrate and phosphate, to reach the surface and for oxygen to reach the lower depths of the ocean. These kinds of reductions can result in biomass loss and changes in species compositions as species are differently affected. There are also indications that oceans organisms are migrating following their optimum temperature ranges. Blue whiting and mackerel, for instance, have now migrated to Icelandic waters and are now common species, whereas they were rarely seen a few decades ago.

The thermo-haline circulation in the North Atlantic varies inter-annually. Research indicates that global warming is slowing down the ocean circulation in the Atlantic Ocean, however drastic changes such as shut down of the Gulf Stream are not considered very likely. Changes in ocean circulation will affect productivity, the fishing industry and absorption of CO_2 from the atmosphere.

The majority of thermal energy at the Earth's surface is stored in the ocean. Solar energy maintains atmospheric and ocean circulation, wind-driven and ocean-current circulations move warm water toward the poles and colder water toward the equator. Air currents are dependent on temperature differences, density distribution, global wind patterns, rotation of the Earth and the depth and the shape of the ocean floor. Temperature and salinity changes caused by precipitation or evaporation lead to different densities of seawater, which are the primary drivers of sea currents such as the Gulf Stream. The Gulf Stream transports warm, salty ocean from the equator to the northern Atlantic Ocean, where the warmer water loses heat to the atmosphere and cools down. The cooler, denser water sinks and becomes deep seawater, returned back to southern regions by the Labrador Current.

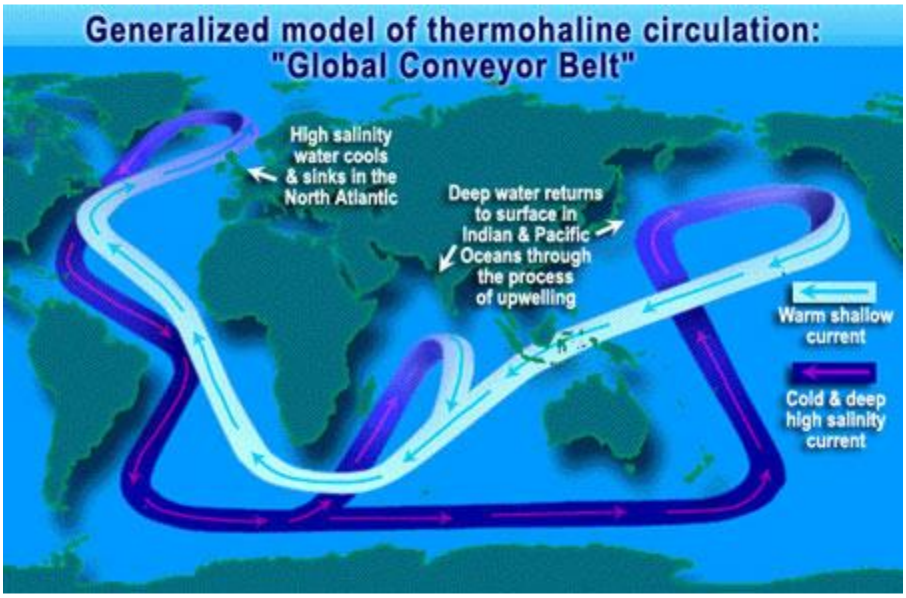

Figure 42. The heat-salinity cycle (thermo-haline circulation) affects nearly all the world's oceans. Source: nsidc.org.

3.4.3 Rising sea levels

The rise in sea level is due to melting glaciers and snow and to a lesser extent by thermal expansion of warmer ocean water. During the 20th century the sea level rise has been 18 cm. Since 1961 the average sea level rise has been approximately 1.8 mm a year but, but since 1993 close to 3.1 mm a year. Even after the concentration of greenhouse gases in the atmosphere reach a balance, sea levels will continue to rise. According to models, sea levels will rise 18-59 cm before the turn of the century, possibly considerably more.

- Rising sea levels will inundate land and submerge low-lying islands, which will also seriously affect the big cities of the world, as eight out of ten of which are built in coastal regions
- Destructive floods, which are becoming more frequent, are more likely to reach further inland than before
- Damage due to coastal erosion will be more extensive due to rising sea levels
- In densely populated areas, all infrastructures at low altitudes are at risk due to rising sea levels. These include roads and transportation systems, water supplies, aquifers, septic tanks, power plants, drainage systems etc.

The actual sea level in Iceland depends on two factors related to climate change: rising sea levels and land adjustments or isostacy (up- or downward movements of the crust) when glaciers melt. It is estimated that sea level rise will affect the Icelandic lowland regions in e.g. the southwest but that the uplift in southeast Iceland due to the decreasing volume of Vatnajökull will balance out the rise in sea level. At Höfn in Hornafjörður it is believed that uplift will be more than the rise in sea level.

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3.5 Vegetation

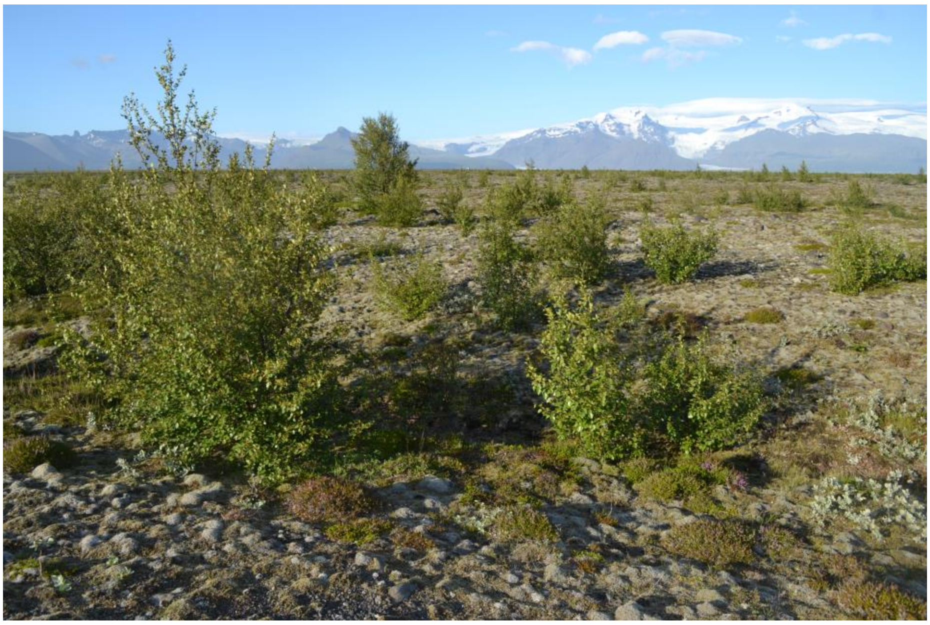

Figure 43. A birch plant on Skeiðarársandur. Photo: Bændablaðið.

Various theories exist about the colonisation of plants in Iceland following the end of the last glacial period. It has been claimed that some plants survived in ice-free areas such as on nunataks and on steep cliffs and then dispersed across Iceland at the end of the glacial. However, recent research indicates that the Icelandic flora does not have a long history, and that the vast majority of plant species migrated to Iceland, by means of ocean currents, birds or wind, after the last ice sheet retreated. The present-day flora is fundamentally Palearctic (northwest European) in character.

Climate (mostly temperature, precipitation and winds) determines the living conditions for plants. The effect of warming climate of the last few decades is already quite clear in Iceland:

- Plant productivity has increased, due to increased plant growth and distribution of plants.
- Mountain birch (*Betula pubescens*) is growing at ever higher elevations; and it has been estimated that for every +1°C increase in average summer and fall temperature, the species line extends upwards by 150 m.
- Effect of climate change on agriculture is seen in increased yield of crops that are traditionally grown, and in the fact that new crop plants have been introduced successfully.
- Conditions for afforestation and soil conservation have already improved drastically, although milder winter climate has also been troublesome and made it possible for tree pests and diseases to better survive the winter.
- The nature of the different plant species makes them thrive either better or worse in a warmer climate. It is likely that continued warming would cause high Arctic or Alpine plant species to recede or even vanish altogether from the Icelandic flora. Among these species are e.g. arctic harebell (*Campanula rotundifolia*), alpine whitlow grass (*Draba norwegica*), and glacier buttercup (*Ranunculus glacialis*).

When the glaciers thin and recede, new land emerges on nunantaks and in front of the glaciers. The primary succession begins as the first plants colonise the newly de-glaciated areas. So-called pioneer species are established closest to the glacier, but, farther away, an increase in the number of species and more complex ecosystems are observed. These areas provide unique opportunity to follow the process of succession and evolution of an ecosystem. Various biological studies have been carried out in the forefields of the southern outlet glaciers of Vatnajökull, including the colonisation of mountain birch on Skeiðarársandur, the origin of life in new ponds on front of Skaftafellsjökull, commencement of soil formation and community development on nunantaks of Breiðamerkurjökull glacier. The upcoming mountain birch forest on Skeiðarársandur covers approximately 30 km^2 and will probably be the largest birch forest in Iceland before 2050.

Teachers and students from the local secondary school, Framhaldsskólinn í Austur-Skaftafellssýsla, in Höfn, have been monitoring an area with five 25 m^2 (5x5) field plots that are visited annually. The highest birch was measured about 3 m. in the fall of 2016 but that plant was located outside of the field plots belonging to the school. Information on the school's projects can be found at the fallowing link: https://nattura.fas.is/index.php/skeidararsandur

Glacial rivers are loaded with suspended material, which with time raises the riverbed and leads to frequent changes in the river path. As well the retreat of the glaciers causes changes in river channels. When a river changes course, moisture conditions at both places change, affecting the growing conditions for plants. Also, the rivers can erode and destroy vegetated areas as they change channels.

In 1997 a new island appeared in Jökulsárlón lagoon and by 2000 the island was ice free. The island was named Skúmey, meaning the island of the great skua (*Catharacta skua*). The South-East Iceland Nature Research Centre in cooperation with others now monitors the succession of plants and other organisms closely. Diverse vegetation has already immigrated to the island, including lichen and moss, which are generally the first to colonise, to flowering plants and crawling shrubbery. Further, 967 nests of barnacle geese (*Branta laucopsis*) were counted in the summer of 2917, the largest breeding colony in Iceland of this newly established species.

Figure 44. Vegetation in Skúmey in spring of 2017. Photo: Snævarr Guðmundsson.

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3.6 Animal life

Climate change has had a profound effect on animal habitats, for example due to changes in plant distribution and growing conditions of the animal's food plants. Insects and bird chicks are for instance very dependent on specific food at a given stage in their development, and if this specific food is not in sync with the developmental stages, it can have dramatic effects on the survival of those animals.

Many land, freshwater and, marine animals have changed their range, migrated to new areas or adapted to new migration patterns, seasonal activities and interactions with other animals because of climate change. Commonly, animals have moved north or up to higher elevations in mountains areas, following changes in vegetation or pray species. Temperature rises also affect water quality and impact ice cover, salinity, oxygen concentrations and currents to name a few. All this may profoundly affect the fauna of these habitats.

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3.6.1 Marine species

Fluctuations in ocean temperature affect the living conditions and harvest yield of exploitable species of Icelandic waters. Ocean temperature and salinity, both affected by climate change, are major factors in determining growing conditions of phytoplankton and thus affect the whole marine food chain. A definitive change, traceable to ocean warming, has occurred in the distribution and size of exploitable fish stocks in Iceland over the last two decades. In general, ocean warming has had a positive influence on the distribution and productivity of southern species, such as angler or monk fish (*Lophius piscatorius*), saithe (*Pollachius virens*) and Atlantic mackerel (*Scomber scombrus*) but a negative impact on northern species, such as shrimp (*Pandalus borealis*), Greenland halibut (*Reinhardtius hippoglossoides*) and capelin (*Mallotus villosus*). The temperature of the sea around Iceland is considered close to optimal for Atlantic cod (*Gadus morhua*), which is why fluctuations in regeneration and stock size have been less around Iceland than further east or west in the Atlantic. It is expected that the spawning grounds of the Atlantic cod will extend north with warming seas, though the ocean ecosystem is complex and difficult to estimate changes with certainty.

Marine mammals are warm-blooded, and most species around Iceland tolerate considerable changes in temperature. The majority of Icelandic whales are migratory, entering Icelandic waters to feed during the summer months. Their mobility allows them to follow the food source at any given time. Hence their distribution will change as their food source will change due to climate change.

Icelandic lobster, or langoustine (*Nephrops norvegicus*), resides in the eastern region of the North Atlantic Ocean. It is found in the warm waters of Iceland's southern coast (from Hornafjörður fjord to Faxaflói bay), on the northern edge of its range. The lobster stock around Iceland is homogenous and strong and has grown exponentially in recent decades, after having been scarce towards the end of the last century. There are clues that the rising temperatures have been beneficial to the stock.

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3.6.2 Birds

Most populations of nesting seabirds around the Northern Atlantic Ocean have declined considerably since the turn of the century. Seabirds are vulnerable for environmental changes by the shore and fluctuations are considerable in cliff birds' stock and their nesting. Further changes are expected in seabirds breeding in decades to come, along with warmer climate. The seabird decline, however, is not uniform over all the country. After 2005 there was a shift change in non-cliff nesting of seabirds on the South coast of Iceland. The most noticeable decline happened in colonies along the south and west coast which is traceable to a drastic decline in the sand eel stock (*Ammodytes marinus*) in the early 20th century. The sand eel is a major food source for many seabirds, fishes and whales.
The population of Brünnich's guillemot (*Uria lomvia*) in Iceland has declined sharply since the middle of the 1990's. Populations of other seabird species, such as the common murre (*Uria aalge*), razorbill (*Alca torda*), northern fulmar (*Flumarus glacialis*) and Arctic tern (*Sterna paradisaea*) have also been declining after the turn of this century. Particularly, the puffin (*Fratercula arctica*) stock has declined by approximately one quarter in Iceland since measurements began in 2003, which is traced to the collapse of the sand eel stock. On the other hand, higher summer temperatures improve living conditions for many terrestrial birds and warmer winters will increase the likelihood that summer vagrants will survive and initiate nests the following spring.

Approximately 35 new bird species attempted nesting in Iceland in the 20th century and many species settled permanently, e.g. blackbird (*Turdus merula*), starling (*Sturnus vulgaris*), lesser black-backed gull (*Larus fuscus*), common gull (*Larus canus*), common shelduck (*Tadorna tadorna*) and barnacle goose (*Branta laucopsis*). The frequency of new settlers seems to have increased in the latter part of the 20th century. Towards the end of this century, it can be expected that climate conditions in Iceland will good enough for additionally over 80 bird species, although it is unlikely they will all settle here. By the end of this centurythe climate may, on the other hand, have become too warm for e.g. phalarope (*Phalaropus fulicarius*) and thick-billed murre (*Uria lomvia*) and the range of other northern species may have become greatly constricted. Milder climate, especially during winter, may increase the possibilities of vagrant birds settling, but the development of new habitats is also a deciding factor. For example, afforestation projects have facilitated the resent establishment of the coniferous forest species goldcrest (*Regulus regulus*) and the Eurasian woodcock (*Scolopax rusticola*).

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3.7.3 Land species

Many new insect species have settled in Iceland during the last three decades, for instance four new species of bumblebees and another four species of wasps. Most of these have likely arrived with imported goods in ship containers or cargo. It is anticipated that insect species will multiply during this century. However, it is not expected that the number of land mammals will increase, unless with human intervention. Rabbits already live in the wild in several regions in Iceland and are believed to continuously expand their range unless appropriate culling measures are taken. Increased productivity of the ecosystem, with rising temperatures, will all else being equal prove beneficial for native and feral mammals, such as the Arctic fox, field mouse, reindeer and American mink.

References:
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3.7 Human society

Climate change and its imon nature and the environment have various consequences for societies all over the world. However, the social effects of climate change are not always as apparent as their effects on the environment and ecosystems as it isn't easily measured. That is why it can be difficult to quantify the impacts of climate change on communities.

3.7.1 Global warming and social impacts

Climate change will not only impact nature, but also human societies and will alter people's lives in a myriad of ways that we are just beginning to understand. In poorer countries climate change can lead to economic shock due to worsening conditions. Warmer climate and increased droughts have widely led to shorter cultivation period and reduced harvesting. For example, in southern Africa the dry season is getting longer, and precipitation is becoming ever more unreliable. The global warming has also increased frequency and intensity of storms which has led to damages of infrastructure and loss of homes. Rising mortality rates in Europe due to higher summer heat, more frequent forest fires, people´s allergies to pollen in the northern hemisphere and wider spread of diseases in some areas are just some examples of factors caused by global warming. This has serious consequences for the poorer communities that have limited potential for adaptation and are often dependent on climate-related resources, as local water- and food sources.

In most of the world, the overall impact of climate change will be highly negative, both for natural systems and human communities. Economic consequences for individuals and nations can be substantial in the future due to storms.

The marine ecosystems and distribution areas have changed, and fish species are increasingly affected by rising sea temperatures. Experts believe this development will threaten the livelihood of several coastal communities.

In northern countries such as Iceland, the local impacts are perhaps more ambiguous:

- Climate conditions for grain production, forestry and soil conservation have greatly improved.
- Warmer climate has improved conditions for various pests and plant diseases, some of which have up until now been non-existent in Iceland.
- Changes in distribution and stock size of fish species can have a profound effect on a fishing village, such as Hornafjörður. For example; haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), monkfish, and saithe have expanded their range in Icelandic waters, while capelin has moved further north.
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3.7.2 Glacier Melting and Social Impacts

The melting of glaciers, especially the ice sheets of Antarctica and Greenland, is one of the main factors contributing to rising sea levels. Rising sea levels enhance costal erosion and may cause floods, pollution of groundwater and lowlands may submerge under water all around the world. Many of the most densely populated areas in Asia, Northern Europe and America are at the highest risk. These are coastal areas that habit hundreds of millions of people,

Millions of people utilise glacier meltwater as drinking water and for irrigation. Water shortage is expected to become a problem around the world, especially in populated areas in India and China when the Himalaya glaciers disappear. Iceland's glaciers contain freshwater supplies amounting to 20 years of precipitation. Icelanders have more freshwater available for each inhabitant than any other nation in the world. This is an extremely valuable natural resource which should be protected and utilized wisely.

The melting of the glaciers directly affects the society of Hornafjörður. Glaciers are melting fast and may be mostly gone in 150-200 years.

- With melting of the glaciers, an extremely valuable part of the regions scenery disappears, with potentially serious consequences for the tourism industry, one of the most important professions in the area and the country.
- Glacier melting leads to uplift, potentially blocking the shipping channel into the harbour in Höfn, thus the fishing industry in Höfn may be at risk.
- The uplift can also cause considerable problems for Hornafjörður sewage system. As the land rises, the level of groundwater becomes lower and changes occur in soil density. This may cause sewer pipes to dislocate and there are indications that this is already happening at Höfn.
- Uplift can cause fjords in the area to dry up exposing fine sediments and mud, and increasing the risk of soil erosion.

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4. Possible countermeasures

Impacts of climate change can be reduced by various countermeasures. Effective measures require concerted action by governments, businesses, institutions and the public. Without actions, the impact of climate change is likely to be greater than our natural and social systems can handle. Countermeasures can roughly be classified into two classes; reduction of CO_2 emissions into the atmosphere and binding atmospheric CO_2 in vegetation or by other means.

Anthropogenic greenhouse gas emissions in Iceland stem mainly from energy processes (50%), industrial processes (24%), agriculture (21%) and waste (4%). In recent years anthropogenic greenhouse gas emissions has increased in Iceland, mainly from industrial processes, energy processes, waste and transportation. At the same time anthropogenic greenhouse gas emission has decreased in fishing industry and agriculture.

4.1 Governments and countermeasures

Anthropogenic climate change is considered one of the most serious environmental problems of today. The responsibility of governments is enormous, and collaboration and cooperation of the world's nations is required for urgent solutions. The United Nations have worked on the issue of global warming, including by developing national agreements and assess the progress in dealing with climate change. Fallowing are the main progresses in these agreements:

- 1992 – the Framework Convention on Climate Change (FCCC) was first approved at the Rio Conference in Brazil.
- 1995 – the *Kyoto Protocol* was agreed, committing parties to internationally binding emission reduction targets
- 2005 – the Kyoto-Protocol became officially operative when sufficient number of nations had signed it; it expires in 2020.
- 2015 – the Paris climate agreement was approved, aiming to keep global temperatures rise this century below 2°C, and preferably below 1.5°C.
- 2016 – the Paris climate agreement came into force when 55 nations had confirmed it.

Iceland became a member of the United Nations FCCC in 1992 and has also signed the Kyoto Protocol and the Paris climate agreement. Iceland further committed to participate in the European Union target of 40% reduction in greenhouse gas emissions by 2030 (as compared to 1990 levels). In November 2015, the Icelandic government announced a climate-change action plan. The plan emphasises cooperation between the government and industries and encourages innovation and climate-friendly solutions. The action plan is based on 16 tasks aimed to reduce emissions, increase carbon fixation, support global climate projects and enhance government capacity to cope with stricter climate commitments.

The main objectives and tasks of the action plan are as follows:

- Energy change in transport. The action aims at 10% of renewable energy sources by 2020.
- Enhancement of national infrastructure for electric cars. The action aims at strengthening infrastructure that are important for the car fleet electrification, such as charging platforms.
- Fisheries guidelines for a reduction in emissions. Actions aim at reducing emissions by 40% in the fisheries industry by 2030 compared with 1990.

- Climate-friendly agriculture. Efforts will be made to provide a reference guideline for agricultural emissions contraction.
- Improving forestry and land reclamation. More resources will go into forestry and land reclamation.
- Reclaiming wetlands. The action aims to set up a project to restore wetlands.
- Carbon neutralization in government operations. Support projects that promote carbon reduction in government operations.
- Efforts to prevent food waste. Promote projects that help reduce food waste.

The action plan also includes projects identifying and communicating the consequences of climate change to the public, including:

- Scientific report on the consequences of climate change in Iceland
- Adaptation to climate change in Iceland
- Better accounting and forecasts on emissions and carbon fixation
- Icelandic glaciers, a natural laboratory to study climate change

Iceland has a lot to offer in reducing greenhouse gas emissions globally, for example with engineering and technology in the field of geothermal energy and land degradation.
For instance, is the United Nations University's Geothermal Training Programme executed in Iceland by Orkustofnun. Its role is to provide young experts from developing countries with specialized training in geothermal research and utilization. In addition, Iceland is an active advocate of integration of gender equality and climate. Part of the action plan will be to strengthen Iceland's climate policy internationally.

- Group on exploitation of geothermal heat worldwide
- Climate change in the Arctic
- The Green Climate Fund
- Contributions to climate related development aid.

4.2 Corporate and Individual Countermeasures

Both corporations and individuals have a major role to play when it comes to reduction in greenhouse gas emissions. Opportunities to countermeasures focus on certain factors, such as, transportation, consumption, land use and energy. Additionally, can corporations in specific fields focus on the specialized technical aspects and operations of the companies with the aim of reducing greenhouse gas emissions.

- Agricultural companies can in various ways minimise the emission of greenhouse gases. For example, by improving feeding practices of farm animals to reduce the production of methane. Implement methane gas production from manure and increase the usage of manure instead of the ready-made nitrogen fertiliser.
- The fishing industry has already taken steps to reduce greenhouse gas emission, for example by electrification of fishmeal factories and by increasing the use of biofuel for fishing vessels.
- Ferroalloy plants have means to reduce emissions, e.g. by increased usage of woodchips in their production or by carbon restoration.

4.3 Carbon Footprint and Carbon Neutrality

Greenhouse gas emission is measured in carbon dioxide equivalent, same applies to the carbon footprint, these are simple and explicit measurement on how much affect a certain product, process or company has on climate change. It's interesting to measure personal carbon footprints to realize which factors in our daily life have the most impact on climate change. In this way, companies and individuals can find ways to reduce their carbon footprint and carbon neutrality. Below are links to calculators where a persona carbon footprint can be calculated, along with information on how to carbon neutralize.

http://www.carbonfootprint.com/
http://kolvidur.is/carbon-calculator/

Specific projects aim to reduce the concentration of carbon dioxide in the atmosphere by increasing the carbon sequestration of forest ecosystems, binding the soil and reducing soil erosion
Kolviður is an accessible way for individuals and companies to neutralize its carbon footprint.
Iceland air offers its passengers to purchase carbon credits, which is a collaborative effort with Kolviður. Additionally, Landvernd, the Icelandic Environment Association and Wow air are collaborating to protect the Icelandic landscape with free donations from airline passengers.
Carbfix is a collaborative project among several institutions, universities and companies to pump CO_2 into the rock layers near the Hellisheiði power plant, creating stable, carbon-rich rock in the basalt. The Researches show that more than 95% of the CO_2 injected has been transformed into fossils in less than two years.

https://wowair.is/um-okkur/wow-air-landvernd/
http://www.icelandair.is/information/about-icelandair/environmental-policy/

4.3.1 Transportation

Most transportation vehicles still burn fossil fuels, although there is a definite trend towards greener more environmentally friendly vehicles. Emission of GHGs from transportation is mostly related to burning of fossil fuels. In 2014, the emission of GHGs from transportation was 19% of Iceland's total emissions. Transportation was the second largest source of emissions, following right behind the emissions from industry and chemical usage. Road transportation counts for 93% of total transportation emissions. Between 1990 and 2014 emission from road transportation increased by 52%, but since 2009 emission from transportation has decreased by 9%. This trend is partly due to individuals driving less because of economic recessions and partly due to the development of more fuel-efficient vehicles.

Possible actions for companies and individuals:

- Reduction of GHG emissions and fuel costs by using eco-friendly vehicles (e.g. which use electricity, hydrogen or methane) or have exhaust emissions that are below 120 CO_2 g/km.
- Reduction of GHG emissions by engaging in ecological driving. Road safety is increased, and fuel usage decreased. Through ecological driving, it is possible to save every tenth tank and minimise wear and tear of the motor and tires, which saves money and reduces pollution.
- Use public transport when possible.
- Choose an eco-friendly mode of transportation, walking or riding a bicycle. Surveys show that a third of all trips taken by the citizens of Reykjavik are no more than 1 km, a distance that can easily be walked in approximately 15 minutes.
- Information technology can be utilised to cut down unnecessary trips, decrease travel cost and time, e.g. with teleconferencing equipment or email.

- Discontinue usage of studded tyres if possible, decreasing the concentration of particulates in the atmosphere.

4.3.2 Energy production and energy consumption

Renewable energy provides over 99% of electricity production in Iceland, with about 73% coming from hydropower and 27% from geothermal power. About 90% of homes are heated with geothermal energy and there are only a few homes, summer houses and swimming pools that utilise electrical power produced with a diesel generator and diesel fuel. Many other countries, for instance Germany and the United States rely on fossil fuels: oil, coal and gas for energy production. Thus, GHG emissions due to energy production in Iceland is rather minimal in comparison to other countries.

Hornafjörður is not in a high-temperature geothermal area and, electrical power is used to heat the houses and water. Geothermal heat (approximately 50–70°C) has been found in three areas within the municipality and further drilling is ongoing in one of these areas, with the goal of supplying heat to all the houses in the town of Höfn.

Possible actions by companies and individuals with regards to energy production focus on decreasing the energy consumption:

- Consider the energy efficiency of electronic equipment.
- Adjusting the heating over the summer months or while away, diminish heating costs and energy consumption
- Electronics on standby, for example televisions, can use 40% of the energy required for full usage; break the circuit while the appliance is not in use.
- During daylight hours, having lights turned off can easily save energy.
- Energy saving light bulbs use up to 80% less energy and last up to 10 times longer than normal light bulbs.

4.3.3 Forestry, Land Reclamation and Wetland Restoration

Increased land use and deforestation restrict the natural uptake of CO_2 through photosynthesis. Restoring damaged land or growing trees results in increased sequestering of carbon dioxide and is a powerful way for both individuals and corporations to counteract the increase of greenhouse gases in the atmosphere. Wetland restoration is also a powerful countermeasure in decreasing greenhouse gas emissions. As bogs are drained, oxygen is absorbed in the soil and plant remnants begin to decompose. This process releases gases into the atmosphere. Approximately 4,200 km^2 of Icelandic wetlands have been drained, partly or fully, through some 34.000 km of draining trenches. Most of this land is in little direct use. Estimates indicate that over 70% of all CO_2 emissions in Iceland stem from drained wetlands.

Restauring wetlands where landuse is minimal is a fast way to reduce total greenhouse gas emissions in Iceland. Greenhouse gas emissions research needs to be explored in different kinds of wetlands to determine with certainty how much total emissions can be reduced by efforts to restore them. One effect needs to be noted, that undisturbed wetlands release methane, which is a stronger greenhouse gas than carbon dioxide, but this effect is considered negligible relative to the yield.

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https://www.althingi.is/altext/pdf/146/s/0289.pdf

4.3.4 Consumption

With a review of consumption and practice, individuals and companies can significantly reduce their carbon footprint. The prioritization of ecological behaviour is:
1. Reduce consumption
2. Reuse
3. Recycle

Advices and information on how to reduce greenhouse gas emission through consumption, while maintaining a quality of life, may be found at the fallowing link:
https://www.ust.is/einstaklingar/loftslagsbreytingar/hvad-get-eg-gert/

4.3.5 Plastic use

Coal, cellulose, natural gas and crude oil are used in the production of plastics. Roughly 2 kg of the oil is needed to produce 1 kg of plastic. Plastic, therefore, contributes to GHG emissions both in the production stage and when burnt or buried in a landfill. The use of single-use plastics is especially troubling. It is estimated that each inhabitant in the European Union uses an average of 500 plastic bags a year, most of which are only used once. It is estimated that about 70 million plastic bags are thrown away in Iceland each year, equalling to 1.120 tons of plastic or 2.240 tons of oil.

The properties of plastics are such that they last very long. Generally, they do not decompose fully in nature, but rather break apart into smaller and smaller particles. A lot of these particles enter the soil, oceans, lakes, and rivers where they may enter the food chain and harm living organisms.
In recent years, more attention has been paid to pollution of the oceans and the fact that they have long been regarded as a garbage bin, for waste and even toxins. Some 60–80% of all garbage in the oceans is plastic and more than 8 million tons are added each year. Vast floating islands of plastics have been observed in the Pacific, Atlantic and Indian Oceans. About 70% of the plastics sink to the bottom, 15% remains floating on the surface and 15% are washed again upon land.

- Many manufacturing companies have the opportunity to reduce the use of plastic products in their production.
- Individuals should utilise reusable bags and containers instead of single use plastic.
- In water should always be consumed from the faucet using a multi-use bottle, rather than purchasing water in a disposable plastic bottle.
- Individuals and businesses can bring most of their plastic consumables in for recycling.

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https://www.ust.is/einstaklingar/graenn-lifsstill/heimilid/einnota-plastumbudir/
http://ibn.is/29-leidir-til-ad-minnka-plastnotkun/

4.3.6 Food waste

About one third of the food that is bought annually, some 1.3 million tons, goes straight into the garbage bin according to the Food and Agriculture Organisation of the United Nations (FAO). That does not include the food that has already been cooked and served and is later thrown away.
Awareness regarding food waste has increased, with the emphasis being on reducing food waste so that we can better utilise our resources and bring down production costs. However, food waste also contributes to emission of greenhouse gases. According to a study done by FAO, it is estimated that world emissions amounting to 3.300.000 Gg (1 Gg=1 million carbon dioxide equivalent) can be directly correlated to food waste. If the average waste of each Icelander is comparable to the average of

European residents, then the annual average of food waste in Iceland is approximately 200 Gg of carbon dioxide. That is about 5% of the annual total emission rate of Iceland in 2013.

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4.3.7 Garbage

As waste decomposes at landfill sites, landfill gas is produced. The concentration of GHGs in the landfill depends on the magnitude of waste and the ratio of organic matter in it. In general, however, it is safe to say that less waste means less greenhouse gases. What can be done is among other things to:

- Be more content and make full use of resources, thus reducing waste
- Compost organic waste thus minimising landfill usage
- Recycle and thus reducing garbage production.

Reference:
https://www.ust.is/einstaklingar/loftslagsbreytingar/hvad-get-eg-gert/heilraedi/

5. Tourism and Climate Change

Together with the fishing industry, tourism is the most important economic activity in Hornafjörður and its importance has increased exponentially in recent years. Winter tourism has become increasingly popular, turning the travel business into annual rather than seasonal activity, and thus strengthening regional development.
Vatnajökull National Park with its accessibility to the many outlet glaciers of Vatnajökull is considered a primary reason for the popularity of the region amongst travellers. The ice caves in the southern outlets are the areas greatest attraction during winters. Even though the fast retreat of the glacier snouts is a constant concern, this also provides an opportunity for the discussion and an ideal setting for educational tourism on climate change and glacier retreat as the evidences are visible and the access to the glaciers in the region is especially good.

Recently there has been an awakening in ensuring high quality tourism and an increasing share of tourists now stress this when choosing a travel company. Vakinn is the official quality and environmental system within Icelandic tourism. Its goals are to: inspire quality, safety and, environmental awareness in the tourist industry; to be a mentor for businesses in the industry and to promote social responsibility of tourist operators. The members of Vakinn are now over 100, and many applications from travel companies still pending.

Climate change can have multiple consequences for the travel industry, as the climate has a direct impact on the industry's operations, travel conditions and the length and quality of the tourism season. Tourism is vulnerable for climate change, but those changes can be both positive and negative depending on the area. Coastal and island tourism is especially perceptive to rising sea levels and flooding, while winter tourism may suffer from the retreat of glacier and less snow cover.

Tourism, however, is not only the potential victim of climate change but also an important cause of it. It is estimated that approximately 5% of CO_2 emissions in the world come from the tourism industry. About 75% of this is attributed to air traffic. It is estimated that emissions from the touring industry will increase by about 130% (mostly from air traffic) over the next 15 years if no countermeasures are taken.

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