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Contribution of Icelandic ice caps to sea level rise: Trends and variability since the Little Ice Age

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[1] In total, Icelandic ice caps contain ~ 3600 km³ of ice, which if melted would raise sea level by ~ 1 cm. Here, we present an overview of mass changes of Icelandic ice masses since the end of the 19th century. They have both gained and lost mass during this period. Changes in ice volume have been estimated both through surface mass balance measurements (performed annually since ~ 1990) and differencing of digital elevation models derived from various satellite and airborne observations. While the glaciers showed little mass loss as the 20th century began, losses increased rapidly after 1925, peaked in the 1930s and 1940s, and remained significant until the 1960s. After being near-zero or even positive during the 1980s and early 1990s, glacier mass budgets declined considerably, and have since the mid-1990s shown an average annual loss of 9.5 ± 1.5 Gt a⁻¹, contributing ~ 0.03 mm a⁻¹ to sea level rise. Since 1995 interannual variability in mass loss is high, ranging from 2.7 to 25.3 ± 1.5 Gt a⁻¹, corresponding to surface mass balances of -0.2 to -2.2 ± 0.15 m_{we} a⁻¹. This variability is driven by climate fluctuations and also by transient reduction of albedo due to volcanic eruptions. **Citation:** Björnsson, H., F. Pálsson, S. Gudmundsson, E. Magnússon, G. Adalgeirsdóttir, T. Jóhannesson, E. Berthier, O. Sigurdsson, and T. Thorsteinsson (2013), Contribution of Icelandic ice caps to sea level rise: Trends and variability since the Little Ice Age, *Geophys. Res. Lett.*, *40*, 1546–1550, doi:10.1002/grl.50278.

1. Introduction

[2] In response to climate warming, the world's small glaciers and ice caps have receded much during the 20th century. Their mass loss accounted for more than half of the land ice contribution to global-mean sea level rise [Meier *et al.*, 2007; Lemke *et al.*, 2007; Church *et al.*, 2011]. However, direct measurements of glacier changes are only available for relatively few glaciers, comprising only a small portion of the Earth's glacier cover. The estimation of the global loss of glacier mass is therefore hampered by having to extrapolate over unmeasured areas, using short, discontinuous data series [Arendt *et al.*, 2002; Braithwaite

and Raper, 2002; Kaser *et al.*, 2006; Oerlemans *et al.*, 2007; Hock *et al.*, 2009; Cogley, 2009; Berthier *et al.*, 2010; Radié and Hock, 2011]. Hence, more wide-ranging mass balance measurements and advanced models are called for to improve projections of the future behavior of ice sheets and glaciers.

[3] Our study adds a piece to the composite puzzle by summarizing available information on Icelandic glacier changes since the beginning of the 20th century. Our observations show both long-term trends and decadal fluctuations in climate and mass balance on glaciers in the middle of the North Atlantic Ocean. Home to Europe's largest nonpolar ice caps, Iceland is situated in the climatically sensitive boundary area between polar and midlatitude atmospheric circulation cells and at a confluence of warm and cold ocean currents (Figure 1). Iceland's glaciers are nourished by high precipitation along the storm tracks of intense cyclonic westerlies crossing the North Atlantic. Due to the warm Irminger Current, the climate is relatively mild and moist, with small seasonal variations in temperature. About 11% of Iceland, or 11,000 km², is covered by ice caps and mountain glaciers [Björnsson and Pálsson, 2008].

2. Post Little Ice Age Climate and Glacier Length Variations

[4] The maximum Holocene extent of glaciers in Iceland was reached near the close of the 19th century [Thorarinsson, 1940]. Glacier recession set in slowly beginning in the 1890s, sped up in the 1930s (after rapid warming starting in the early 1920s), and peaked in the late 1930s, simultaneously to a strong retreat of glaciers in South-East Greenland [Björk *et al.*, 2012]. Even though warming was accompanied by increased precipitation, concomitant with intensified cyclonic activity (Figures 2a and 2b), glaciers generally retreated rapidly during this period. In keeping with cooler summers from the early 1940s to the mid-1980s, rates of glacier recession gradually declined, and even almost ceased in the late 1960s. Towards the end of this time, when temperatures had become as cold as those prior to 1920, the glaciers had generally retreated by hundreds of meters since the 1890s, some even up to 3 km. For small valley glaciers with moderate elevation ranges, typical retreat rates for nonsurging glaciers in the period 1930 to 1960 and after 1995 were ~ 10 m a⁻¹ or less, whereas several of the south-flowing outlet glaciers of the Vatnajökull ice cap retreated by 50–100 m a⁻¹ during this period [Jóhannesson and Sigurdsson, 1998; Magnússon *et al.*, 2005]. Around 1970 and until 1995, an increasing number of nonsurging glaciers advanced, some by tens of meters to a few

All Supporting Information may be found in the online version of this article.

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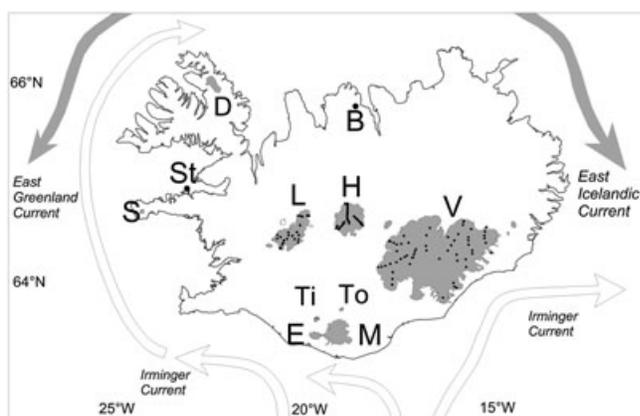


Figure 1. Map of Iceland (103,000 km²) with major ocean currents and distribution of glaciers: Drangajökull (D), Langjökull (L), Hofsjökull (H), Vatnajökull (V), Eyjafjallajökull (E) Mýrdalsjökull (M), Torfajökull (To), Tindfjallajökull (Ti), Snæfellsjökull (S). Location of Stykkishólmur meteorological station marked as St. Dots indicate locations of annual mass balance measurements (60 on Vatnajökull, 23 on Langjökull, 25 on Hofsjökull).

hundred meters in total, while others continued to retreat but at reduced rates. After 1985, the climate warmed again, especially after the mid-1990s (Figure 2a). After 2000, the mean annual temperature had become approximately 1.0 °C higher than in the mid-1990s which is 3 to 4 times higher than the northern hemisphere average warming over the same period [Jones *et al.*, 2012]. This greater warming appears to be linked to changes in atmospheric and oceanic circulation in the vicinity of Iceland, with ocean temperatures off the southern coast increasing rapidly from 7°C to 8°C in the mid-1990s (Figure 2c) [ICES Report on Ocean Climate, 2010], which may be related to a weakening of the North Atlantic subpolar gyre [Häkkinen and Rhines, 2004; Hátún *et al.*, 2005; Lohmann *et al.*, 2008; Bersch *et al.*, 2007; Robson *et al.*, 2012].

3. Estimates of Mass Balance from Topographic Maps and Field Measurements

[5] Changes in glacier volume have been estimated by subtracting surface elevation maps of the country, drawn at different times in the 20th century (Figure 2d) [Gudmundsson *et al.*, 2011; Pálsson *et al.*, 2012; Jóhannesson *et al.*, 2011, 2013]. While the average mass balance proved only slightly negative over the century's first three decades, it became more noticeably so in the 1930s (~ -1 m_{we} a⁻¹; expressed as meters of water equivalent averaged over the entire glacier area). From the mid-1940s to the 1980s, the mass balance gradually increased again, slowing nearly to zero in the 1980s. Some glaciers gained mass around 1990 but since the mid-1990s Icelandic glaciers have been losing mass at an accelerating rate. Similar decadal variations in glacier mass balance have been measured in the Swiss Alps [Huss *et al.*, 2010].

[6] Since the ~ 1990 s, an annual, comprehensive mass budget record has been maintained at several ice caps, based on snow probing and on stake measurements of snow thickness and snow/ice melting, as well as measurements of snow density at specific locations (Figure 1)

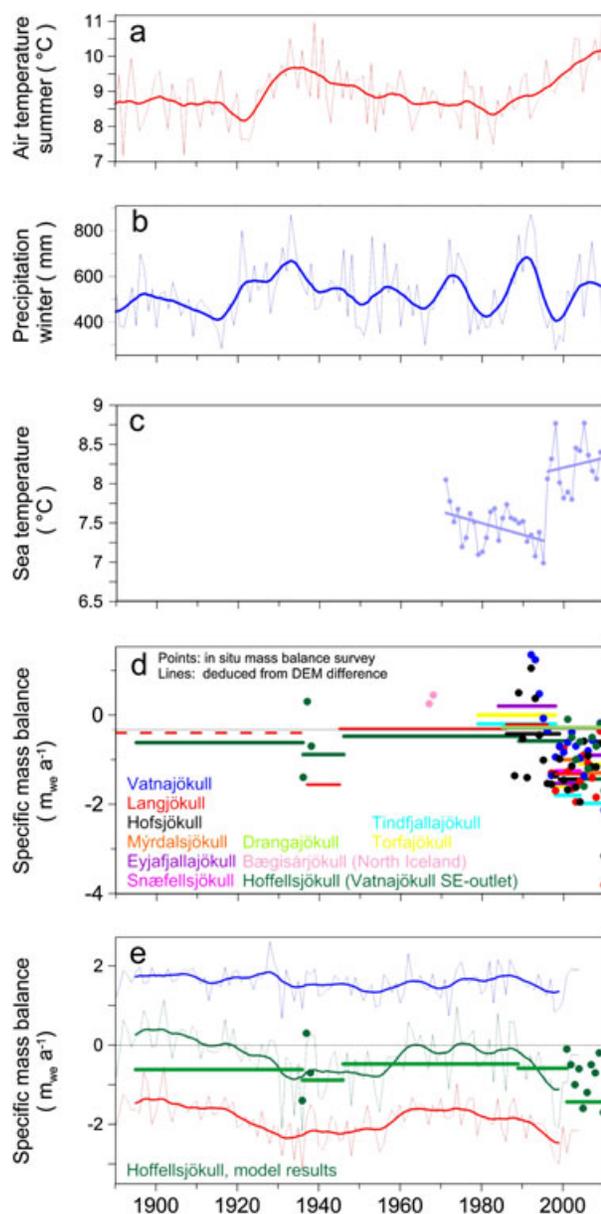


Figure 2. Records of climate and mass balance during the 20th century and the early 21st century. (a) Summer temperatures (June–September) and (b) winter precipitation (October–May) at the Icelandic Meteorological Institute's Stykkishólmur station. The time series are filtered using an 11 year triangular running average. (c) Ocean temperature at depths of 0–200 m off South Iceland (in Selvogsgrunnur) [ICES Report on Ocean Climate, 2010]. (d) Specific mass balance. Lines: Geodetic mass balance rates derived from glacier surface maps. Dots: Annual mass balance based on in situ stake measurements. Error limits for mass balance components are estimated to be ± 0.15 m_{we} a⁻¹. See tables and references in a Supplement. (e) Simulated evolution of the winter, summer, and annual mass balances of Hoffellsjökull (SE outlet of Vatnajökull) from 1890 to 2010. The trend of the modeled winter balance (1890 to 2010) is -0.015 m_{we} a⁻¹. The mass balance model was calibrated with annual field measurements over the last two decades. Horizontal lines: Geodetic mass balance derived from comparison of digital elevation models (DEM). Dots: Measured annual mass balance.

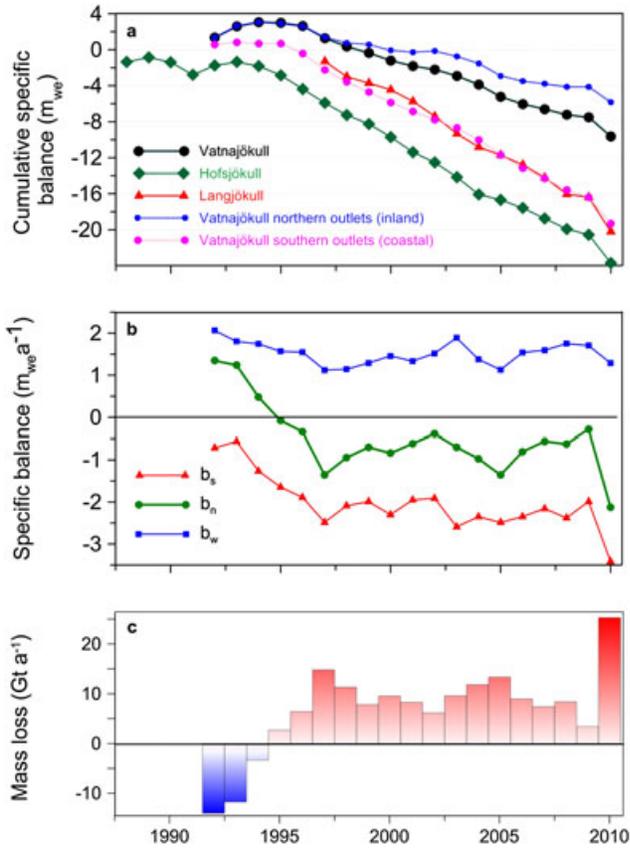


Figure 3. Cumulative specific balance, specific balance, and mass loss of Iceland's glaciers based on stake measurements. See tables and references in a Supplement. (a) Cumulative mass balance of Vatnajökull, Langjökull, and Hofsjökull, 1990–2010. Hofsjökull data have been bias-corrected with geodetic measurements here [Jóhannesson *et al.*, 2013]. (b) Specific mass balance of Vatnajökull, 1992–2010, given in meters of water equivalent ($m_{we} a^{-1}$) where b_w stands for winter balance, b_s summer balance, and b_n annual balance. The trend of the winter balance is $-0.16 m_{we} a^{-1}$ for the period 1992–1997, $0.03 m_{we} a^{-1}$ for the years 1997–2010, and $-0.01 m_{we} a^{-1}$ from 1992 to 2010. (c) Estimated annual mass loss of all of Iceland's glaciers, 1992–2010.

[Björnsson and Pálsson, 2008]. Consistent with the ice volume changes derived from topographic map differencing, the field mass balance measurements show that the Icelandic ice caps have lost mass every year since the mid-1990s (Figure 3a). For the period of 1995–2010, the cumulative mass loss averaged over the entire glacier area, was $13 m_{we}$ from Vatnajökull ($8 m_{we}$ from the inland outlets and $20 m_{we}$ from the maritime outlets), $22 m_{we}$ from Hofsjökull [Jóhannesson *et al.*, 2013] (Figure 3a). Because the subglacial topography is well-known [Björnsson and Pálsson, 2008], the relative change in ice volume can be estimated. Over this 16 year period, Vatnajökull lost 3.7% of its total ice mass and Hofsjökull 11%. For the period 1997–2010, the mass loss of Langjökull was $20 m_{we}$, as much as 11% of its total ice mass. A clear difference is evident in the mass balance sensitivity for glaciers in maritime and more continental climates (Figure 3a).

[7] Although the total mass loss differs between the three main Icelandic ice caps, their temporal changes in mass balance reveal similar characteristics. The annual net mass balance of Vatnajökull was positive from 1991 to 1994, close to zero for 1994–1995, and has remained negative since that time (Figure 3b). However, the net mass loss of Vatnajökull since 1995 has shown considerable annual variation from 2 to $17 \pm 1.5 Gt a^{-1}$ (-0.3 to $-2.1 \pm 0.15 m_{we} a^{-1}$ mean specific mass balance), with some inland outlets even having annual mass balance close to zero in some years.

4. Causes of the Multidecadal and Interannual Variations in Mass Balance

[8] The general mass loss reflects higher summer temperatures, longer melting seasons, warm winters reducing the proportion of precipitation falling as snow, and earlier exposure of low-albedo glacier ice in spring, due to thinner winter snow accumulation. The albedo may range from 0.8 in the brighter central regions of the ice caps to less than 0.1 in many ablation areas because of the melt-out of volcanic ash layers. Typically, radiation supplies two times more melt energy than the turbulent fluxes of sensible and latent heat [Björnsson, 1972; Oerlemans *et al.*, 1999; Gudmundsson *et al.*, 2009]. Due to high correlation of temperature with radiation, the ablation can be successfully described by positive degree-day models [e.g., Gudmundsson *et al.*, 2009]. The sensitivities of the ice caps' mass balance to climate warming have been calculated as -0.6 to $-3 m_{we}^{\circ} C^{-1}$ [Gudmundsson *et al.*, 2011; Pálsson *et al.*, 2012; Jóhannesson *et al.*, 2013] and are among the highest worldwide [Hock *et al.*, 2009].

[9] On closer inspection, fluctuations in mass balance are strongly related to spatial and temporal variations of albedo, which the degree-day models may fail to account for. In some years (i.e., 1993, 1994), summer ablation was abruptly reduced by snowfalls on melting surfaces. A summer snowstorm can reduce ablation for days or even weeks and lead to substantial differences. Surface albedo in the ablation area may be 0.1 to 0.3 before a snowfall and increase to 0.8 to 0.9 after.

[10] Large-scale deposition of volcanic tephra aerosols from several recent eruptions (Hekla in 1991, Gjalp in 1996, Eyjafjallajökull in 2010, and Grímsvötn in 2004 and 2011) increased radiative forcing of glacier melt. The largest mass loss in a single year (2009–2010) is due to the Eyjafjallajökull eruption (14 April to 22 May 2010), during which airborne tephra was deposited on all the major ice caps in Iceland [Gudmundsson *et al.*, 2012]. Surface albedo was considerably reduced, and shortwave radiation flux entering the glaciers increased significantly. On Langjökull ice cap, 100–150 km from the volcano, absorbed solar radiation increased by a factor of 2.5, from 45 to $115 W m^{-2}$ between 15 May and 15 September. The 2010 summer melting became $5.0 m_{we} a^{-1}$, calculated as a mean value over the entire ice cap, almost twice the mean (1997–2009) summer melting of $2.8 m_{we} a^{-1}$. At the end of summer 2010, the total accumulation over the three previous years had been melted away in the interior of the ice cap. For this year, there was no accumulation area on Langjökull; typically, it comprises 60% of the ice cap. During the winter 2010–2011, the 2010 ash was covered with snow and permanently buried in the accumulation area. However, in the ablation area, the albedo

of ice exposed in the summer of 2011 remained significantly lower than it had been during the pre-eruption period 1997–2009. Extra surface melt related to lower surface albedo following volcanic eruptions through the years 1995–2010 was about 20 Gt (of which ~ 15 Gt were due to the April 2010 eruption). This is 13% of the total glacier melt over the 16 year period.

[11] Occasionally, volcanic eruptions take place underneath Icelandic ice caps. Over the period 1995–2010, however, ice melted by subglacial eruptions only comprised 2% of the country's total ice melt. As an example, the englacial eruption in October 1996 (at Gjalp volcano) directly melted 4.0 Gt of ice, [Gudmundsson *et al.*, 1997; Björnsson and Pálsson, 2008]. This subglacial meltwater is drained out in jökulhlaups. Subglacial geothermal heat flow, including geothermal areas but excluding eruptions, may continuously melt 0.5 Gt a^{-1} altogether, i.e., less than 3% of the typical total glacier ablation [Björnsson, 2002].

[12] To extrapolate mass changes to all glaciers in Iceland, we apply the country-wide mean specific balance for the measured glaciers, which cover 90% of the total glacierized area. This results in an estimated total ice loss of $9.5 \pm 1.5 \text{ Gt a}^{-1}$ ($\sim 0.03 \text{ mm a}^{-1}$ sea level equivalent) since the mid-1990s, with individual years varying from 2.5 to $25 \pm 1.5 \text{ Gt a}^{-1}$ (Figure 3c). Second to the Greenland Ice Sheet and glaciers in the coastal areas of Greenland [Barletta *et al.*, 2012; Sasgen *et al.*, 2012], Icelandic ice caps supply at present the highest rate of glacier meltwater input to the North Atlantic, about twice the contribution from Svalbard [Nuth *et al.*, 2010], which again is twice that of Scandinavia [Andreassen *et al.*, 2005].

[13] The recent estimates of Icelandic ice losses ($11 \pm 2 \text{ Gt a}^{-1}$ from 2003 to 2010) from the Gravity Recovery and Climate Experiment (GRACE) satellite gravity field measurements [Jacob *et al.*, 2012] coincide with our findings ($11.0 \pm 1.5 \text{ Gt a}^{-1}$ for the same period). Due to limited spatial resolution, leakage from the much stronger South-East Greenland gravity signal, and other potential errors, it is not clear if GRACE results capture the annual variations or impacts of singular events (e.g., volcanic eruptions) revealed by our in situ measurements.

5. Modelling of Mass Balance

[14] In order to further analyze mass balance evolution from the late 19th century, we applied a coupled mass-balance-ice-flow model to the Hoffellsjökull outlet glacier in South-East Vatnajökull [Adalgeirsdóttir *et al.*, 2011]. The mass balance model is forced by daily mean temperature and precipitation records from nearby meteorological stations and calibrated with seasonal stake measurements of winter and summer mass balance [Jóhannesson, 1997]. The model was constrained with observed ice volume changes during the 20th century as well as available data on ice flow velocities. On Hoffellsjökull, the simulated winter, summer, and annual mass balances (Figure 2e) show variations in accord with the available records of measured mass balance (Figure 2d). Long-term mass balance declined gradually from 1900 to the 1930s, remained steadily negative until the 1950s, increased noticeably between 1955 and 1965, and thereafter remained only slightly negative until the early 1990s. Our analyses indicate that the net mass balance of Icelandic glaciers relates directly to fluctuations in

air temperature, rather than precipitation (Figures 2 and 3). The model calculation does not suggest any centennial-scale trends for the winter balance, despite considerable variation from year to year (Figure 2e). Work is underway to apply the coupled model to other glaciers in Iceland.

6. Conclusions

[15] Our observations show decadal variations of mass balance on glaciers in Iceland since the beginning of the 20th century: positive in the first two decades and in the 1980s to mid-1990, strongly negative in the 1930s and post-1995. Over the last 16 years, the mass loss of all Icelandic glaciers has been $9.5 \pm 1.5 \text{ Gt a}^{-1}$, contributing $\sim 0.03 \text{ mm a}^{-1}$ to sea level rise. However, some inland glacier outlets have occasionally experienced mass balances close to zero during this period. The observations raise the question as to whether such variations may be expected in the North Atlantic area in the coming decades, superimposed on the projected trend of increasingly negative glacier mass balance in the region. Our study reveals that the influence of volcanic eruptions can be strong over a single year following the eruption; but over multiple years, the climate fluctuations have the largest influence because the volcanic ash is transient at the glacier surface. It is rapidly covered by winter snow in the accumulation area and washed away by surface melt in the ablation area.

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