

Overview of Icelandic Glaciers



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Introduction:

Iceland, an island located in the North Atlantic Ocean, is lying on the constantly active geologic border between North America and Europe. Iceland is well known for its cryosphere contents, such as icecaps and glaciers, which plays a significant role in various issues like hydro power generation, sea level rise etc. These glaciers and ice caps cover almost 11% of land area of the country (approximately 11,100 km² out of the total area 103,125 km², figure 1).

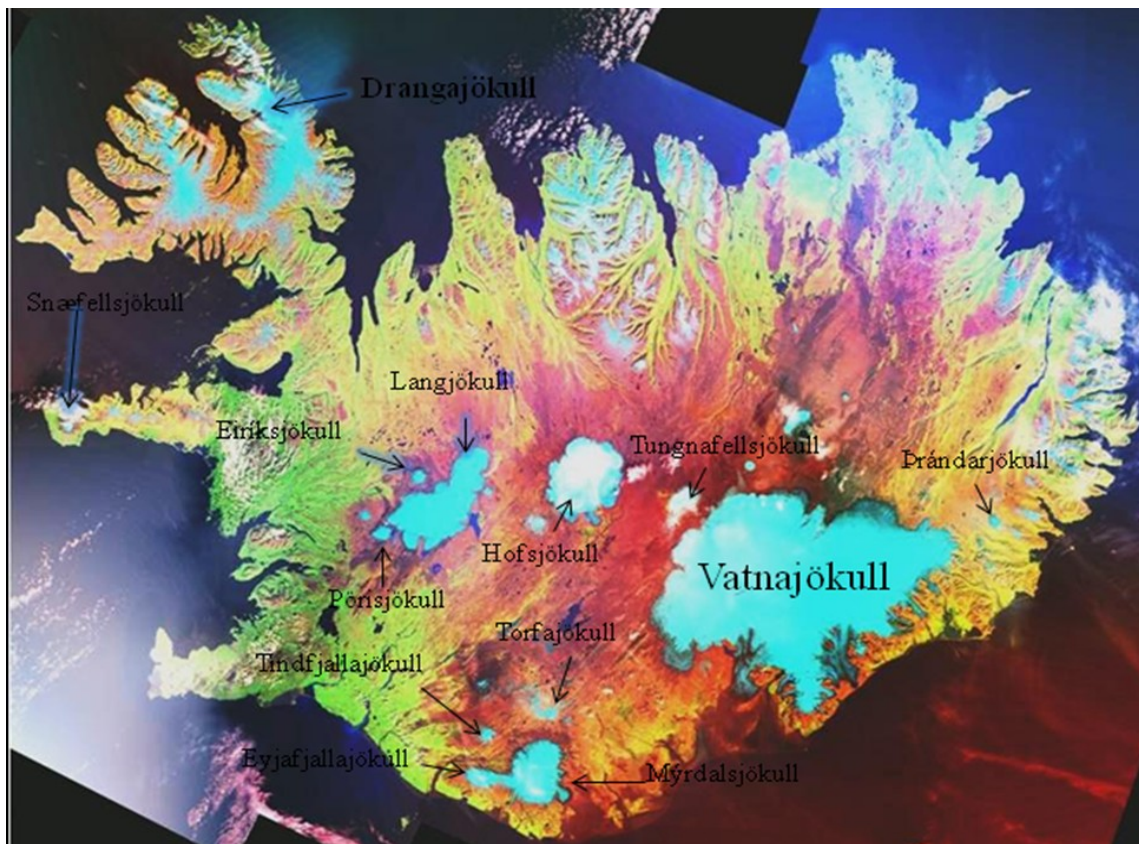


Figure 1: Landsat TM imagery, showing major icecaps and alpine glaciers of Iceland

Iceland has a relatively mild oceanic climate and small seasonal variations in temperature. Average winter temperatures tend to be around 0⁰ C near the southern coast, where the average temperature of the warmest month is only 11⁰ C and the mean annual temperature is about 5⁰ C (Einarsson, 1984). Along the northern coast, the climate is effected more strongly by the polar East Greenland Current, which occasionally brings sea ice. In the central highlands, permafrost can be found at altitudes above 550–600 m. Heavy snowfall is

frequently induced by cyclones crossing the North Atlantic, where air and water masses of tropical and arctic origins meet. At higher elevations, this leads to snow accumulation. Hence, the majority of icecaps and glaciers can be found in Southern Iceland (figure 1 and 2).

Icecaps conceal unexplored landforms and geological structures, including active volcanoes, geothermal sites and sub glacial lakes. Jökulhlaups from geothermal and volcanic locations are frequent. These floods are more dangerous and have threatened inhabited regions, damaged vegetation, disrupted roads and communications, and even temporarily deterred ash from entering coastal waters. About 60% of today's glacial area is underlain by active volcanoes, occasioning intensive studies of glacier volcano interaction.

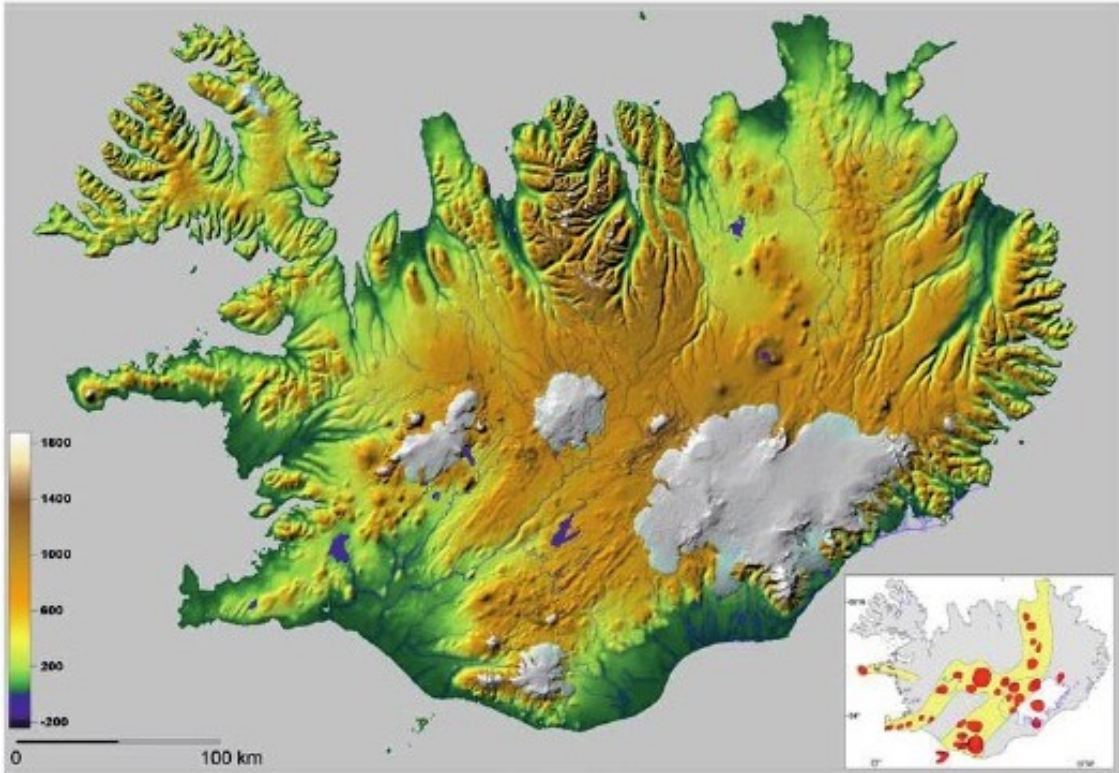


Figure 2: Topography of Iceland, with glacier distribution. The main icecaps are bordered by smaller glaciers. The inserted geological map shows the active volcanic zone and the central volcanoes (Source: H. Björnsson and F. Pálsson)

GLACIERS AT LAST GLACIAL MAXIMUM

Overview of glaciation in Iceland

Glaciation in Iceland works to provide one of the best study sites in all of the North Atlantic due its unique location and geological characteristics. Its location in the North Atlantic proves to be very sensitive to climatic perturbations as well as sea level variances. Of utmost importance, however, is Iceland's volcanic origin. The constant creation of new land from the mantle plume beneath Iceland allows basal accumulation rates to overrun its erosion rates, thus preserving the geological history. Furthermore, the types of volcanic products found throughout the country dictate their origin. For example, a lava flow is clearly of interglacial or interstadial origins, yet an eruption of hyaloclastites and tills on Moberg, or flat-top, mountains is indicative of subglacial volcanism.

Both sedimentological and stratigraphical along with $\delta^{18}\text{O}$ records in deep-sea sediments indicate that Iceland has experienced over 20 glaciations during the past 4-5 Myr. The most visible erosion of the Icelandic landscape began to occur around 2.5 Myr BP when extensive volcanism allowed for increased topographic relief. This allowed for the creation of valleys up to 400 m deep between 2.5 and 0.5 Myr BP at a rate of 10-20 cm/ka. During the past 0.5 Myr, erosion rates increased to 50–175 cm/ka. Marine sediment cores from the North Atlantic estimate that glaciations in the Northern Hemisphere began between 10 and 5 Ma BP and large-scale glaciations appears 2.75 Ma BP.

Glaciation during the Last Glacial Maximum

The Weichselian glaciation was the most recent during the Last Glacial Maximum (LGM) and began approximately 100 cal ka BP. The glaciers reached their maximum extent around 21 ka BP and retreated around 10 ka BP. It involved a single central dome ice cap with an upper plateau elevation of 2000 m above the current sea level and extends significantly offshore. Models of paleo glaciation in Iceland are still very ambiguous, as the number of factors that must be accounted for are extensive. These models of the LGM depict glaciation with restricted and extensive glaciation models of areas of anywhere from 2 to $4.5 \times 10^5 \text{ km}^2$ and volumes of $1.4\text{--}4.8 \times 10^5 \text{ km}^3$. The optimal model depicts an ice sheet with an area of $3.29 \times 10^5 \text{ km}^2$ and a volume of $3.09 \times 10^5 \text{ km}^3$. This model would require 5 degrees of atmospheric cooling from the present day and would stretch well beyond the current coastline.

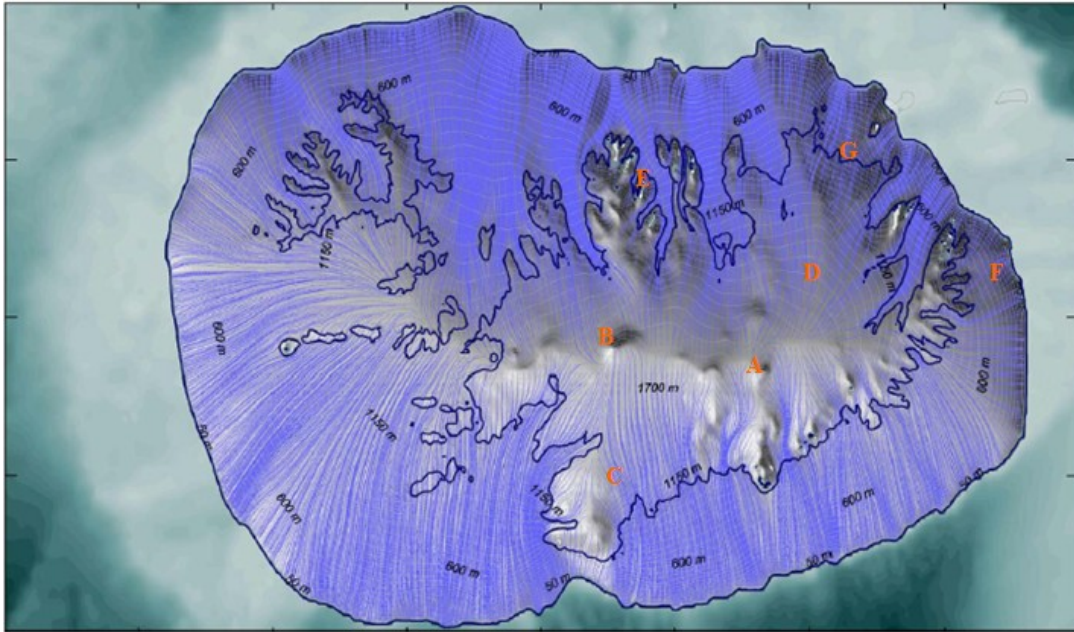


Figure 3: Iceland during the Last Glacial Maximum

A variety of empirical field evidence is used for modelling the glaciation extent during the LGM. One of the most easily visible post-glacial features visible in the present day are terminal moraines, which have been found at distances of 50-150 km from the present coastline at depths of approximately 200 m. One such example is a terminal moraine 20 m high and 800 m wide found 140 km off the coast of Western Iceland. Another feature identified is troughs, or u-shaped valleys, found both on and offshore. Additional ice contact and directional features are visible, such as glacial striae found on Grímsey Island, 40 km offshore of Northern Iceland, which indicate basal dynamics.

Glacial history can also be traced through off-shore sediment cores, such as those from Djúpáll, 50 km off the North-Western coast, which indicates deglaciation by 30.9 ka BP. Other dates indicate glacial retreat as little as 15.3 ka BP. Another feature indicative of glacial extents are found on nunataks and summit altitudes of Moberg Mountains. Moberg or table mountains are those which are volcanic and formed sub glacially, such as those in the Tröllaskagi and Flateyjarskagi peninsulas (see E in figure 3). Another piece of evidence to show past glaciations is the flora that survived the Weichselian. This requires ice free areas, such as those in northeastern Tröllaskagi and northwestern Flateyjarskagi. These ice-free areas exist because in addition to being elevated above the main outlet ice streams, they also remain topographically isolated from the local ice accumulation centres and associated local glaciers.

Features of LGM ice sheets

During the LGM, there was a central ice cap, roughly centred over the present-day Vatnajökull glacier. As the ice sheet extends offshore, a significant portion of the ice sheet is grounded below sea level. Variations in natural topography as well as climate variations depict the direction of glacier flow from the central dome. Iceland is a unique case in terms of basal flow dynamics, as the enhanced geothermal activity below the glaciers provide enhanced basal sliding with extensive regions of fast flow. Furthermore, an intricate positive feedback mechanism is at play beneath Icelandic glaciers. As the ice sheet extends and thickens, isostatic depression occurs. Upon glacial retreat, crustal rebound occurs, which triggers intensive subglacial volcanism and further melting. This geothermal activity leads to substantially high levels of subglacial melt, widespread basal decoupling, and the formation of outlet ice streams and fast flow.

From the central dome above Vatnajökull extends an east-west oriented ice sheet (See A in figure below). This forces half of the meltwater to drain northward and half southward. From the main sheet extends a portion from the western edge of the dome toward the north-western peninsula (B). In the south exists another leg further dividing the ice sheet toward present-day Mýrdalsjökull (C) and in the north-east a leg toward Melrakkaslétta (D). There are also several other independent ice accumulation centres throughout the island with nunataks breaking through the ice, particularly in the south, south-east, and central north. The ice streams found in the fjords of the north and north-east provide effective drainage of the ice sheet and provide extensive mass turnover into the offshore ice lobes and shelves (E and F). The glacial extent is typically fairly far offshore, except for in the east and north-east where it is grounded much closer to the current day sea-level. This effective drainage allowed the Langanes Peninsula to remain ice free during the LGM (G). Toward Mýrdalsjökull in south, extensive drainage and offshore shelving allow the region to be relatively ice-free and pinned very close to the coastline (C).

In northern Iceland, there are four major ice streams: Skagafjörður, Eyjafjörður, Fnjóskadalur and Bárðardalur which occupy the main fjords dissecting the highland areas and which drain the inland ice sheet (E). Erosion from LGM ice sheets is so extensive that virtually no evidence exists of pre-LGM topography, with the exception of the outer Reykjanes Peninsula. The total freshwater runoff of Icelandic LGM glaciers, including iceberg calving, was 600 km³/yr.

LGM conditions

Taking into account the field evidence, models must further alter the temperature and precipitation regimes throughout Iceland during the LGM. Models indicate that large-scale glaciations appear with only a 3 degree cooling perturbation from the current climate. For the predicted ice sheet extent, cooling of up to 10-12.5 degrees and over 50% precipitation suppression in the north must have occurred. A 5 degree cooling model allows for a glaciation that covers 90% of Iceland and extends well offshore in many areas.

The high melting rates of glaciers in Iceland can potentially lead to rapid basal decoupling, destabilization, and large meltwater pulses into the North Atlantic. This can have far-reaching implications for oceanic thermohaline circulation, which is sensitive to salinity and density inputs and is controlled by the overflow from the Nordic Seas around Greenland, Norway, and Iceland. Although fairly controversial, it has even been suggested that large scale melting, or Heinrich events, in Europe (namely Scandinavia, Britain, and Iceland ice sheets) occurred simultaneously with the atmospheric alteration that triggered the massive Laurentide ice sheet surges.

Modelling the LGM conditions

As previously mentioned a variety of paleoclimate changes must be considered in order to yield an optimal LGM simulation. The most difficult are the regions in which field evidence is deficient. Models of the basal dynamics involve the use of simplified grounding-line dynamics and empirical depth related calving algorithms to the marine margin. The main factors considered are: spatial distributions of sub-glacial topography, bathymetry, geothermal heat flux, and surface temperatures. Occasionally, models must be greatly modified in order to fit the empirical field evidence (ex. high northern aridity levels in order to justify the glacial striae found on Grímsey Island).

GLACIER DISTRIBUTION RELATED TO CLIMATIC AND TOPOGRAPHICAL CONDITIONS

The regional distribution of glaciers in Iceland indicates how precipitation arrives with prevailing southerly winds (Figure 2). On the highest southern slopes of Vatnajökull and Mýrdalsjökull, i.e. above 1,300 m, annual precipitation exceeds 4,000– 5,000 mm, peaking at 7,000 mm (Figure 4), while it reaches 3,500 mm on Hofsjökull and Langjökull. The largest icecaps are notified in the southern and central highlands (Table 1). On top of the larger icecaps, average temperatures are below or close to freezing throughout the year, with most of the precipitation falling as snow. While the summer balance is normally negative in the central portion of Vatnajökull, it may turn to slightly positive.

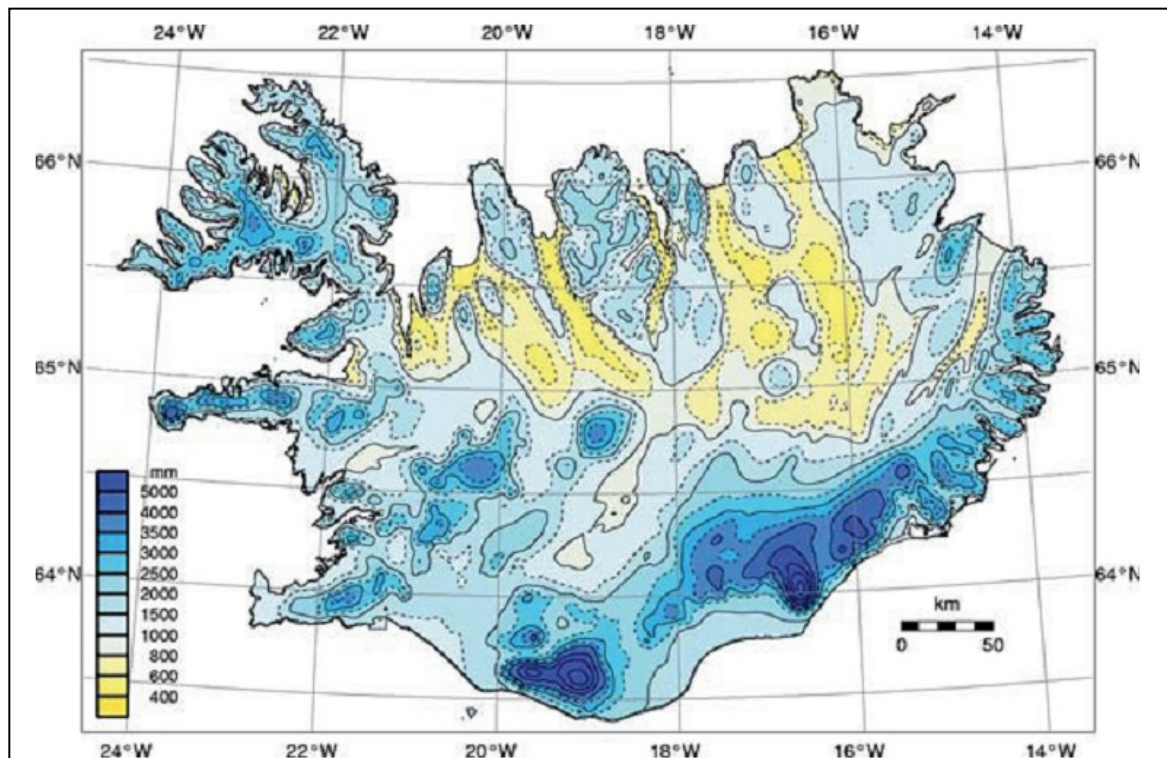


Figure 4: Mean annual precipitation of Iceland in 1961-1990 (Crochet et.al. 2007).

The southernmost outlets of Vatnajökull and Mýrdalsjökull descend to 100 m elevation or less (lowest 20 m), where even winter balances are slightly negative. Of the annual precipitation, most of it falls as liquid water resulting in net ablation through entire year. Summertime net losses typically measure 9 m (water equivalent) at the snouts of

Vatnajökull. For glacier outlets in central Iceland, which terminate at 600–800 m, summer balances at the snouts range from -4 to -6 m.

Glacier (year) km ²	Area km ³	Volume m	Mean thickness m a.s.l.	Surface elev., range and mean m a.s.l.	Bed elev., range and mean m	Max. ice thickness m a.s.l.
Vatnajökull (~2000)	8,100	3,100	380	0–2110; 1215	-300–2110; 670	~950
Langjökull (~2000)	900	190	210	430–1440; 1080	410–1330; 865	~650
Hofsjökull (~2000)	890	200	225	620–1790; 1245	470–1650; 1020	~760
Mýrdalsjökull (~2000)	590	140	240	120–1510; 995	15–1375; 760	~750
Drangajökull (~1990)	160	~24	~150	60–910; 665		~260
Eyjafjallajökull (~1990)	80			190–1635; 1135		
Tungnafellsjökull (~1990)	43			920–1520; 1335		
Práandarjökull (~1945)	27			760–1235; 1035		
Eiríksjökull (~1990)	24			550–1665; 1390		
Þórisjökull (~1990)	22			770–1325; 1165		
Tindfjallajökull (~1990)	20			650–1450; 1190		
Snæfellsjökull (~2000)	16	0.5	30	600–1440; 980	600–1440; 950	~110
Torfajökull (~1990)	13			780–1170; 1015		
Hrútfell (~1990)	8			690–1400; 1205		
Hofsjökull in Lón (~1990)	6			870–1145; 1045		
Gljúfurárjökull (~1990)	3			610–1355; 1015		250
Tröllaskagi glaciers	~190					
Total	~11,100	~3,600				

Table 1: General features of Glaciers in Iceland

Central Iceland has several steep mountain peaks reaching over 1,400 m above sea level and maintaining small glaciers. The dry inland regions farther north receive an annual precipitation of only 400–700 mm, lifting the glaciation limit even higher than 1,600 m in the rain shadow north of Vatnajökull. In northern coastal areas this limit descends to 1,100 m, as evidenced by over 100 small cirque glaciers and corries, frequently facing north and located above the main valleys and around the highest peaks, those reaching altitudes of 1,300–1,500 m. These summits receive an annual precipitation of up to 2,000 mm, brought to a large extent by northerly winds. Accumulation is locally increased through snow drift, whereas melting is in many places reduced by the shadowing effect of narrow valleys.

In the extensive north western peninsula called the West Fjords, annual precipitation reaches 3,000 mm, and the glaciation limit registers lowest in Iceland, at 600–700 m. The mountain plateau on this peninsula lies between 700 m and 900 m above sea level, so that a number of niches and some 10 small cirque glaciers are found at elevations between 600 and 700 m. The highest part of the peninsula is covered by the icecap Drangajökull, Iceland's northernmost glacier. It terminates below 200 m and, together with the Breiðamerkurjökull outlet of Vatnajökull, extends closest to the sea of any of the country's glaciers.

Glacier Geometry:

Maps of the surface and subglacial topography of all the major icecaps have been produced by interpolating continuous profiles spaced about 1 km apart, using radio echo-sounding for ice thickness along with precision altimetry (Sverrisson et al., 1980; Björnsson, 1982, 1986a,b, 1988, 1996; Björnsson et al., 2000; Björnsson and Einarsson, 1990; Magnússon et al., 2004, 2005a,b,c, 2007). Specific drainage basins have been delineated, glacier mass balance monitored and the meltwater contribution to various rivers estimated. Statistics derived from available maps are presented in Table 1 and Figure 5. Glacier surface and bedrock maps reveal previously undiscovered land forms and geological structures within the active volcanic regions and identify the locations of calderas, volcanic centres and pressure swarms.

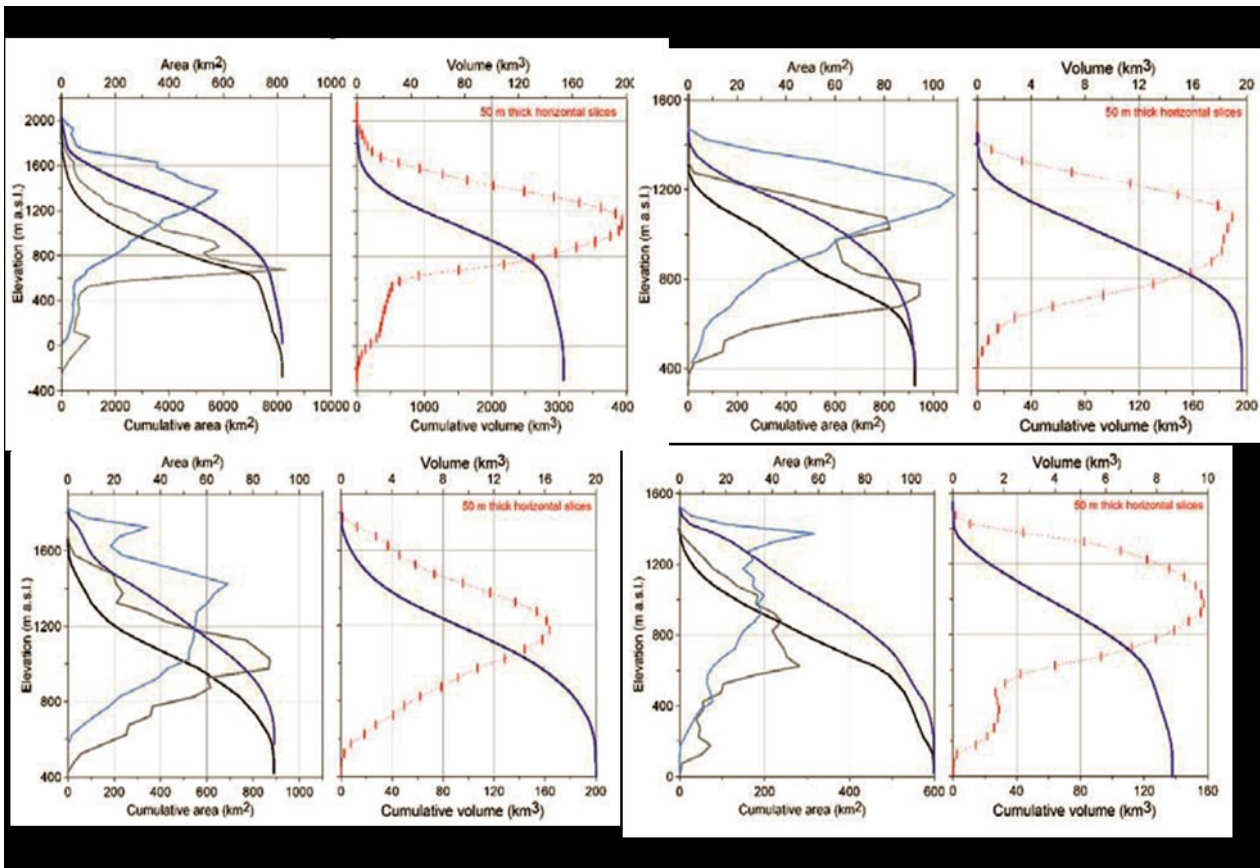


Figure 5: Area and volume distributions along with elevation, for Iceland's largest icecaps.

Bedrock areas are shown with black and grey lines, glacier surfaces with blue lines

Furthermore, maps of glacier surfaces are available, providing important details about surface elevations, structures and slopes, as well as charts of the various glacier outlets. The geometry of subglacial meltwater cupolas and of ice-dammed lakes in geothermal areas can also be viewed on present-day maps. Typically, only 10–20% of the bed of the glaciers lies above today's glaciation limit. Thus, Iceland's 1,200 m larger icecaps subsist thanks mainly to their own height.

Vatnajökull lies on a highland plateau of 600–800 m above sea level, with 88% of its bed lying above 600 m; it is actually only 20% of the bed that exceeds 1,100 m, which is the glaciation limit for southern Iceland. Six mountain ranges form the main glaciation centres within Vatnajökull, peaking at 1,200 to 2,000 m: Grímsfjall (1,700 m), Bárðarbunga (1,800 m), Kverkfjöll (1,930 m), Öräfajökull (2,000 m), Esjufjöll (1,600) and Breiðabunga (1,200 m). Another example of how an icecap has little other than ice reaching above the glaciation

limit is Mýrdalsjökull, which is underlain by a huge central volcano that has rims of 1,300–1,380 m around a caldera 650–750 m deep. Only 10% of the Mýrdalsjökull bed rises over the glaciation limit of 1,100 m above sea level. Hofsjökull also covers a major central volcano; with rims of 1,300–1,650 m surrounding a caldera that drops to an elevation of about 980 m. Around 20% of the Hofsjökull bed exceeds an elevation of 1,200 m, while 11% surpasses 1,300 m. The Langjökull icecap covers a 50-km-long mountain chain that rises to only 1,000–1,250 m, placing a mere 5% of the bed above 1,200 m.

Since about 1990, annual mass balance measurements are available for largest icecaps: Hofsjökull (since 1987/88), Vatnajökull (since 1991/92), Langjökull (since 1996/97) and Drangajökull (since 2004/05), and some measurements also exist for smaller icecaps (Björnsson, 1971; Björnsson et al., 1998, 2002; Sigurðsson and Sigurðsson, 1998; Sigurðsson et al., 2004, 2007). Bedrock maps are used in conjunction with the glacier surface maps for delineating the locations of water-drainage basins feeding glacial rivers (Figure 6),



Figure 6: Water drainage basins at the glacier bed for the principal rivers draining Vatnajökull. Sub glacial water-filled cupolas, located under depressions in the glacier surface, collect melt water and periodically drain by means of jökulhlaups

The average mass balance of Vatnajökull for glacier years 1991/92 to 2005/06 is shown in Figure 7, and the temporal variation in Figure 7. The winter balance was generally highest in the early 1990s, diminished to a minimum in 1996–1997, rose to a maximum in 2003, and since then has slowly declined. Summers were comparatively cold during the first half of the 1990s, as reflected in low summer ablation. The high summer melting of 2000, on the other hand, was primarily attributable to warm, windy weather.

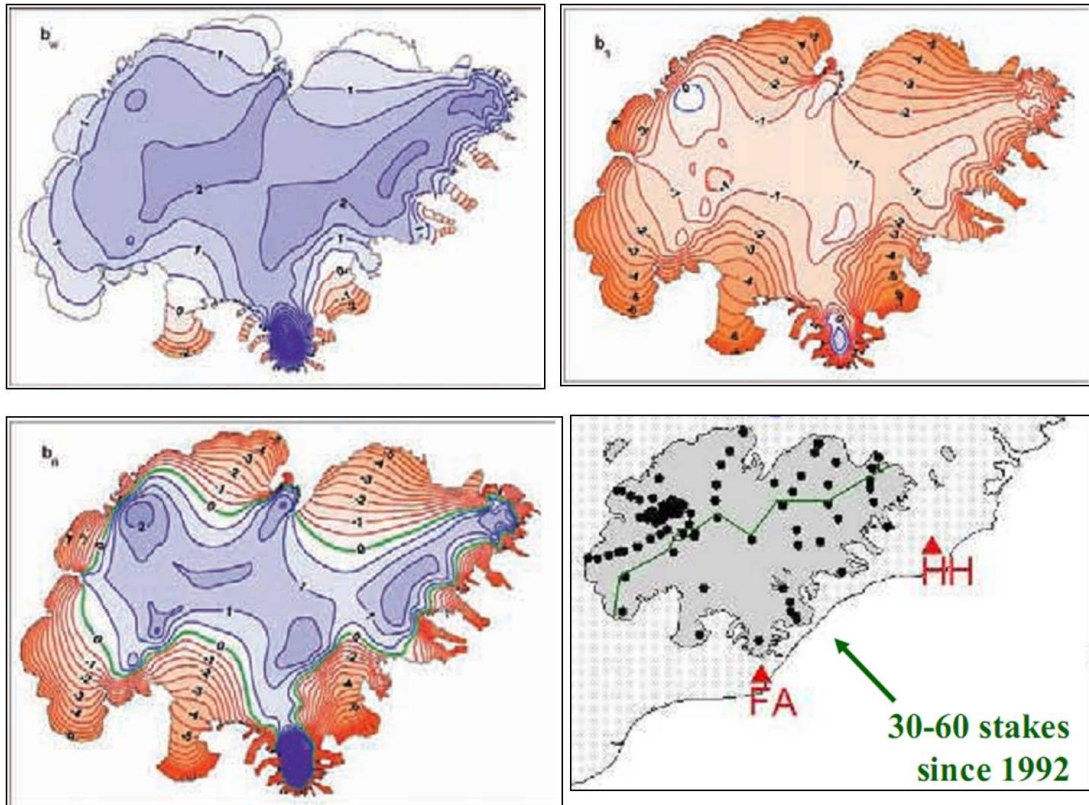


Figure 7: Maps of average mass balance (m water equivalent) for Vatnajökull, glacier years 1991/92 to relative to the summer surface at about 50 sites 2005/06.

On Vatnajökull, the annual net balance remained positive from 1991/92 to 1993/94, approached zero in 1994/1995, and has been negative since then (Figure 8). Vatnajökull has lost about 0.8 m a^{-1} since 1995/96, as an average over the whole glacier. The total mass loss of Vatnajökull in 1994/95 through 2005/06 was 9.2 m (water equivalent) or 84 km^3 , and the icecap lost about 2.7% of its total mass. In addition to surface melting, continuous geothermal activity at the bed of Vatnajökull and transitory volcanic eruptions melted about $0.55 \text{ km}^3 \text{ a}^{-1}$ on average in the 1990s, which equals only 4% of the total surface ablation of $\sim 13 \text{ km}^3 \text{ a}^{-1}$ during one average year of zero mass balance.

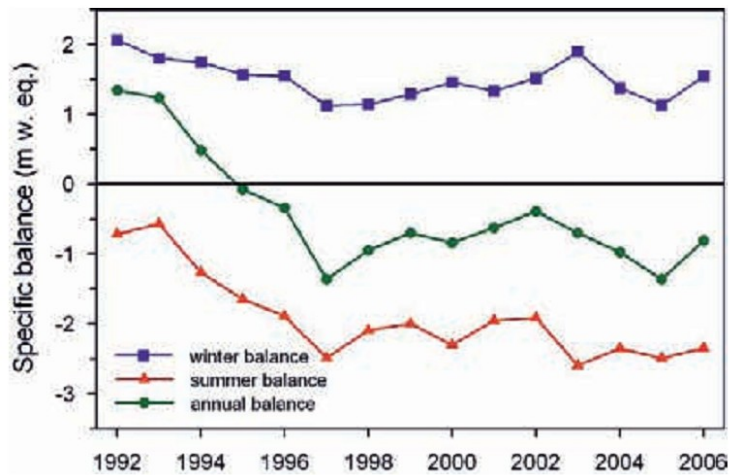


Figure 8: Temporal variations in Vatnajökull mass balance (for years 1991/92 to 2005/06)

Note: Specific mass balance is given in m water equivalent)

The volcanic eruption in Gjalp in October 1996 by itself melted $\sim 4.0 \text{ km}^3$ of ice in years of zero mass balance; 55–65% of the glacier surface typically lies above the equilibrium line altitude. During the period of 1992 to 2007, the accumulation area of the ice flow basins of Vatnajökull varied from 20 to 70% of their total area (Figure 9), the equilibrium line altitude (ELA) fluctuated by 200–300 m (300 to 400 m), and the annual net balance ranged from plus to minus one metre. A 100-m change in ELA affects the net mass balance of Vatnajökull by 0.7 m a^{-1} .

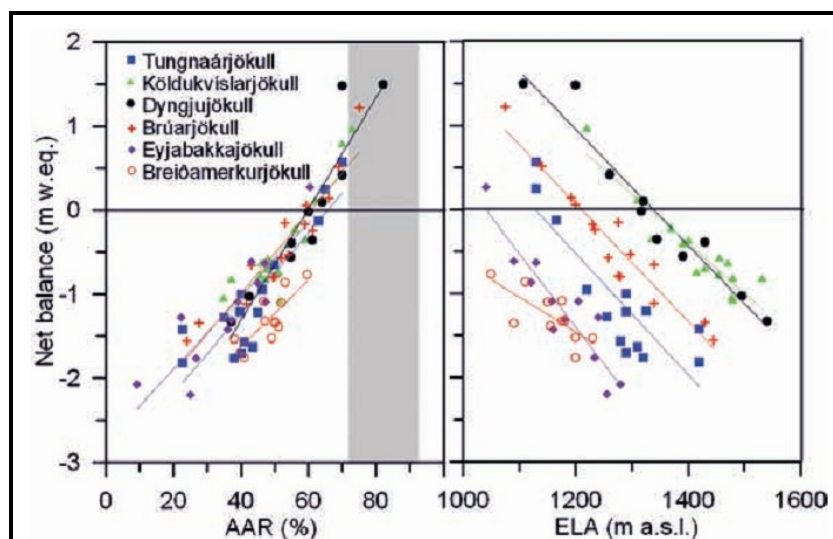


Figure 9: Relationship between net annual balance (bn), accumulation area ratio (AAR) and equilibrium line altitude (ELA) for Vatnajökull (in glaciological years 1991/92 to 2005/06).

During years of zero net balance, the runoff from Vatnajökull relating specifically to the summer balance was about $50 \text{ l s}^{-1} \text{ m}^{-2}$, averaged over the entire glacier and entire year, but dropped to half of this in years of the most positive mass balance, i.e. in the early 1990s. The mass balance records for Hofsjökull and Langjökull show characteristics similar to Vatnajökull. The net balance of Langjökull has remained negative throughout the survey period of 1996/97 to 2005/06, while the accumulation area has varied from 10% to 40% of the glacier. Total mass loss over the period 1996/97 to 2005/06 was 12.8 m (13.1 km^3 ice) or 7% of the ice mass. In instances of zero mass balance, annual turnover rates approximate 0.4% of total volume of Vatnajökull and 0.8% of Langjökull (Figure 10) and Hofsjökull

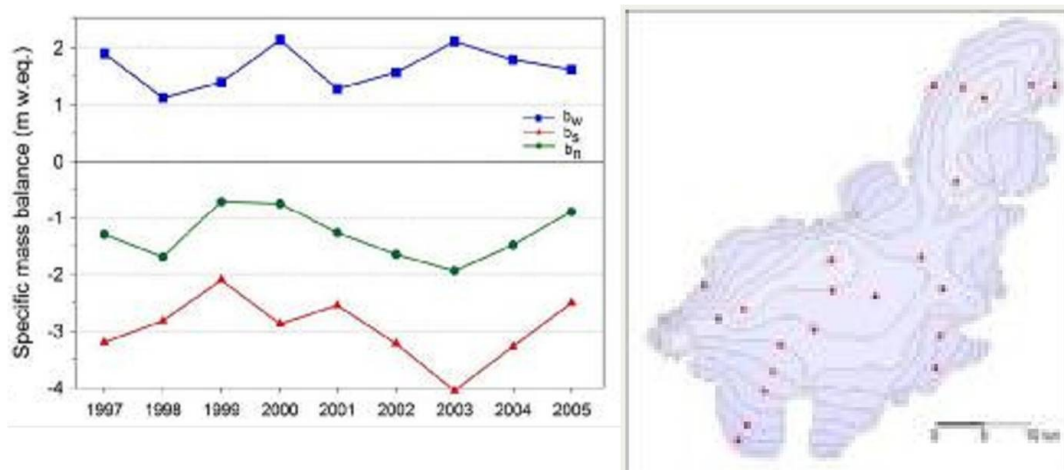


Figure 10: Mass Balance observations of Langjökull for balance years 1997-2005

The average surface velocity has been estimated based on summertime GPS measurements at most of the mass balance sites (Figure 11). In addition, velocity maps for extensive areas have been derived from satellite data obtained from InSAR and SPOT (Björnsson et al., 2001a; Fischer et al., 2003; Magnússon et al., 2005b; Berthier et al., 2006). Steeply sloping glaciers, whether hard- or soft-bedded, seem to move with sufficient speed to keep in balance with annual mass balance. In contrast, surge-type glaciers, characterised by gently sloping surfaces (typically $1.6\text{--}4^\circ$), move too slowly to maintain a balance in relation to their mass balance rate (Björnsson et al., 2003). Surge intervals vary between glaciers, lasting from several years up to a century; moreover, surge frequency is most often neither regular nor clearly related to glacier size or mass balance.

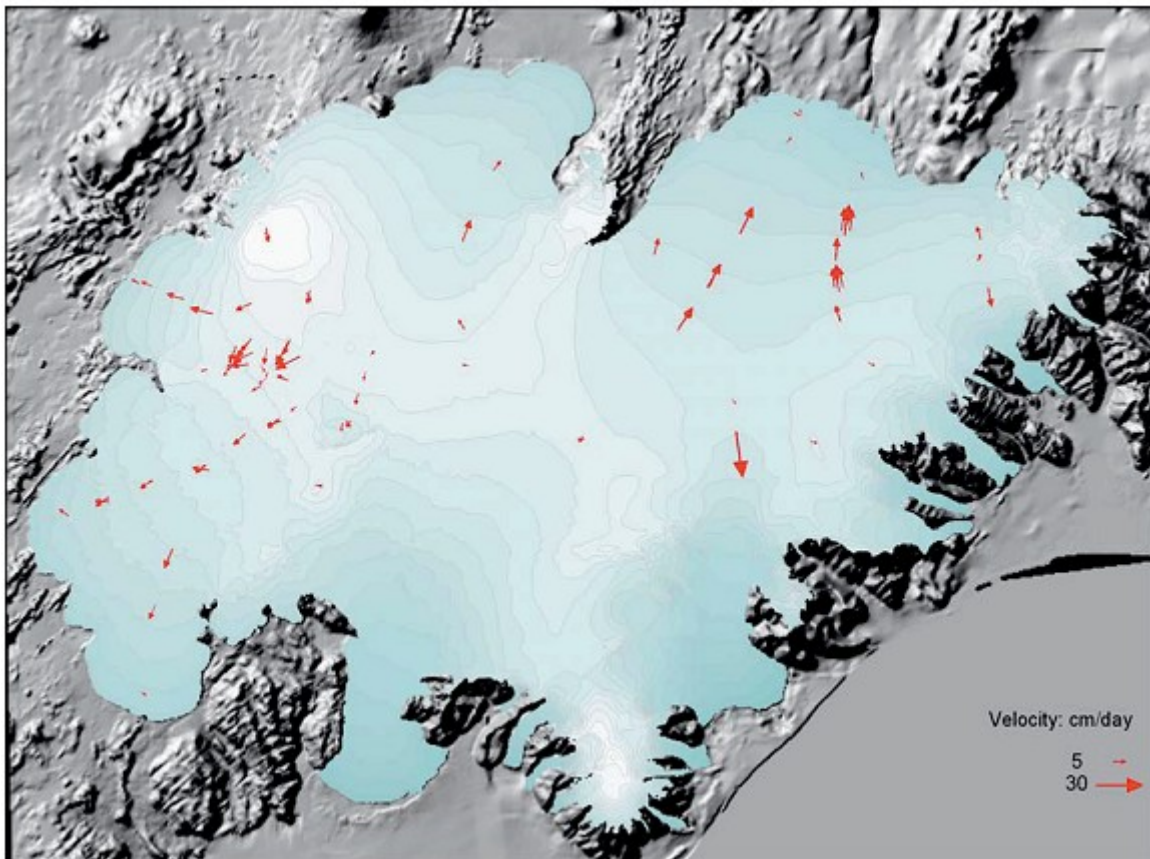


Figure 11: Measured summer velocity at mass balance sites on Vatnajökull in 2006, using Global Positioning System measurements

Altogether, 26 surge-type glaciers have been identified in Iceland, ranging in size from 0.5 to 1,500 km² (Figure 12). About 80 surge advances have been recorded, extending from dozens of metres up to 10 km (Björnsson et al., 2003). For all of the major icecaps, surges account for a significant portion of total mass transport through the main outlet glaciers and have important implications for outlet dynamics and hydrology (Þórarinnsson, 1969; Björnsson, 1998; Björnsson et al., 2003; Magnússon et al., 2005a). They reduce ice-surface slopes, alter glacier hypsometry through mass transport, and increase the area and roughness of the glacier surface. In the wake of a surge, the resulting surface roughening and ice deposition at low elevations accelerates surface melting due to solar radiation and turbulent heat exchange; thus, runoff to glacial rivers increases. During the 1990s, ~3000 km² of Vatnajökull (38% of the icecap area) was affected by surges, which transported about 40 km³ of ice from accumulation areas to ablation areas. This amounted to approximately 25% of the total ice flux to ablation areas during this period.

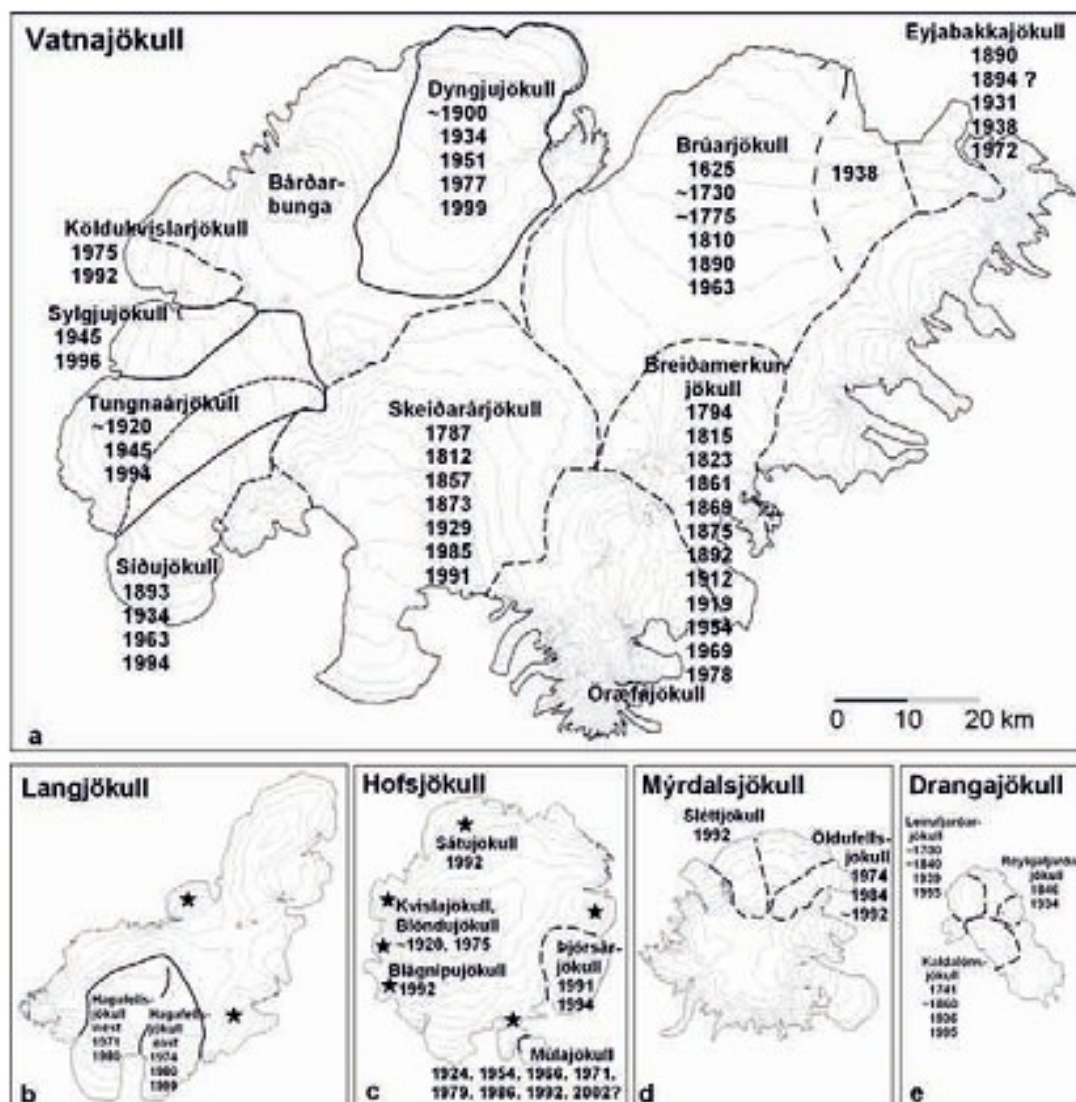


Figure 12: The geographic distribution of Iceland's surging glaciers, of which 26 have been identified, ranging in area from 0.5 to 1,500 km². About 80 surges have been recorded, with advances ranging from dozens metres up to 10 km (Björnsson et al., 2003)

Future Outlook:

Numerical models have been developed for describing glacier dynamics (Jóhannesson, 1997; Jóhannesson and others, 1995, 2006, 2007; Aðalgeirsdóttir, 2003; Aðalgeirsdóttir et al., 2003, 2005, 2006a, 2006b; Guðmundsson et al., 2003; Marshall et al., 2005; Flowers et al., 2003, 2005). Other recent work has yielded models for describing the distribution of precipitation in Iceland (Crochet, 2007; Crochet et al., 2007; Rögnvaldsson et al., 2004, 2007; Rögnvaldsson and Ólafsson, 2005). Furthermore, glacier mass balance has been described

through a degree-day model building on the following factors: temperature and precipitation outside of the glaciers, a constant temperature lapse rate, degree-day scaling factors for snow and ice, and horizontal and vertical precipitation gradients. Plausible predictions of regional temperature and precipitation trends in Iceland have been developed based on downscaling of global coupled atmosphere-ocean simulations. In comparison with 1961–1990, the project scenario predicts a warming of 2.8⁰C and a 6% increase in precipitation by 2071–2100. The increases in temperature and precipitation vary according to season (Figure 13).

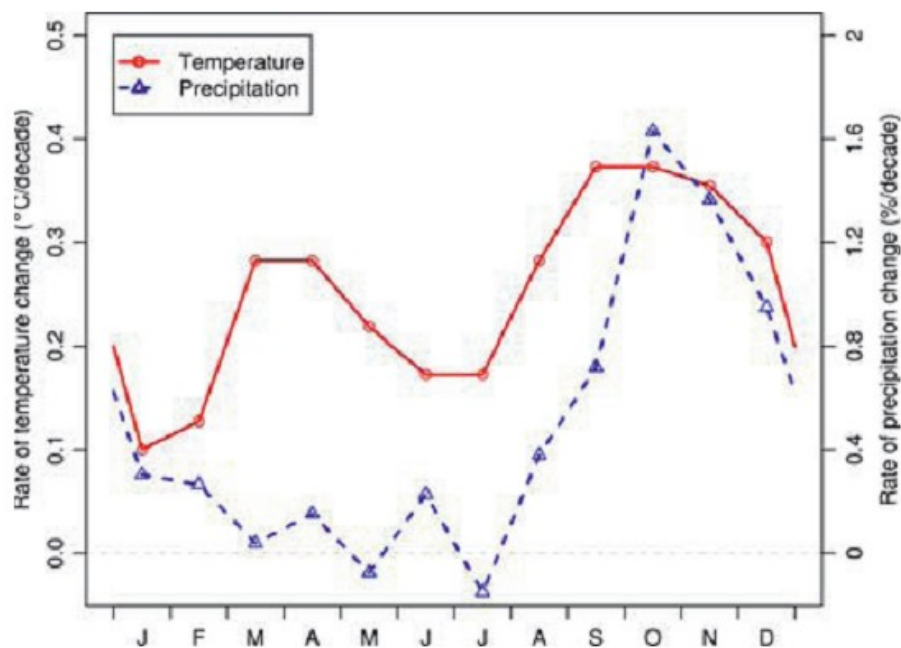


Figure 13: Scenario for temperature and precipitation changes during the 21st century, averaged over Ice land (see Jóhannesson et al., 2007)

Model run results for Hofsjökull, Langjökull and southern Vatnajökull are shown in Figure 14. The resulting retreat rate is similar for Hofsjökull and Vatnajökull, which are predicted to lose 25% of their present volume within half a century, meaning that it is only on their highest peaks where ice will survive throughout the next 200 years. Langjökull is predicted to diminish by 35% in volume over 50 years and to disappear after 150 years. Considering how fast Icelandic glaciers are predicted to melt in the near future, it is not surprising that icecaps disappeared from the island during the Climatic Optimum of the early Holocene. Meltwater runoff is expected to increase initially, but to peak after 40–50 years and then to decline to present-day values 100 years from now. The runoff increase will be highest for the lowest parts of Langjökull (~2.8 m a⁻¹) and next highest for Vatnajökull in parts

extending nearly to sea level. The seasonal rhythm of discharge is also expected to change, with some rivers drying up entirely, while others will be left to discharge exclusively precipitation after the glaciers have melted away.

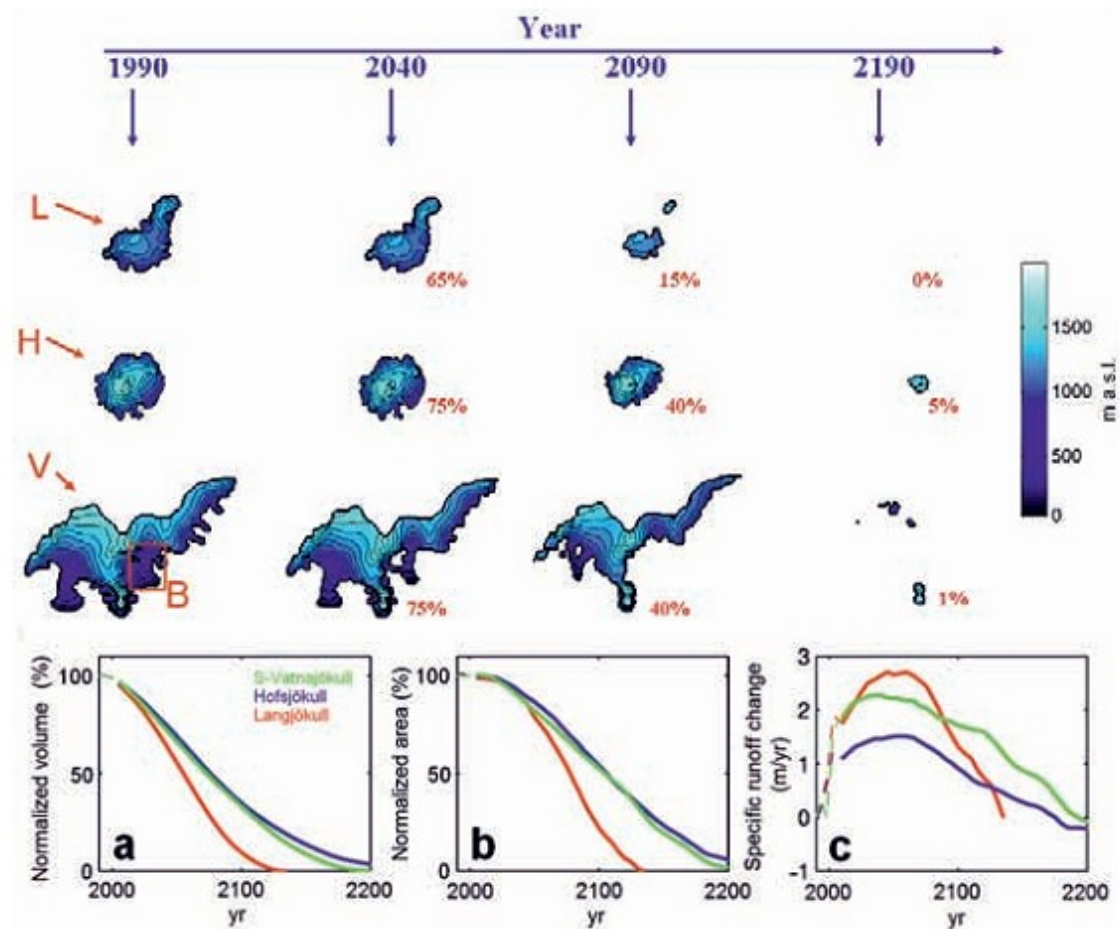


Figure 14: Simulated responses of Langjökull (L), Hofsjökull (H) and southern Vatnajökull (V) from 2000 through 2200 to the climate-change scenario shown in Figure 14. Volume and area reductions are normalised to present-day values, with specific runoff referring to today's ice-covered areas and combining meltwater and precipitation

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