Icelandic glaciers

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Abstract – Some 11% of Iceland is covered by glaciers. They contain 3,600 km$^3$ of water, equivalent to a 35-m-thick ice layer spread evenly over the whole country; if melted, it would raise global sea level by 1 cm. This is Iceland’s greatest water storage, corresponding to the precipitation of 20 years. Dynamic in nature, these glaciers are responsive to climate fluctuations and affect their environment profoundly. Also, they lie over active volcanoes; these induce jökulhlaups that can threaten areas of habitation. The country’s glaciers feed its largest rivers and currently provide at least one-third of its total runoff. Since a general glacier recession set in at the end of the 19th century, the largest icecap, Vatnajökull, has decreased by about 10% in volume (300 km$^3$), contributing 1 mm to the concurrent rise in sea level. During the last ten years, ice losses have accelerated, thereby detracting 2.7% (84 km$^3$) from the total icecap volume. Typically, radiation provides two-thirds of the melt energy, turbulent fluxes one-third. However, transitory volcanic eruptions and continuous geothermal activity at the bed of Vatnajökull added some 5.5 km$^3$ to surface melting during the 1990s, with one particular volcanic eruption melting 4.0 km$^3$. In all of Iceland’s major icecaps, surges account for a significant portion of total mass transport through the principal outlet glaciers, playing an important role in outlet dynamics and hydrology. Taking the 20th century as a whole, surges contributed at least 10% to the total ice transport to ablation areas of Vatnajökull. Plausible future climate scenarios, coupled with models of mass balance and ice dynamics, suggest that the main icecaps will lose 25% to 35% of their present volume within half a century, leaving only small glaciers on the highest peaks after 150–200 years. Glacier meltwater runoff will peak after 50 years, then decline to present-day values by 100 years from now. When the glaciers have disappeared, the entire river discharge will come directly from precipitation.

INTRODUCTION

An island of 103,000 km$^2$, Iceland lies in the North Atlantic Ocean, close to the Arctic Circle. Thanks to the warm Irminger Current, the land enjoys a relatively mild oceanic climate and small seasonal variations in temperature. Average winter temperatures hover around 0°C near the southern coast, where the average temperature of the warmest month is only 11°C and the mean annual temperature is about 5°C (Einarsson, 1984). Along the northern coast, the climate is affected 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. At present, about 11% of the country is covered by glaciers (Björnsson, 1978, 1979; Figure 1).

Classified as "warm-based" or "temperate", Icelandic glaciers are dynamic in nature. Not only do they respond actively to climatic fluctuations, but constitute long-lasting reservoirs of ice that turns to meltwater and feeds the country’s main rivers, some of which have been harnessed for hydropower. These icecaps conceal unexplored landforms and geolog-
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Figure 1. 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. – Íslandskort sem sýnir legu helstu jökla.

cal structures, including active volcanoes, geothermal sites and subglacial lakes. Catastrophic floods (jökulhlaups) from geothermal and volcanic locations are frequent. These floods have periodically threatened inhabited regions, damaged vegetation, disrupted roads and communications, and even temporarily deterred fish from entering coastal waters. About 60% of today’s glacial area is underlain by active volcanoes, occasioning intensive studies of glacier-volcano interaction.

During Pleistocene and post-glacial times, the island and its surrounding sea-floor topography have been significantly shaped by glacial erosion and glacial or fluvio-glacial deposits. Glaciers have carved alpine landscapes characterised by cirques, sharp mountain peaks, broad lowlands, and long, steep U-shaped valleys or narrow fjords. The largest agricultural regions in the south and west were created by glacial and fluvio-glacial sediments in late glacial and early Holocene periods. In addition, the topography and sediments of near-shore marine environments have been heavily influenced by glacial erosion and deposition. The impact of glacial rivers is evidenced by deeply eroded canyons and sediments transported onto sandur deltas. Iceland’s specially-named Palagonite Formation is largely the product of subglacial volcanic activity that was later subjected to erosion.

Because of their profound environmental effects, the Icelandic glaciers and associated phenomena have long attracted interest, so that a wealth of general information is available on the country’s volcanic and hydrological events. More recently, a considerable amount of more precise hydrological, glaciological and volcanological data have been collected, while meteorological observations on the glaciers have revealed relationships between climate and mass bal-
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The accumulated glaciological data now allow for a modelling of the mass balance and ice dynamics and for using coupled models in order to evaluate glacier response and glacial runoff in conjunction with any given past or future climate change. This paper reviews the data that have been gathered and modelling work that has been carried out.

GLACIER DISTRIBUTION AS RELATED TO CLIMATIC AND TOPOGRAPHICAL CONDITIONS

The regional distribution of glaciers in Iceland indicates how precipitation arrives with prevailing southerly winds (Figure 1). 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 2), while it reaches 3,500 mm on Hofsjökull and Langjökull. Also noteworthy is that the largest icecaps are situated 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 (up to 0.5 m) when repeated cold spells with northerly winds bring fresh snow to the glacier, thereby maintaining a high surface albedo. Icelandic higher-altitude summers are chilly in any case, so that in the uppermost parts of the glaciers, days when melting occurs number only 10 to 20 per year, though at lower levels the ablation season typically lasts three to four months (June through mid-September).

The southernmost outlets of Vatnajökull and Mýrdalsjökull, not far removed from the sea coast, descend to 100 m elevation or less (lowest 20 m), where even winter balances are slightly negative. Even though annual precipitation there may total up to 1,500 mm or more, most of it falls as liquid water, resulting in net ablation during every season of the year. Summertime net losses typically measure 9 m (water equivalent) at the snouts of Vatnajökull (terminating at elevations around 100 m). For glacier outlets in central Iceland, which terminate at 600–800 m, summer balances at the snouts range from -4 to -6 m.

Central Iceland also 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 lo-
Table 1. Glaciers in Iceland. General features. – *Skrá um tölur sem lýsa jöklum: flatarmáli, rúmmáli, hæð yfirbords, botns og jafnvægislínu, afkomu og skríðhraða.*

<table>
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<tr>
<th>Glacier (year)</th>
<th>Area (km²)</th>
<th>Volume (km³)</th>
<th>Mean thickness (m a.s.l.)</th>
<th>Surface elev. range and mean (m a.s.l.)</th>
<th>Bed elev. range and mean (m)</th>
<th>Max. ice thickness (m a.s.l.)</th>
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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 northwestern 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 3. Glacier surface and bedrock maps reveal previously undiscovered landforms and geological structures within the active volcanic regions and identify the locations of calderas, volcanic centres and fissure swarms. 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 larger icecaps subsist thanks mainly to their own height. Even though Vatnajökull, for instance, 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), Öræfajökull (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. This means that 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.

**MASS BALANCE AND MELTWATER DRAINAGE**

Surface maps indicate the directions of large-scale ice flow and show the limits of ice-drainage basins for the principal rivers flowing from the glaciers (Figure 1). Since about 1990, annual mass balance measurements have been conducted at the 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). The mass balance data provide a basis for estimating the meltwater contribution to glacial river systems. Bedrock maps are used in conjunction with the glacier surface maps for delineating the locations of water-drainage basins feeding glacial rivers (Figure 4).
The average mass balance of Vatnajökull for glacier years 1991/92 to 2005/06 is shown in Figure 5, and the temporal variation in Figure 6. 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. 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 6). 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\(^3\) (which amounts to 6 times the average winter balance), 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 km\(^3\) a\(^{-1}\) on average in the 1990s, which equals only 4% of the total surface ablation of \(\sim 13\) km\(^3\) a\(^{-1}\) during one average year of zero mass balance. The volcanic eruption in Gjálp in October 1996 by itself melted \(\sim 4.0\) 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 7), 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\(^{-1}\).

During years of zero net balance, the runoff from Vatnajökull relating specifically to the summer balance was about 50 l s\(^{-1}\) km\(^{-2}\), 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. Rain on the glacier during the five summer months may add 10–20 l s\(^{-1}\) km\(^{-2}\) to specific discharge from the glacier.

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 and Hofsjökull.
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Figure 5. Maps of average mass balance (m water equivalent) for Vatnajökull, glacier years 1991/92 to 2005/06. Specific mass balance in m water equivalent, \( b_w \): winter balance, \( b_s \): summer balance, \( b_n \): annual net balance (see Björnsson et al., 1998). Mass balance was calculated by a stratigraphic method, based on measured changes in thickness and density relative to the summer surface at about 50 sites.

Kort af meðalafkomu á Vatnajökli frá 1991/92 til 2005/06; \( b_w \): vetrarafkoma, \( b_s \): sumarafkoma, \( b_n \): ársafkoma í metrum vatns.

GLACIO-METEOROLOGY

During a 100-day period every summer, several automatic meteorological stations have been operated on some of the Icelandic icecaps; these operations began on Vatnajökull in 1994 and on Langjökull in 2001. Radiation components have been measured directly in situ, whereas turbulent fluxes have been calculated corresponding to wind, air temperature and humidity in the boundary layer.

As a rule, net radiation is shown to be the outstanding factor in melting, although it is occasionally equalled by eddy fluxes (Figure 8). During the melting period, radiation typically provides two-thirds of the melt energy, and turbulent fluxes one-third (Björnsson, 1972; Björnsson et al., 2005; Oerlemans et al., 1999; Guðmundsson et al., 2006). At higher stations on the icecap, turbulent exchange becomes less significant. There are sporadic cases of radiation contributing somewhat to melting when eddy fluxes are negative. Solar radiation absorption increases substantially when winter snow has disappeared from the ablation zones, exposing ice covered with tephra layers; under these conditions albedo may decrease to as low as 10%. Net radiation comes to a peak in ablation areas in June, in accumulation areas in August. Turbulent fluxes increase during the summer, peaking in August and September. The atmospheric boundary layer is found to be dominated by katabatic flows, especially in the lower, steeper regions of each icecap. It is only during the passage of intense storms that the katabatic winds of ablation zones become negligible.
During volcanic eruptions, the impact of tephra fall is short-lived in the accumulation area, in most cases only affecting ablation in the following summer. The high ablation on Vatnajökull in the summer of 1997 was to a large extent caused by low average albedo following exposure of the tephra layer from the Gjálp eruption in October 1996. Moreover, dust originating from the jökulhlaup deposits on Skeiðarársandur in November 1996 was later spread by wind over broad expanses of the icecap.

The observed daily melting rates have been successfully simulated by energy balance calculations based on meteorological observations on each glacier. However, temperatures measured on the glacier itself do not provide the most successful degree-day predictions of ablation; instead, temperature data from outside the glacier provide more reliable predictions, when projected onto the glacier using a constant wet adiabatic lapse rate according to elevation. Air temperatures in the low-albedo neighbourhood of the glacier indicate daily variations in global radiation flux more precisely than the damped boundary layer temperatures above the melting icecap itself.

GLACIER DYNAMICS

The average surface velocity has been estimated based on summertime GPS measurements at most of the mass balance sites (Figure 9). 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 1.6–4°), 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. Altogether, 26 surge-type glaciers have been identified in Iceland, ranging in size from 0.5 to 1,500 km² (Figure 10). 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 (Pórarinsson, 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, ~3,000 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. For some outlet glaciers, the contribution of surges to mass transport exceeds even this. Viewing the 20th century as a whole, surges were responsible for at least 10% of the total ice flux to ablation areas.

Surges increase river sediment loads (and hence sediment concentrations) substantially, especially in the finest grain sizes (Pálsson and Vigfússon, 1996; Pálsson et al., 2000; Sigurðsson, 1998). For one to two years following surges in Vatnajökull, the sediment concentration of affected outlet rivers generally attains 7–10 kg m⁻³. These concentrations are comparable to those during glacier outburst floods. During the 1963–1964 surge of Brúarjökull on the north side of Vatnajökull, the river Jökulsá á Brú had an average suspended sediment concentration of 6.5 kg m⁻³. During surges that typically last less than one year, a denudation rate has been observed of 14 mm a⁻¹, averaged over the entire glacier bed (see Björnsson, 1979).

Figure 7. Relationship between net annual balance \( (b_n) \), accumulation area ratio (AAR) and equilibrium line altitude (ELA) for Vatnajökull (in glaciological years 1991/92 to 2005/06). – Tengsl ársafkomu \( (b_n) \), stærð safnsvæðis af heildarfrotarmáli jökuls (AAR) og hæðar jafnvægislínun (ELA) á Vatnajökli 1991/92 til 2005/06.
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Figure 8a. Contribution of energy fluxes during the ablation season of 2004 to meltwater discharge \((Q_A)\) from the outlet Brúarjökull \((1,600 \text{ km}^2)\) in NE Vatnajökull. The data consisted of meteorological measurements at three sites on the glacier and mass balance measurements at 15 sites. 8b. Relative contribution of various energy fluxes to the total energy provided for melting during the ablation season: \(Q_R\) total radiation, \(Q_{Rs}\) short wave, \(Q_{Rl}\) long wave, \(Q_H\) turbulent fluxes, \(Q_{Hd}\) sensible heat, \(Q_{Hl}\) latent heat. – Framlag orkustrauma til leysingar og aflønslis \((Q_A)\) á Brúarjökli sumaríð 2004. \(Q_R\) heildargeislun, \(Q_{Rs}\) sölgeislun, \(Q_{Rl}\) himin- og jarðgeislun, \(Q_H\) varmastraumar með lofti, \(Q_{Hd}\) skyrbær varmi, \(Q_{Hl}\) dulvarmi. Hægri mynd sýnir hlutfall af heild.

JÖKULHLAUPS

Glacier-related floods, called jökulhlaups or outburst floods, are particularly frequent in Iceland. Their sources are of three types: geothermal fields that constantly melt the glacial ice above them so that meltwater accumulates and drains periodically, volcanic eruptions which melt the ice into water that drains without delay towards the glacier margin, and precarious ice dams which form lakes at glacier margins (Þórarinsson, 1974, 1975; Rist, 1955, 1970, 1973, 1976, 1981, 1984; Tómasson, 1973, 1974, 1996; Tómasson and Pálsson, 1980; Björnsson, 1974, 1975, 1976, 1992, 2002; Jóhannesson, 2002; Guðmundsson et al., 1995, 1997, 2003; Flowers et al., 2004). At present, Iceland has some fifteen of the last-named type of jökulhlaup source, i.e. marginal ice-dammed lakes (Þórarinsson, 1939; Björnsson, 1976). Active volcanoes and hydrothermal systems underlie 60% of the area of Icelandic icecaps. Jökulhlaups drain regularly from six subglacial geothermal areas (about 1 km\(^3\) a\(^{-1}\) of water). Geothermal activity under glaciers reflects the interaction of water with magmatic intrusions, creating geothermal fluid which melts the glacier ice above and thereby causes a depression in the glacier surface. The relatively low basal pressure potential under such depressions causes meltwater to accumulate in cupolas which gain size until becoming unstable and bursting out from the glacier in a jökulhlaup. One area to which particular attention has been devoted is the Grímsvötn vicinity of Vatnajökull, where there has been geothermal activity for centuries (Figures 4 and 11). Using Grímsvötn lake as a natural calorimeter, data on the mass balance of its drainage basin allow for estimating the heat output which produces the fluid phase at the subglacial geothermal area as 1.2 TW (or about 30% of the total heat) and the output which produces the vapour phase as 3.0 TW (or about 70%) (Björnsson, 1983, 1988; Björnsson et al., 1982; Björnsson and Kristmannsdóttir, 1983; Björnsson and Guðmundsson, 1993; Guðmundsson et al., 2002).

Jökulhlaups may profoundly alter landscapes, devastate vegetation, and threaten lives as well as the roads, bridges and hydroelectric plants along glacier-fed rivers. The effects of jökulhlaups on the landscape appear in massively eroded canyons and in sediment
deposits on outwash plains. While the high sediment loads during both surges and jökulhlaups play an important role in building up some of the sandur deltas, the total sediment mass transported during a jökulhlaup lasting only two to three weeks may be five times greater and the basal area excavated much more concentrated than during a surge. This applies to typical jökulhlaups from the subglacial lake Grímsvötn down to Skeiðarársandur, which at 1,000 km² is Iceland’s most widespread outwash plain. During a volcanic eruption, total sediment transport in the resulting jökulhlaup over Skeiðarársandur may be another five times higher. Volcanic eruptions under Mýrdalsjökull, on the other hand, each result in a jökulhlaup transporting many times this amount of sediment onto the Mýrdalssandur outwash plain; such single-episode deposits suffice to shift the coastline several hundred metres seawards. The Mýrdalssandur jökulhlaups are Earth’s largest contemporary floods, rivalled only by floods associated with the end of the last glaciation 11,500 years ago. Looking at the central highlands, where jökulhlaups are topographically constrained, the thereby more focused erosion has created spectacular canyons, e.g. Jökulsárgljúfur. Some of the major Pleistocene river canyons may also have formed through such catastrophic floods of glacial origin.
RECENT GLACIER VARIATIONS

During the Climatic Optimum 7,000 years ago, the Pleistocene ice still remaining over Iceland disappeared almost entirely, presumably leaving only small icecaps on the highest mountains, such as Öræfajökull (Eyþórsson, 1931, 1935; Ahlmann, 1937, 1939, 1940; Ahlmann and Thorarinson, 1937a,b, 1938, 1939; Þórarinson, 1943, 1964, 1966; Guðmundsson, 1997;
From about 8,000 to 3,000 years ago, the climate of Iceland was considerably warmer and drier than at present, with average temperatures believed to have been \(\sim 2^\circ C\) higher than in the period 1920–1960 (Einarsson, 1963; Vinther et al., 2006).

During Neoglaciation, Icelandic glaciers have undergone two outstanding periods of expansion. The first one occurred during the climatic deterioration around 500 years B.C., which was at the onset of Subatlantic time (Bergþórsson, 1969; Dugmore, 1989; Stötter, 1991; Sharp and Dugmore, 1985; Stötter et al., 1999; Wastl et al., 2001; Kirkbridge and Dugmore, 2001, 2006; Schomacker et al., 2003; Black et al., 2004; Flowers et al., 2007, 2008). As the climate became colder and precipitation presumably increased, glaciers edged downwards from the highest summits. Capable of reacting quickly, some steep Alpine glaciers attained their post-Würm maximum. The outermost moraines fronting Kviárjökull and Svinafellsjökull (outlets from Öræfajökull) probably stem from this period. Still other glaciers expanded over the highland plateau, developing into the present Icelandic icecaps. Vatnajökull merged into a single icecap from its beginnings in outlets from several glaciation centres (Öræfajökull, Grímsfjall, Bárðarbunga, Kverkfjöll, Esjufjöll and Breiðabunga).
From the beginning of the settlement of Iceland (around 874 A.D.) up to the thirteenth century, the climate resembled that of the later warm period from 1920 to 1960, with average air temperatures probably 3 to 4°C below those of the Climatic Optimum (Bergþórsson, 1969; Ogilvie, 1992; Ogilvie and Jónsson, 2001; Kirkbridge, 2002). Thus land which is now largely hidden by Breiðamerkurjökull was vegetated and even occupied by several farms. Then the second outstanding period of icecap expansion during Neoglaciation set in, called the Little Ice Age and destined to last from the Middle Ages till the close of the 19th century. During this period, some glacier outlets advanced around 10–15 kilometres, devastating vegetation along with several farms. The firm line in southern Iceland crept down from 1,100 to 700 m in the latter part of the Little Ice Age (Figure 12). For steeper outlets, glacier advance culminated in the 1750s; for broad lobes from the plateau icecaps, it culminated between 1850 and 1890.

![Figure 12. Firnline variations in southern Iceland during the past millennium. Adapted from Þórarinsson (1974). — Hjarnmörk við sunnanverðan Vatnajökul.](image)

While advancing, glaciers excavated their sediment floor; for example, some of the most active southern Vatnajökull termini typically excavated their beds down to hard surfaces 200–300 m below sea level. One instance is the 20–km-long trench, 2–5 km wide and extending to 300 m below sea level, that was created as Breiðamerkurjökull advanced and ploughed away sediment during the course of the Little Ice Age (Björnsson, 1996; Björnsson et al., 2001b; Magnússon et al., 2007; Nick et al., 2007).

During the 1890s, however, a general recession commenced, becoming quite rapid after 1930. On the other hand, cooler summers became the rule after 1940 (Figure 13), so that glaciers in general retreated more slowly during the 1960s, and many steep glaciers even started advancing around 1970. Since 1985, the once more warmer climate has steadily led to more widespread retreat, and every non-surge outlet glacier in Iceland has been retreating since 1995 (Bárdarson, 1934; Eyþórsson, 1931, 1963, 1962–1966; Pórarinsson, 1943; Rist, 1967–1987; Jóhannesson, 1986; Sigurðsson, 1998, 2005; Jóhannesson and Sigurðsson, 1998; Sigurðsson et al., 2007; Hanna et al., 2004). The rate of retreat has accelerated due to high summer melt, but no long-term changes in precipitation have been observed. Since 1890, the leading Vatnajökull outlets have drawn back as far as 2–5 km, and the icecap’s volume has decreased by about 300 km³ (~10%), contributing 1 mm to the rise in global sea level. In the warm period since 1995, the ice surface elevation in ablation zones has decreased by dozens of metres, with margins retreating at rates up to ~100 m a⁻¹. The southern outlet glaciers of Vatnajökull have been particularly vulnerable to such warming, since many had carved down into soft sediments during their Little Ice Age advance and therefore now have beds lying hundreds of metres below the elevation of the current terminus. In addition, frontal lakes form during their retreat, facilitating and speeding it up through the melting and calving of the floating termini. Because Iceland’s major rivers are glacial in origin, and have in many cases been harnessed to generate hydropower, this recession has had a noteworthy hydrological impact. During the second half of the 20th century, the glacial contribution to the country’s runoff was estimated to be about 30% (1,500 m³ s⁻¹ of 5,000 m³ s⁻¹) (Rist, 1956; Tómasson, 1981, 1982; Jónsdóttir, 2008). These estimates, however, were for years before the increased summer melt following 1995/96. Current glacier runoff comprises at least one-third of total runoff. River courses have also changed, leading to problems for farmers and the Road Administration.
Figure 13. Summer temperature and winter precipitation at several Icelandic meteorological stations in the 19th and 20th centuries. Time series are filtered using the 11-year triangular running average. – Medalhiti sumars og vetrarúrkoma á nokkrum veðurstöðvum.

FUTURE OUTLOOK

Numerical models have been developed for describing glacier dynamics (Jóhannesson, 1997; Jóhannesson and others, 1995, 2006a,b,c, 2007; Aðalgeirsdóttir, 2003; Aðalgeirsdóttir et al., 2003, 2005, 2006a, 2006b; Guðmundsson et al., 2003a,b; 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.

Figure 14. Scenario for temperature and precipitation changes during the 21st century, averaged over Iceland (see Jóhannesson et al., 2007). – Svíðsmynd um líklegar breytingar í hitastigi og úrkomu á 21. öld.
Plausible predictions of regional temperature and precipitation trends in Iceland have been developed in the Nordic project Climate and Energy (Rumukainen, 2006; Bergström et al., 2007; Fenger, 2007; Jóhannesson et al., 2007), based on downscaling of global coupled atmosphere-ocean simulations. In comparison with 1961–1990, the project scenario predicts a warming of 2.8°C and a 6% increase in precipitation by 2071–2100. The increases in temperature and precipitation vary according to season (Figure 14). Model run results for Hofsjökull, Langjökull and southern Vatnajökull are shown in Figure 15. 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 their glaciers have melted away.

CONCLUSION

Scientifically speaking, the following fields of glaciological studies are probably the most significant regarding Iceland: a) the hydrology of temperate icecaps, b) interactions between glacial and volcanic phenomena, c) glacier hazards due to jökulhlaups, d) surges and the stability of ice masses, and e) the future evolution of glaciers and their role as indicators of climate change, based on the location of the island in the North Atlantic Ocean, just under the Arctic Circle. The study of all these fields is supported by unusually detailed data, easily accessible on maps of glacier surface and bedrock topography (using records derived from radio-echo soundings, GPS measurements and satellite observations), along with a wide range of glacier mass balance and glacio-meteorological and hydrological observations. The whole of this basic information has been applied towards increasing the overall understanding of Icelandic glaciers and developing and revising numerical models to simulate the growth and decay of present and former glaciers and to simulate the impact of climate change on glacial runoff. The current Icelandic icecaps are important analogues for warm-based Pleistocene ice sheets and may otherwise provide a suitable natural laboratory for a variety of glaciological research. The knowledge gained should have substantial international potential for forecasting and comprehending the future conditions of today’s cold-based polar icecaps.

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ÁGRIP

Um 11% af Íslandi er þakið jöklum. Þeir geyma um 3,600 km³ af vatni sem janfgildir 35 m þykku lagi jafnþreifðu yfir allt landið. Þetta er stærsta vatnsforða-búr landsins og jafngildir úrkomu sem á það fellur í 20 ár. Bráðni allur þessi í hækkgaði um 1 cm í heimshöfum. Jökularnir bregðast fljótt við sveiflum í loftslagi og hafa mikil áhrif á umhverfi sitt. Undir þeim eru mörg virk eldfjöll og frá þeim falla jökulhlaup sem ogna bygð allt til sjávar. Jökularnir veita vatni í stærstu ár landsins og frá þeim kemur nú um þriðjungur vatns sem rennr frá landinu. Eftir að jökular tóku að hoppa í lok 19. aldar eftir nökkurra alda vaxtarskeið hefur stærsti jökull landsins, Vatnajökull, minnkað um 10% að rúmmáli (300 km³) og lagt 1 mm til hækkunar sjávARBÓRÓS. Undanfarin 10 ár hefur hert á jökulrýrnuninni og hann misst 2,7% af rúmmáli sínu (84 km³). Að meðaltali fá jökular um tvo þriðju af orku af orku til leysingar frá söl- og himingeislun og einn þriðja frá hlýju og röki lofti sem berst inn yfir jökulinn. Á söðasta áratug 20. aldar bræddu eldgos og stöðugur jarðhiti um 5,5 km³ sem bættist við yfirborðsbráðnu; þar af um 4 km³ við Gjalpargosíði. Í öllum helstu hveljöklum landsins berst umtalsverður hlutí í húsi frá þriðjungurframhlaup og þau hafa mikil áhrif á flæðiís og vatns frá mörgum skriðjökul um. Líkt og líklegt þó til þess að við þriðjuframhlaupum þeirrit 10% af heildarísmagni til leysingarsvæða Vatnajökuls meðframhlaupum. Líkanreikningar af afkomu og ís-flæði benda til þess að við líklegar loftslagsbreytingar á komandi árum muni fjördurfi til þriðjungur af nú-verandi rúmmáli meginjökulanna hverfa innan hálfr ár aldar og eftir 150 til 200 ár verði eingöngu smájökular eftir að hæsti fjallstindum. Afreinssli frá jökulum nédi hámarki eftir um hálfa öld en yrði eftir um 100 ár jafnt því sem nú er. Súna minnkaði það hrað. Þegar jökular综合征 hverfa mun afreinssla til ána berast beint frá úrkomu.

Rannsóknir á jökulum á Íslandi hafa lagt mikilvægan skerfi til alþjóðlegra jökularrannsókna, einkum til
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