Remote sensing of mountain glaciers and ice caps in Iceland

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ABSTRACT

In 2000, Iceland’s glaciers covered 11,079 km², or 10.7% of its contiguous area. There are 269 named glaciers, including 14 ice caps with 109 associated outlet glaciers, 8 ice flow basins, 55 cirque glaciers, 73 mountain glaciers, and 5 valley glaciers. Twenty-one surge-type glaciers have been documented. The superposition of ice caps on active volcanoes and associated rift zones within the neovolcanic zones of Iceland produces aperiodic jökulhlaups. Jökulhlaups also result from the failure of ice dams on ice-marginal lakes.

In association with Icelandic scientists, airborne thermal infrared surveys of some glaciers were carried out in 1966, and, in 1974, the first analyses of satellite images of glaciers in Iceland were published. Icelandic scientists began radio-echo sounding to determine the thickness of ice caps in 1976. The start of systematic, annual field measurements of the fluctuations of Iceland’s glaciers were begun in 1930; now in the 21st century, between 40 and 50 termini are being measured annually. Systematic instrumental measurements of meteorological variables were started in the 19th century at a few coastal stations, and later expanded to a nationwide network. On September 8, 1972 the first medium-resolution satellite images (ERTS-1/Landsat-1) of Iceland’s glaciers were acquired; subsequently, a variety of imaging and nonimaging sensors on different polar-orbiting satellites have provided aperiodic coverage of Iceland’s glaciers.

Long-term sets of glaciological data, whether compiled from sequential map series, ground observations (termini fluctuations), and other ground measurements (mass balance studies) or from analyses of data acquired by satellite sensors, such as Landsat MSS, RBV, TM, ETM+, OLI, Seasat radar, Terra ASTER, and ICESat GLAS, have successfully documented changes in the area and mass balance (volume) of Iceland’s glaciers. Glacier variations, when correlated with changes in climate, show a close correspondence for more than 100 years of observation. Since the mid-1990s, in response to a warmer climate, most of Iceland’s glaciers have been undergoing an annual average shrinkage of about 0.3%. Except for glacier ice at the highest elevations, at the present rate of shrinkage, Iceland may be deglacierized by 2200.

18.1 INTRODUCTION

18.1.1 History of mapping Iceland’s glaciers

The earliest Norse settlers in Iceland (about 874 AD) brought their knowledge of glaciers (þjókkull) with them from their experience with glaciers and glacial rivers in Norway, such as Hardangerjökulen and its
associated glacial rivers flowing into Eidfjord. Some of Iceland’s glaciers (Figs. 18.1, 18.2) first appeared on maps in the 16th century (Sigurðsson 1978), and descriptions of its glaciers were included in several books published in the 18th century (see Thorarinsson 1960 and historical review in Williams and Sigurðsson 2004), including the first map of an outlet glacier, Sólheimajökull, by Arni Magnússon in 1704/05 (Thorarinsson 1960).

Gunnlaugsson (1848) published the first comprehensive map of Iceland, which showed the geographic location of its major ice caps. The Danish General Staff (later Danish Geodetic Survey) began planetable mapping of Iceland, including its glaciers, in 1902 (Böðvarsson 1996), but the mapping was not completed before the onset of World War II. From the end of World War II until the late 1980s, the U.S. Department of Defense, in cooperation with the Iceland Geodetic Survey (Landmælingar Islands), published several series of maps at various scales of Iceland, including complete coverage at 1:50,000 scale in Series C762 and 50% coverage in the latest Series C761. The Iceland Geodetic Survey (now called the National Land Survey of Iceland) continued to publish maps at various scales until 2006 when the NLSI stopped publishing maps, and the only complete coverage of Iceland by them is at a scale of 1:250,000.

18.1.2 Scientific analysis of Iceland’s glaciers

Sveinn Pálsson’s pioneering work on Iceland’s glaciers, which was completed in 1795, is the first comprehensive scientific treatise on glaciers for an entire country (Williams and Sigurðsson, 2004).
The geologist/glaciologist Thoroddsen (1892, 1906, 1911) published several comprehensive works on Iceland’s glaciers during the latter part of the 19th century and the early part of the 20th century. The Icelandic geologist/glaciologist Thorarinsson (1943) reviewed fluctuations of glaciers in Iceland during the past 250 years and published many papers and books on its glaciers until his death in 1983; Thorarinsson (1958), using Danish Geodetic Survey maps, also measured the area of Iceland’s largest glaciers.

Eythorsson (1963), a meteorologist/glaciologist, began the first annual measurements of glacier termini in 1930, which he compiled each year until his death in 1968. The hydrologist/glaciologist Rist (1976) continued the annual compilation until his retirement in 1987; since then, Sigurðsson (1998) has continued the compilation annually. The result of 80 years of annual field measurements of the fluctuations of glaciers, conducted by scientists and volunteers, has been an annual compilation in Jökull for 60 years (Jón Eyþórsson, Sigurjón Rist, and Oddur Sigurðsson, 1951–present). With these works, Iceland has an excellent long-term database of glacier fluctuation, and it continues; in 2009, 40–50 glacier termini were measured at various field locations. Additional information about the glaciers of Iceland has been summarized by Thorarinsson (1975), Björnsson 1979, Rist (1985), Björnsson and Pálsson (2008), Sigurðsson and Williams (2008a), and Björnsson (2009).

18.1.3 Air and spaceborne imaging and remote-sensing analysis of Iceland’s glaciers

Airborne remote sensing of Iceland’s glaciers was begun in the 1930s (vertical and oblique aerial photographs) (Nørlund 1944) to support the Danish topographic mapping program in Iceland (Böðvarsson 1996). In the mid-1940s, mid-1950s, and early 1960s, the U.S. Army Air Force (U.S. Air Force after 1947) carried out systematic aerial photographic surveys to support a 1:50,000-scale
series topographic mapping program, in cooperation with the Iceland Geodetic Survey. In 1966 the U.S. Air Force (Air Force Cambridge Research Laboratories), in cooperation with the U.S. Geological Survey and several Icelandic scientific institutions, carried out airborne thermal infrared surveys of volcanic and geothermal areas in Iceland (Friedman et al. 1969), including the area around Kverkfjöll, an outlet glacier in northern Vatnajökull (Friedman et al. 1972).

On September 8, 1972 the first Landsat MSS images of Iceland’s glaciers were acquired, including an image of the partially cloud-obscured terminus of Skeiðarárjökull and the southern part of Óræfajökull and several of its outlet glaciers. The USGS (1976, 1977) published the first Landsat image maps of Iceland, including a fall and winter image of Vatnajökull.

Images from the Landsat 1–5, 7, and 8 series of spacecraft (1972–present), including images from the Multispectral Scanner (MSS), Return Beam Vidicon (RBV), Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+), and Optical Line Imager (OLI) sensors have been used by many glaciologists to analyze surficial glaciological and subglacial (tectonic and volcanic) features and changes in the ice caps and associated outlet glaciers of Iceland, with particular emphasis on Vatnajökull and its outlet glaciers. Analysis of a low solar-elevation-angle (less than 6°) Landsat image of Vatnajökull (U.S. Geological Survey, 1977) provided new information about subglacial tectonic and volcanic features (Thorarinsson et al. 1974). Other Landsat images provided information about glaciological features (Williams 1986a, b, 1987), including glacier facies (Williams et al. 1991), the Brúarárjökull outlet glacier (combined with ERS-1 SAR data) (Hall et al. 1995), and a comparison of satellite image versus ground-based measurement of fluctuations of several outlet glaciers (Williams et al. 1997). Landsat images and maps were used to do a preliminary glacier inventory of the Langjökull Group of glaciers (Williams 1986b).

Four satellite image mosaics of Iceland, using image data from four different sensors, have been compiled: a Landsat-1 MSS image mosaic in 1974, a Seasat radar mosaic in 1978, a Landsat-5 TM mosaic in 1993, and a SPOT-5 mosaic in 2006. Areas of Iceland’s glaciers were measured on Landsat images and ancillary sources by Björnsson (1978a), Williams (1983), and Sigurðsson and Williams (2008b) (Table 18.1). Additionally geodetic airborne laser altimeter surveys were made of Skeiðarárjökull and Breiðamerkurjökull (Garvin and Williams 1993); ICESat GLAS profiles of the Drangajökull ice cap were compared with April 2003 GPS ground survey profiles (Shuman et al. 2008). Airborne LiDAR mapping of Iceland’s ice caps and mountain glaciers was begun in 2008 and continues (Jóhannesson et al. 2013).

18.2 REGIONAL CONTEXT

18.2.1 Geography and geology

Iceland, a glacierized volcanically active island, is situated in the North Atlantic Ocean between Greenland’s Blosseville Coast located about 280 km to the northwest with the Færøe Islands and Shetland Islands of Scotland lying about 425 km and 700 km, respectively, to the southeast. The island has an area of 103,000 km², and is centered at about 65°N latitude and 19°W longitude; except for the northern part of the island of Grímsey, Iceland lies south of the Arctic Circle. About 10.7% is covered by glaciers, with most of the glacierized area (97%) contained in the six largest ice caps and associated outlet glaciers (Figs. 18.1 and 18.2, Table 18.1). Björnsson and Pálsson (2008) calculated the volume of ice in Iceland’s glaciers to be 3,600 km³.

Iceland is the largest island on the Mid-Atlantic Ridge; it also straddles the transverse Greenland–Færoes Ridge, which extends from Greenland to Ireland. The island sits astride tectonically active rift zones, characterized by frequent subaerial, subglacial, and submarine volcanic eruptions and earthquakes sourced along the plate boundary between the North American and Eurasian Plates. Transform faults are located in southwestern Iceland (Southwest Fracture Zone) and northern Iceland (Tjörnes Fracture Zone). Extending to the southwest from Iceland is the submarine Reykjanes Ridge; extending to the north of Iceland is the submarine Kolbeinsey Ridge (also known as the Iceland–Jan Mayen Ridge).

The oldest volcanic rocks in Iceland are Miocene in age; they are located in the dissected plateau basalts of the western (maximum age 16 Myr), northern (maximum age 12 Myr), and eastern (maximum age 14 Myr) parts of Iceland. Active zones of tectonic rifting and effusive volcanism are situated between the older plateau basalts including a western neovolcanic zone, an extension onshore of the Reykjanes Ridge, which stretches
Table 18.1. Area of Iceland’s glaciers from analysis of aerial photos and satellite images.

<table>
<thead>
<tr>
<th>Glacier name</th>
<th>Area (km²)</th>
<th>Image source</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vatnajökull ice cap</td>
<td>8,086</td>
<td>Landsat 7</td>
<td>2000</td>
</tr>
<tr>
<td>Langjökull ice cap</td>
<td>920</td>
<td>Landsat 7</td>
<td>2000</td>
</tr>
<tr>
<td>Hofsjökull ice cap</td>
<td>889</td>
<td>Vertical aerial photo</td>
<td>1999</td>
</tr>
<tr>
<td>Myrdalsjökull ice cap</td>
<td>597</td>
<td>Vertical aerial photo</td>
<td>1999</td>
</tr>
<tr>
<td>Drangajökull ice cap</td>
<td>146</td>
<td>SPOT-5</td>
<td>2004</td>
</tr>
<tr>
<td>Eyjafjallajökull ice cap</td>
<td>80</td>
<td>Vertical aerial photo</td>
<td>2003</td>
</tr>
<tr>
<td>Tungnafellsjökull ice cap</td>
<td>38</td>
<td>Landsat 7</td>
<td>2000</td>
</tr>
<tr>
<td>Dórísjökull ice cap</td>
<td>30</td>
<td>Landsat 7</td>
<td>2000</td>
</tr>
<tr>
<td>Eiríksjökull ice cap</td>
<td>22</td>
<td>Landsat 7</td>
<td>2000</td>
</tr>
<tr>
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<td>15</td>
<td>SPOT-5</td>
<td>2000</td>
</tr>
<tr>
<td>Torfajökull mountain glacier</td>
<td>11</td>
<td>Vertical aerial photo</td>
<td>1999</td>
</tr>
<tr>
<td>Prándarjökull ice cap</td>
<td>17</td>
<td>SPOT-5</td>
<td>2000</td>
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<tr>
<td>Snæfellsjökull ice cap</td>
<td>12</td>
<td>Ground measurements</td>
<td>2002</td>
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<td>Landsat 7</td>
<td>2000</td>
</tr>
<tr>
<td>Hofsjökull eystri ice cap</td>
<td>5</td>
<td>SPOT-5</td>
<td>2000</td>
</tr>
<tr>
<td>Okjökull mountain glacier</td>
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<td>Landsat 7</td>
<td>2000</td>
</tr>
<tr>
<td>North Iceland glaciers</td>
<td>179</td>
<td>SPOT-5</td>
<td>2004–2006</td>
</tr>
<tr>
<td>East Iceland glaciers</td>
<td>13</td>
<td>SPOT-5</td>
<td>2003</td>
</tr>
<tr>
<td>Other glaciers</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>11,079</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

beyond the northern end of Langjökull ice cap. The eastern neovolcanic zone extends in a northeasterly direction from Surtsey, Heimaey, and other islands in the Vestmannaeyjar Archipelago to the northern side of Vatnajökull and from there, as the northern neovolcanic zone, in a northerly direction to the north coast of Iceland.

Two active major central volcanoes, Hofsjökull and Öræfajökull, are situated outside the rift zones. In western Iceland, an east to west-trending active zone of volcanism is separated from the other neovolcanic zones (Sæmundsson 1980; Thorarinsson and Sæmundsson 1980). The major historic centers of volcanism and rifting created topographically higher regions upon which the four largest of Iceland’s ice caps (Vatnajökull, Langjökull, Hofsjökull, and Myrdalsjökull) are located (Figs. 18.1 and 18.2). The average elevation of Iceland is 500 m above mean sea level; a nunatak on Öræfajökull, an internal ice cap contiguous with Vatnajökull, is the highest point on the island at 2,110 m. Subglacial volcanism during the Pleistocene created mountains upon which four additional ice caps are situated (Tungnafelljökull, Dórísjökull, Eiríksjökull, and Hrutfellsjökull) (Figure 18.2). Three ice caps lie outside the neovolcanic zones, one in the northwest,
Drangajökull, and two in the southeast, Brándarjökull and Hofsjökull eystri. One ice cap, Snæfellsjökull, lies on the western edge of the east to west-trending volcanic zone in western Iceland.

The majority of Iceland’s glaciers are mountain glaciers, and most of these are cirque glaciers situated in the dissected plateau basalts of the Tröllaskagi area of northern Iceland to the west and southwest of Eyjafjörður (Fig. 18.2; Sigurðsson and Williams 2008a). The location of the four largest ice caps (and some other ice caps and mountain glaciers) within the neovolcanic zones creates conditions under which aperiodic subglacial volcanic activity is followed by glacier outburst floods (jökulhlaups), especially from subglacial calderas and associated rift zones within the margins of Vatnajökull and Mýrdalsjökull (Fig. 18.2). Glaciological hazards in Iceland, including both types of jökulhlaups, volcanic and lacustrine, and surge-type glaciers, will be addressed in more detail later in this chapter.

18.2.2 Climate and climate variability

The climate of Iceland was described in the modified Köppen classification as comprising two categories, “polar” for the northern third of the island, and “humid” maritime temperate, with no dry season and a short cool summer for the southern two thirds (see de Blij et al. 2004, their fig. 16.3, pp. 206–207). The northern one third can be better characterized, however, as “humid microthermal” (deBlij et al. 2004). The variability of seasonal temperature and precipitation for the island is governed by the convergence of polar air masses from the northwest and initially tropical now-temperate air masses from the southwest. Warm Gulf Stream waters flowing north-northeast in the North Atlantic Ocean turn to the east-northeast south of Iceland, with one branch (Irminger Current) turning to the north-northeast to flow clockwise along the western, northern, and eastern coasts and the other branch flowing to the northeast over the submarine ridge between Iceland and the Faeroe Islands. Intense low-pressure systems periodically travel along the fluctuating frontal boundary between the polar and temperate air masses, producing rainfall in summer and snowfall in winter, with the greatest precipitation occurring in southern Iceland and a tenfold reduction in the highlands north of Vatnajökull. For example, annual precipitation on the higher southern slopes of Vatnajökull, Mýrdalsjökull, and Eyjafjallajökull can exceed 4,000 mm (Crochet 2007); in the “rainshadow north of Vatnajökull in the Ódáðahraun, annual precipitation can be less than 400 mm. Virtually all of the ice caps receive an annual precipitation total greater than 2,000 mm. Storms that pass south of Iceland bring colder temperatures in the polar air mass side of the frontal boundary; storms that pass to the north between Greenland and Iceland bring milder temperatures in the temperate air mass side of the frontal boundary. Polar pack ice and icebergs carried southwest along the east coast of Greenland in the East Greenland Current can sometimes be carried in an east-flowing branch which moves along the northern coast of Iceland, and, although rare historically under conditions of severe pack ice concentration, can move south along the east coast of Iceland (Thorarinsson 1975). Both Thoroddsen (1916–17) and Grove (1988) used sea ice as a “proxy record of past climate during historic time in Iceland (since about 874 AD). Grove (1988) was particularly interested in relating sea ice conditions north of Iceland to glacier advances during the Little Ice Age.

Accurate meteorological observations were begun at a few sites in the early 19th century (Williams and Sigurðsson, 2004). By the latter part of the 19th century, an extensive network of meteorological stations had been established at various ports, and extended later into the settled interior of Iceland and at airfields. As a result of this comprehensive record of meteorological variables, the climate of Iceland can be accurately determined since the late 19th century, which corresponds with the end of the Little Ice Age, and which also marks the maximum extent of glacier advance during that period (Sigurðsson 2005). Eythorsson and Sigtryggsson (1971) and Einarsson (1976, 1984) have analyzed these data and described changes in the climate of Iceland. Ólafsson et al. (2007), in an editorial, summarized the climate of Iceland: mean annual temperatures range from about 0°C in winter to about 10°C in summer; mean annual precipitation is about 1,000 mm in the south, less in the north.

The principal factors governing the presence (or absence) of glaciers in Iceland are mean annual temperature (especially mean summer temperature), mean annual precipitation (especially mean winter precipitation), and topographic elevation. These factors, in turn, govern the glaciation limit (Neuendorf et al. 2005, p. 273) throughout Iceland: the lowest occurs at about 700 m in the Vestfirðir (Northwest Fjords), and the highest north of
Vatnajökull at more than 1,500 m. On the southern
flanks of Vatnajökull, Mýrdalsjökull, and Eyjafjallajökull, where the highest mean annual precipitation occurs, the glaciation limit is about 1,100 m (Thorarinsson 1975).

The climate in Iceland was colder during the Little Ice Age, and outlet glaciers and mountain glaciers expanded to their maximum extent at the end of the cold period, about 1890. During the 20th century, Iceland’s glaciers retreated to positions equivalent to their probable locations of about four centuries earlier. The 1940s, in particular, were characterized by rapid retreat of glacier termini and thinning. However, during intervals in the 1970s and 1980s, extending into the early 1990s, the majority of Iceland’s glaciers thickened and advanced. Since the mid-1990s, most of Iceland’s glaciers have retreated and thinned very rapidly in response to warmer summers (Sigurðsson 2005). Fig. 18.3 shows the close correlation of annual fluctuations of the terminus of the Sólheimajökull outlet glacier in southern Iceland and Hrynningajökull outlet glacier in western Iceland with variations in mean annual summer temperature at Stykkishólmur, where a coastal meteorological station in western Iceland recorded data during the period 1930 to 2010.

18.3 SPECIAL TOPICS AND METHODOLOGY

18.3.1 Types of glaciers

In general, glaciers are of two types with regard to the reaction of the terminus to variations in mass balance:

- nonsurge type
- surge type.

**Figure 18.3.** Graph showing annual variations in the terminus of Sólheimajökull, an outlet glacier from the Mýrdalsjökull ice cap, southern Iceland, and Hrynningajökull outlet glacier from the Snæfellsjökull ice cap, western Iceland, correlated with mean summer temperature (May–September) at the Stykkishólmur meteorological station, western Iceland: 1930–2010 (updated from Sigurðsson 2006).
The terminus of a surge-type glacier ordinarily retreats most of the time regardless of climate and mass balance and advances only occasionally at a quasiregular interval of time (usually of the order of decades) (Björnsson et al. 2003). The terminus of a nonsurge-type glacier in Iceland will react more or less directly to changes in mass which, in turn, depends primarily on radiation and mean summer temperature (Fig. 18.3). Occasional anomalies in precipitation also appear in glacier oscillations such as the retreat of glacier termini during the cold and dry period in the 1960s (Crochet 2007, Sigurdsson et al. 2007, their fig. 6).

The climate-induced oscillations in mass balance of glaciers in Iceland is primarily based on two factors:

- radiation and air temperature during the summer
- precipitation during the winter.

In Iceland, decadal variations of temperature have been much greater than those of precipitation (Sigurðsson et al. 2007). Therefore, they are the most important climatic factors in the variations of glaciers.

In Iceland several nonclimatic factors also affect the mass balance of glaciers. The most important of those are:

- subglacial volcanic activity
- subglacial geothermal activity
- debris on the glacier surface—volcanic airfall (tephra), landslides, etc.
- iceberg calving into water bodies.

### 18.3.2 History of Iceland’s glacier variations

During the Last Glacial Maximum (Weichsel), Iceland was almost entirely covered by glacier ice. During the warmest part of the Holocene, about 7800–5600 years BP, glaciers in Iceland more or less disappeared (Flowers et al. 2008, Geirsdóttir et al 2009), leaving only the highest mountains with ice caps. The maximum glacier extent of postglacial time in Iceland occurred around 1890 (Sigurðsson 2005). Therefore, glaciers have, by their advance, obliterated a substantial portion of the evidence of fluctuations prior to 1890 and we have to rely on scarce stratigraphical information and other geological evidence. Patches of peat, tree stumps, and lumps of diatomite with intact stratigraphy in the outwash from major outlet glaciers confirm in rather inexact terms a much greater extent presently than during the middle of the Holocene.

At the time of settlement about 900 AD, the presence of glaciers and the turbid water of the glacial rivers were noted and recorded in early manuscripts such as The Book of Settlement (Benediktsson 1986). The same source gives ample place names that include glaciers in their names. This confirms that the major glaciers were present during that time; however, they were much smaller than during the 20th century.

According to historical documents, glaciers advanced with minor retreat events more or less continuously at least since the 17th century, until the end of the 19th century. Grazing areas, forests, and inhabited districts were overrun by glaciers, indicating that this was the greatest advance of glaciers since the last glaciation (Sigurðsson 2005).

During the Little Ice Age Icelandic glaciers reached their maximum extent about 1890. The retreat of glaciers, however slow, was obvious during the first decades of the 20th century (Björnsson 1988). In the 1920s, considerable climate warming resulted in a high rate of retreat of all glaciers in the country. This retreat continued at a moderate pace until about 1970. During the period 1970–1995 nonsurge-type glaciers advanced almost continuously due to a cooler climate in an area reaching from Labrador and across southern Greenland to Iceland (Hanna et al. 2004). During the first decade of the 21st century glaciers have retreated faster than at any time since 1930, when the Iceland Glaciological Society began monitoring glacier front variations (Figs. 18.1 and 18.3) (Jóhannesson and Sigurðsson 1998, Sigurðsson 1998, 2006). During the past decade, glacier surface area has decreased on average by about 0.3% per year, as deduced from repeated tracing of outlines of glaciers from map overlays of Landsat 7, SPOT-5, vertical aerial photos, with complementary data from oblique aerial stereo photographs and ground verification for some glaciers, and by about 0.4% in thickness according to mass balance measurements (Sigurðsson 2006). According to models of mass balance, Icelandic glaciers will essentially disappear during the next two centuries if global warming continues as expected (Jóhannesson et al. 2007).

Outlines of all Icelandic glaciers have been traced recently on map overlays from aerial photos, Landsat 7, and SPOT-5 images (Sigurðsson and Williams 2008b), and interpretation of the location of the outlines has been verified by oblique aerial stereo
photographs and ground measurements at the end of a warm summer.

Nonsurge-type glaciers in Iceland usually do react to mass balance changes almost immediately (Sigurðsson et al. 2007) (Fig. 18.3). Best fit ($r^2 = 0.716$) between the 5-year running mean of front variations of Sólheimajökull outlet glacier, southern Iceland and summer temperature at Stykkishólmur in western Iceland is attained if glacier reaction to mass balance change has a 1-year time lag. Similar values occur for other nonsurge-type glaciers independent of their size.

During the 20th century glaciers in Iceland retreated approximately as far as they had advanced from 1600 to 1900 (Sigurðsson 2005). Glaciers decrease in proportion to their size. The largest glaciers have retreated about 4–5 km but the small mountain glaciers of northern Iceland have retreated only of the order of 100 m. Cirque glaciers that are covered by debris in the ablation area have decreased very little in length. A few of the smallest glaciers have disappeared, leaving only remnants such as ice-cored moraines.

18.3.3 Identifying the outline, transient snow line, and firn line of glaciers

The main problems in identifying the glacier margin by remote sensing in Iceland are mainly debris cover on outlet glaciers and snow cover at high elevations. Many small mountain glaciers may be completely covered with snow for extended periods, some for decades.

Glaciers may become covered by surficial debris by several means. In steep-sided landscape landslides or rockslides frequently fall on the glaciers’ surfaces (Sigurðsson and Williams 1991). These can usually be identified in early stages on satellite images. Later the landslides merge with debris at the terminus and are then difficult to distinguish from the morainal and fluvioglacial deposits in the outwash plain. Cirque glaciers commonly accumulate debris in the ablation area; such surficial debris may cover more than half of the surface area of the glacier. This debris results from rock fall at the head wall and is not easy to identify on satellite images or discern between the proglacial area and ice-cored moraines. Field observations are needed to accurately map the position of the glacier terminus. When ground observations are not feasible oblique aerial photography, particularly in stereo, will suffice generally.

Glaciers in Iceland commonly are covered by deposits of tephra downwind from sites of recent explosive volcanic eruptions. In the ablation area this will wash off with meltwater or rain; in the accumulation area it will be covered with subsequent snow. However, outlet glaciers, such as Kótlujökull, Skeiðarárjökull, and Dyngjújökull, that originate near the most active volcanoes generate quite voluminous layers of tephra that melt out of the glacier ice in the ablation area. This is a very efficient insulation material that affects mass balance and, thereby, variations at the terminus.

Satellite images commonly reveal the transient snow line (Jaenicke et al. 2006), which delineates the approximate position of the equilibrium line at the end of the ablation season. The firn line is also often easily detectable in late summer. Because of the presence of tephra layers in Icelandic glaciers the difference between the transient snow line and the firn line is, in many instances, obvious on satellite images. The firn line defines the long-term equilibrium line altitude (ELA), thereby allowing for determination of the accumulation area ratio (AAR). The AAR is close to constant for different ice flow basins and, therefore, the firn line is very helpful in accurate identification of ice divides on ice caps.

Calving of glaciers into the sea or lakes affects their overall mass balance to a great extent because the masses of glacier ice that melt (e.g., icebergs) beyond the margin of the glacier are not included in the ablation caused by climatic change. Lakes at the glacier margin are easily identified and the increased velocity resulting from the calving process is commonly visible by the pattern of tephra layers even on satellite images (e.g., Breiðamerkurjökull; Williams and Sigurðsson 2004, their fig. 18.3).

18.3.4 Jökulhlaups

Ice-dammed lakes are common in Iceland. Periodically, these ice dams fail, either suddenly or with a gradual exponential increase in discharge. In either case, the result is a dramatic release of water from behind the dam. As noted, the phenomenon was first described scientifically by Thorarinsson (1939) with regard to two types of glacier outburst floods. He used the term jökulhlaup for both; it has since been adopted into the international terminology of glaciology and by other geoscientists (Neuendorf et al. 2005, p. 345).

Most ice-dammed lakes are in tributary valleys (Thorarinsson 1939). A few are subglacial, formed
by subglacial geothermal areas that continuously melt the glacier from below. This causes a subsidence in the surface of the glacier, creating a cauldron bounded by concentric fractures that, in turn, forms a trap collecting subglacial water and forming a cupola at the glacier bed (Björnsson 1988). The burst of water from this cupola in a jökulhlaup accentuates the existing cauldron on the glacier surface which gradually is lifted from below by water from surficial, englacial, and subglacial meltwater and geothermally melted glacier ice and filled from the top by accumulating snow until the next jökulhlaup occurs. These cauldrons are easily detected on satellite images, forming concentric fissures that outline the depression on the surface of the glacier. The extent of inundation by floods is only in exceptional cases caught by remote sensing.

The impact of jökulhlaups on the topography may be huge. Large canyons may be cut into the landscape in a very short period of time; outwash plains of large or repeated jökulhlaups are easily discerned on satellite images. The largest of those in Iceland is the Skeiðarársandur outwash plain which covers an area of about 1,000 km². During a recent jökulhlaup (November 1996) 750 km² of the outwash plain was inundated (Snorrason et al. 2002). The hazard represented by jökulhlaups for Icelandic society is very great. On average, there are about 5–10 jökulhlaups per year in Iceland (Sigurdsson and Einarsson 2005). Usually, there is at least one per century that exceeds 100,000 m³ s⁻¹ and 5–10 per century that are tens of thousands of m³ s⁻¹. These will inevitably cause damage to infrastructure, such as the roads and bridges that traverse glacial outwash plains. The most catastrophic jökulhlaups are induced by subglacial volcanic eruptions. The jökulhlaup associated with the 1996 Gjálp eruption within Vatnajökull is described below.

18.4 THREE CASE STUDIES

18.4.1 Transient tephra lines

On average, a volcanic eruption occurs every 3–4 years in Iceland (Gudmundsson et al. 2008). Volcanic tephra is frequently deposited on glacier surfaces within the country. These layers of tephra appear in the ablation area as dark undulating bands often easily identifiable on satellite images and aerial photos (Larsen et al. 1998). Melting of the glacier surface will displace the outcrops of tephra layers (horizons) upglacier because they are dipping at a slight angle into the ice. However, these bands move gradually toward the terminus because of the movement of the glacier and eventually merge with other debris at the margin of the glacier. By identifying individual tephra layers and determining their age, the turnover time of each outlet glacier can be calculated (Sigurðsson 2010).

The forward motion of surge-type glaciers is episodic with great leaps forward during surges, but becoming more or less stagnant during periods of quiescence. By tracing identified tephra layers on images at two or more different times, glaciers with normal downglacier movement (equilibrium velocity) can be distinguished. Stagnant ice masses can be identified by displacement of tephra horizons upglacier indicating a surge-type glacier (e.g., Brúarjökull) (Fig. 18.4).

Tephra horizons keep their stratigraphic position all the way down to the terminus. This indicates that the flow within the glacier mass is more or less perfectly laminar even where the thickness of the glacier is halved and doubled again by flowing across subglacial serrated volcanic mountain ridges (e.g., Tungnárjökull).

18.4.2 Classification of the Vatnajökull ice cap according to three different outlines

Tracing the outline of an ice cap or two or more different glaciers within the same region at two or more different times will generally indicate which glaciers or which outlet glaciers from the ice cap are showing a surge-type and tidewater (“abnormal”) or nonsurge-type (“normal”) flow process. During a period of positive mass balance, surge-type glaciers retreat except during surge events, whereas nonsurge-type glaciers advance. During the quiescence phase surge-type glaciers retreat at a higher rate than nonsurge-type glaciers during a time of negative mass balance. For two different map outlines of surge-type and nonsurge-type glaciers, glaciers that have surged in the interval of time between outlines are easily identified.

In Fig. 18.5, three different outlines of Vatnajökull ice cap are shown. The partial 1903–1904 outline of southeastern and southern Vatnajökull is traced from the Danish General Staff map, scale 1:50,000; the 1945–1946 outline (complete) is traced.
from Army Map Service maps, Series 762, scale 1:50,000 published in 1950. The outline from 1991 to 1992 is traced on a map overlay from Landsat 5 satellite images taken on September 7, 1991 (middle and eastern part of the ice cap) and July 14, 1992 (the westernmost outline). The ice cap is successively smaller in the three cases. However, some outlet glaciers extend farther out as plotted on more recent maps or traced on overlays of satellite images than from earlier datasets; these are all surge-type glaciers, such as Brúarjökull on the northeast margin and Síðujökull on the southwest margin. In other cases the respective distance between successive outlines is much greater for some glaciers than others. This may be explained by variable rates of calving glaciers (tidewater glaciers, such as Breiðamerkurjökull) or surge-type glaciers during quiescence phases (Tungnárjökull between the first two outlines). Between 1945 and 2006 all but one of the recognized surge-type outlet glaciers of Vatnajökull ice cap underwent a surge event.

**Figure 18.4.** Brúarjökull outlet glacier with distinct tephra horizons. One of them, tephra from the Grímsvötn eruption in 1629, is traced at two different times: 2000 (yellow), and 2006 (red) projected on IRS satellite image. Figure can also be viewed in higher resolution as Online Supplement 18.1.

### 18.4.3 The impact of the 2004 jökulhlaup on glacier dynamics of Skeiðarárjökull

In this study the influences of the 2004 jökulhlaup on the ice dynamics of Skeiðarárjökull are investigated by means of optical imagery acquired by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) aboard the EOS Terra satellite. Skeiðarárjökull is the largest southward-trending outlet of the Vatnajökull ice cap with a catchment area of approximately 1,450 km². Its elevation ranges from 1,740 m down to 100 masl at the terminus. Jökulhlaup draining under Skeiðarárjökull in autumn 2004 was associated with a volcanic eruption at the subglacial Grímsvötn caldera (November 1–6, 2004) (Martinis et al. 2007). The meltwater discharge of this outburst flood peaked on November 2 and finally ended in early December, having released a total volume of ~0.8 km³ from Grímsvötn.
Six optical ASTER scenes (band 1, 0.52–0.60 μm) covering the time period 2001–2005 are used to compare short-term (September 27, 2004 to November 30, 2004) variation in surface velocity related to the jökulhlaup using mean annual velocities. Surface velocities and the flow pattern of the glacier tongue are derived by image-to-image cross-correlation determined using IMCORR software (Scambos et al. 1992) applied to five ASTER image pairs. This technique automatically tracks the motion of small-scale features like crevasses, debris, dirt cones, or other objects at the glacier surface. Generally, the four annual ASTER pairs (2001–2002, 2002–2003, 2003–2004, 2004–2005) offer a higher density of correlated points, due to the similar surface conditions during the summer period when the ice is exposed on the whole glacier tongue (see the mean annual flow pattern of the time interval September 27, 2004 to July 28, 2005 in Fig. 18.6a). Therefore, surface features are well correlated. Cross-correlation of the annual pairs yields very similar flow patterns with a pronounced north-northeast to south-southwest trending central flow line of maximum speed (up to 1.05 m day\(^{-1}\)) in contrast to the lateral parts of slower movement (<0.1 m day\(^{-1}\)). Feature tracking of the data pair covering the jökulhlaup (September 27, 2004 to November 30, 2004) was complicated by snow cover in the ASTER scene acquired on November 30, 2004, especially at higher elevations of Skeiðarárjökull. Nevertheless, correlation point density is reduced only marginally in the lower parts of the glacier on this date (Fig. 18.6b), because surface features are not completely masked by the thin snow cover. A considerable increase in flow velocity of up to 0.4 m day\(^{-1}\) compared with annual values can be observed, probably due to enhanced glacier sliding triggered by the higher amount of subglacial meltwater drainage during the jökulhlaup, caused by the Grímsvötn volcanic eruption (Münzer et al. 2007). Extensive acceleration over nearly the whole width of the glacier suggests widespread lubrication at the glacier bed. This phenomenon is hardly explainable by the classical jökulhlaup theory of floodwater drainage in a single subglacial conduit (Nye 1976); a sheet flow or
coupled sheet and tunnel seems more likely (Jóhannesson 2002; Flowers et al. 2004). This corresponds to the new theory of meltwater discharge during glacial torrents already confirmed for a major jökulhlaup at Skeiðarárjökull in 1996 (Magnússon et al. 2005).

18.5 REGIONAL SUMMARY

In 2000, 10.7% (11,079 km²) of the land area of Iceland (103,000 km²) was covered by glaciers (Table 18.1). Iceland’s glaciers can be placed within eight regional glacier groups (Fig. 18.2). Most of the area, 10,718 km² (97%) of glacier ice, is contained in the six largest ice caps and associated outlet glaciers in five of the groups (Table 18.1): Vatnajökull (73%), Langjökull (8.3%), Hofsjökull (8%), Mýrdalsjökull (5.4%), Drangajökull (1.3%), and Eyjafjallajökull (less than 1%). All six ice caps have annual precipitation in excess of 2,500 mm; Langjökull receives more than 3,500 mm; and Mýrdalsjökull, Eyjafjallajökull, and Vatnajökull exceed 4,000–5,000 mm, peaking at 7,000 mm. Hofsjökull and Drangajökull receive about 3,500 mm of precipitation annually (Björnsson and Pálsson 2008, Sigurðsson et al. 2004).

According to Sigurðsson and Williams (2008a), the 269 named glaciers in Iceland include 14 ice caps (including 2 contiguous ice caps), 109 outlet glaciers (from the ice caps), 8 ice flow basins in the Hofsjökull ice cap, and 3 ice streams (in Breiðamerkurjökull). There are also 55 cirque glaciers, 73 mountain glaciers, and 5 valley glaciers, most of which are in the Tröllaskagi and other highlands of northern Iceland. There are 21 surge-type glaciers (Björnsson et al. 2003), not counting 7 candidates. There are 38 named snow patches. The total number of named glaciers do not include the 6 glaciers that “disappeared” during the second half of the 20th century: 3 mountain glaciers which melted, 2 distributary outlet glaciers, and 1 outlet glacier that receded into their respective ice caps.

Figure 18.6. Surface velocity field of Skeiðarárjökull outlet glacier, derived from ASTER data for the periods (a) September 27, 2004 to July 28, 2005, (b) September 27, 2004 to November 30, 2004 (Martinis et al., 2007).
The primary glaciological hazard is the jökulhlaup. Jökulhlaups are of two types, those that result from subglacial volcanic and associated geothermal activity and those that result from the failure of ice-dammed ice-marginal lakes (proglacial lakes). Other glaciological hazards include surge-type glaciers, snow avalanches, and flooding from ice dams on rivers.

Since 1930 an increasing number of glacier termini have been measured annually in the field; in 2009 between 40 and 50 glacier termini (mostly outlet glaciers) at 55 separate locations were being measured. Accurate mapping of Iceland began in 1902, and several series of maps at various scales have been published of Iceland’s glaciers. Radiosounding of the thickness of Iceland’s ice caps was begun in 1976 (Björnsson 1978b, 1988). Geodetic airborne laser altimetry or LiDAR (Jóhannesson et al. 2013) and airborne thermal infrared imagery has been analyzed for Icelandic glaciers. Image and nonimage data acquired by sensors on polar-orbiting satellites, including MSS, RBV, TM, ETM+, and OLI imaging sensors on the Landsat series (1972–present), SPOT (Berthier et al. 2006), radar images from sensors on Seasat and InSAR images from ERS-1 (Magnússon et al. 2005), images from ASTER on Terra (Martinis et al. 2007), and surface elevation profiles from GLAS data on ICESat, etc., have been analyzed to provide information on fluctuations of termini, changes in area, and other glaciological parameters of Iceland’s glaciers.

Long-term datasets include quantitative measurements of the weather and climate of Iceland (since the late 19th century); repetitive mapping of Iceland’s glaciers (begun in southeast Iceland in 1903); field measurements of fluctuations of glacier termini (begun in 1930); determination of the thickness of Iceland’s ice caps by radio-echo sounding (begun in 1976); repetitive acquisition of aerial photographs (begun in the 1930s); acquisition of airborne thermal infrared imagery (1969); geodetic airborne laser altimetry surveys (1993) and in 2008–2013; and repetitive acquisition of satellite images (begun in 1972); as well as other sensor data from polar-orbiting satellites. All these datasets provide glaciologists with the opportunity to monitor changes in Iceland’s glaciers over time and to correlate changes in climate in Iceland with fluctuations of termini, area, and volume of Iceland’s glaciers during the past 80 years (since 1930), for more than 100 years in the case of the earliest modern maps (since 1903 for outlet glaciers of Vatnajökull in southeastern Iceland) (Jóhannesson et al., 1995; Sigurðsson and Jónsson, 1995; Jóhannesson, 1997; Jóhannesson and Sigurðsson, 1998). Many of the datasets are updated annually, so the correlation of climate change with fluctuations of Iceland’s glaciers will continue during the 21st century and beyond.

Since the turn of the century, the glaciers of Iceland are shrinking in area at an average rate of 0.3% a year. If the shrinkage in area (and volume) of Iceland’s glaciers continues at the same rate, Iceland is likely to become nearly completely deglaciated (except at the highest elevations) by 2200 (Jóhannesson et al. 2007).

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18.7 REFERENCES


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