Reviewed research article

Mass and volume changes of Langjökull ice cap, Iceland, ∼1890 to 2009, deduced from old maps, satellite images and in situ mass balance measurements

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Abstract – *We describe the mass balance of Langjökull ice cap, Iceland, (∼920 km^2, ∼190 km^3) during several time intervals of different climate conditions that span the 20th century until present. The elevation range of Langjökull is 460–1440 m a.s.l. with a zero mass balance equilibrium line altitude (ELA) of 1000 m (southern outlets). The mass balance of the ice cap has been observed in situ every year since 1996–1997 and also assessed from estimation of glacier volume changes by comparing series of elevation maps from: 1937, 1945–1946, 1986, 1997 and 2004. The glacier margin of the Little Ice Age maximum (LIA; ∼1890) was estimated from the location of end moraines. The difference between the 1997–2004 annnual specific net balance estimated by volume change and in situ measurements is negligible (∼5 cm$_{we}$). During the two warm periods 1936–1946 and 1997–2009 the mean mass balance was similar; -1.6 and -1.3 m$_{we}$ yr^{-1}, respectively. The colder climate during 1946–1986 and cooler yet in 1986–1997 resulted in specific mass balance close to zero; -0.3 and -0.2 m$_{we}$ yr^{-1}, respectively.*

INTRODUCTION

At present about 11% of Iceland (103,000 km^2) is covered by glaciers (Figure 1; Björnsson and Pálsson, 2008). Icelandic ice caps are temperate, characterized by high annual mass turnover rate (1.5–3 m$_{we}$ yr^{-1}). They are highly sensitive to climate fluctuations and currently melting at a fast rate (e.g. Björnsson and Pálsson, 2008; Gudmundsson *et al.*, 2011). Iceland, an island in the North Atlantic Ocean, close to the Arctic Circle, enjoys a relatively mild and wet oceanic climate and small seasonal variations in air temperature due to the warm Irminger ocean current. 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; Björnsson and Pálsson, 2008). Along the northern coast, the climate is affected by the polar East Greenland Current, which occasionally brings sea ice. Heavy snowfall is frequently induced by cyclones crossing the North Atlantic, where air and water masses of tropical and arctic origins meet.

Langjökull (∼920 km^2, ∼190 km^3) is the second largest ice cap in Iceland, located in the mid west of the island (Figure 1). The two largest outlets of Langjökull surge at an interval of ∼10–20 years (Björnsson *et al.*, 2003a), and there are indications

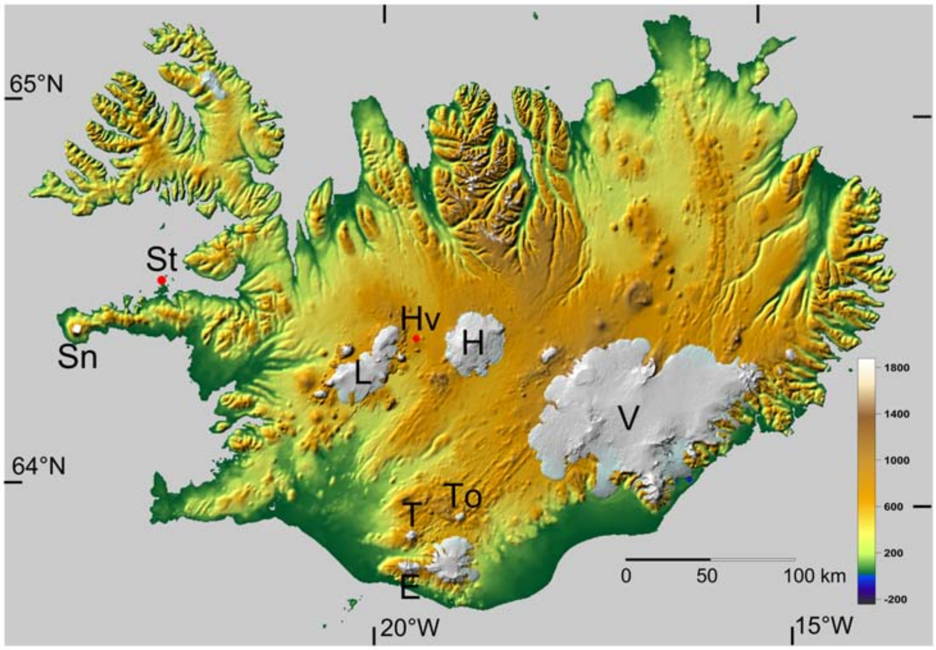

Figure 1. Location of Langjökull (L), Hofsjökull (H), Eyjafjallajökull (E), Vatnajökull (V), Snæfellsjökull (Sn), Tindfjallajökull (T) and Torfajökull (To) ice caps, Iceland. Stykkishólmur (St) and Hveravellir (Hv) are locations of meteorological stations. – *Íslandskort sem sýnir legu helstu jökla og tveggja veðurstöðva (St: Stykkishólmur, Hv: Hveravellir).*

that some of the other outlets may also surge (Palmer *et al.*, 2009). Due to the low lying surface elevation span, and distribution of surface area with elevation (large areas close to typical ELA), (Figure 2), Langjökull is more sensitive to climatic variation than the higher elevated Vatnajökull ice cap (8100 km^2; 50–2110 m elevation span) and Hofsjökull ice cap (900 km^2; 500–1800 m) (Aðalgeirsdóttir *et al.*, 2006; Gudmundsson *et al.*, 2009a; Figure 1).

In April/May 1997 the bedrock and surface topography of Langjökull was mapped by radio echo sounding and DGPS surveys along profiles approximately 1 km apart (Figures 2 and 3). The surface mass balance and velocity has been measured at 22–23 sites each year since 1997 and glacio-meteorological observations were initiated in 2001 (Figure 4a; Björnsson *et al.*, 2002; Gudmundsson *et al.*, 2009b). This data has been used to calibrate models to predict the past evolution and future outlook of the glacier (Flowers *et al.*, 2007, Gudmundsson *et al.*, 2009a; 2009b). In addition to the 1997 surface map, three surface maps exist based on measurements in 1937, 1945 and 1986, and a surface map constructed using stereo image pairs, acquired on 12, 14, 17 and 19 August 2004 with the optical HRG sensor onboard the SPOT5 satellite (Berthier *et al.*, 2004, 2006). Furthermore, the margin of the Little Ice Age maximum extent (∼1890) was mapped and area-volume scaling method used to estimate the corresponding ice volume.

In this paper, we explain the methods we use to construct the 1997 and 2004 maps of the glacier and how those maps, along with DGPS and kinematic GPS observations on and around the glacier, are used to improve the accuracy of older maps. We describe the mass balance based on annual *in situ* measurements, the long term net balance variation from volume changes deduced from the existing surface maps, as well as the mass balance sensitivity to both summer and annual temperature variations.

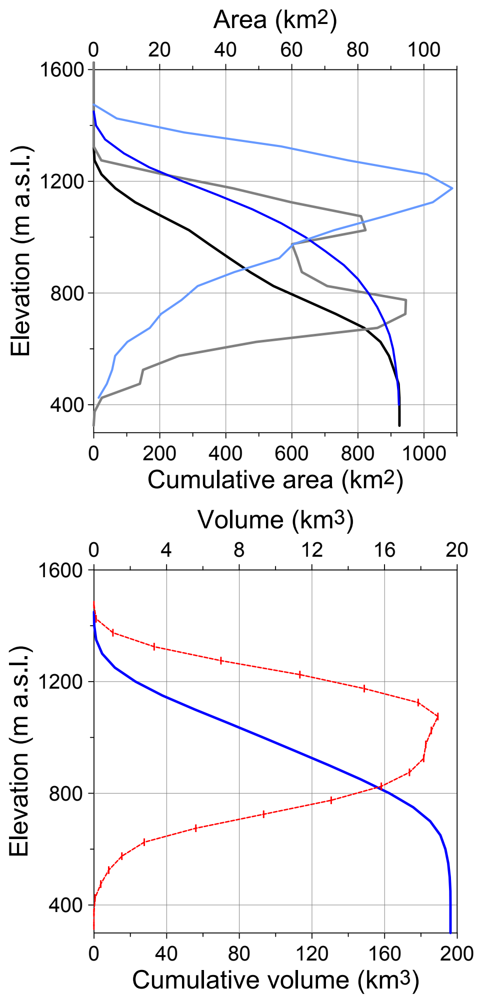

Figure 2. Langjökull 1997: Upper graph: Surface (light blue) and bedrock (grey) area distribution (50 m elevation steps), and cumulative area (black, dark blue). Lower graph: Volume distribution by elevation (50 m slices) (red), and cumulative ice volume (blue). – *Langjökull: Dreifing og uppsafnað flatarmál botns og yfirborðs (efri mynd) og rúmmál íss (neðri mynd) með hæð.*

DATA AND METHODS

In situ mass balance measurements

The mass balance of Langjökull has been measured using a stratigraphic method; changes in thickness and density are measured relative to the summer surface (e.g. Paterson, 1994; Björnsson *et al.*, 2003b). The survey sites are situated along a number of approximate flow lines that cover the elevation range of the ice cap, selected to describe the spatial variability (Figure 4a). The mass balance values span the time interval between given survey dates, which are not fixed annually. The dates in the autumn are separated by approximately one calendar year, which roughly coincides with the hydrological year between October 1 and September 30. The surveys in the spring were carried out between late-April and mid-May.

Digital winter and summer mass balance grids (Figures 4b-d) are produced by manually interpolating between the observed balance values. Mass balance contour lines are hand-drawn, digitized and a matrix of grid cells (200x200 m) calculated using kriging interpolation. Volumes are calculated by integrating over the digital maps. Error limits for the area integrals of the mass balance are cautiously assigned as 5–15%.

Surface maps; construction and evaluation

In the bedrock radio echo sounding campaign of Langjökull in 1997, the surface was also surveyed with differential GPS along profiles about 1 km apart (Figure 3); on average there are 10 m between points along the profiles, a data redundancy that allows low pass filtering along the profile to reduce random noise. GPS base data for post-processing were collected at the base camps (the first at the top of the ice cap's northern dome, the second 3 km south of the southern dome summit; distance between base and rover from 0 to ~25 km. The base stations were tied to several permanent GPS stations. The point vertical accuracy is estimated ~1–3 m, mostly random noise; statistical analysis of ~200 profile crossover points yields standard deviation of 1.06 m. A surface DEM was constructed from this data (Figure 3), with an average elevation accuracy estimated <2 m. This is the first surveyed map of the ice cap above 1100 m elevation.

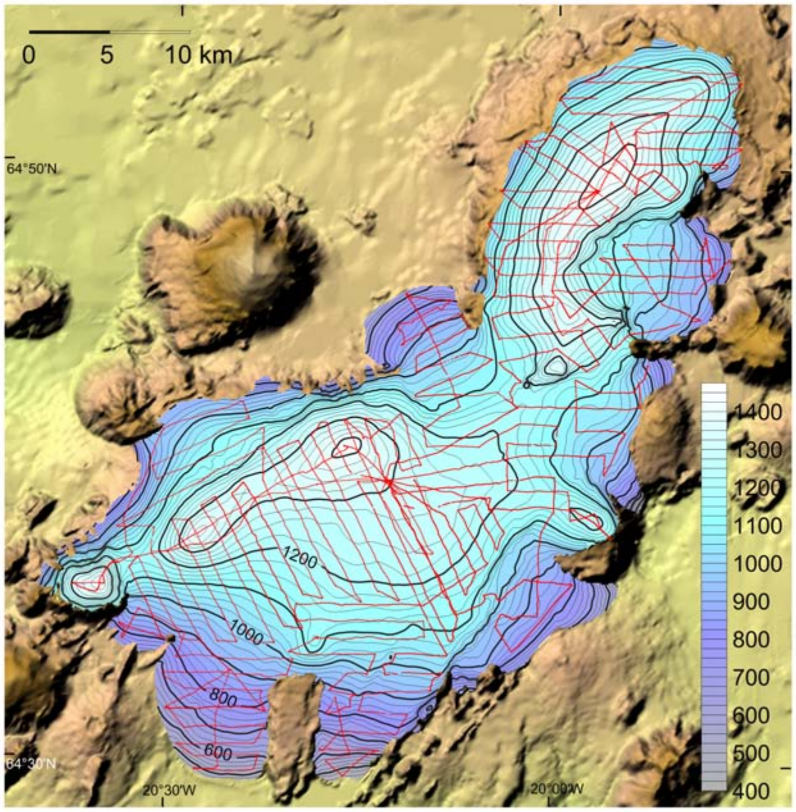

Figure 3. The surface of Langjökull based on April 1997 DGPS survey data (25 m contour lines). Survey lines of DGPS and RES profiles are shown in red. – *Kort af yfirborðshæð Langjökuls eftir GPS hæðarmælingum á íssjármælisniðum frá 1997. Rauðar línur sýna legu mælisniðanna.*

Three DEMs were constructed from four 5x5 m pixel resolution SPOT5 HRG images acquired from 12, 14, 17 and 19 August 2004, using the PCI Geomatica software (Toutin, 2006); the images of the dates 12/14, 14/17 and 17/19 as stereo pairs. None of the DEMs covered the whole glacier, but by combining them one complete DEM could be compiled (Figure 5). A collection of ground control points (GCPs) such as crossroads, a road crossing a river (i.e. items recognized on the SPOT5 images) were surveyed by static or kinematic GPS (red triangles in Figure 5). Profiles along tracks and roads were surveyed by kinematic GPS. Some of the GCPs were used as input to Geomatica to calibrate the SPOT5 satellite model, together with carefully chosen tie-points recognized on the both images of each stereo pair used to extract the DEMs. The profiles, GCPs and 22 GPS surveyed sites on the glacier surface were then used to evaluate the resulting complete 2004 DEM (the final product), yielding an accuracy of $\sim$1 m in elevation.

Three published maps exist for Langjökull, all with 20 m contour lines: from 1937 (Geodetic Institute, Copenhagen), 1945 (AMS series C762, mapped by the Army Map Service, Corps of engineers, U.S. Army, Washington D.C.) and 1986 (DMA series C761 produced by the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC), Washington DC). The 1986 and 1945 maps are derived by standard aerial photographic methods and the 1937 map from trigonometric geodetic survey and oblique photographs. All the maps include only estimated contour lines (indicating shape or form, not actual con-

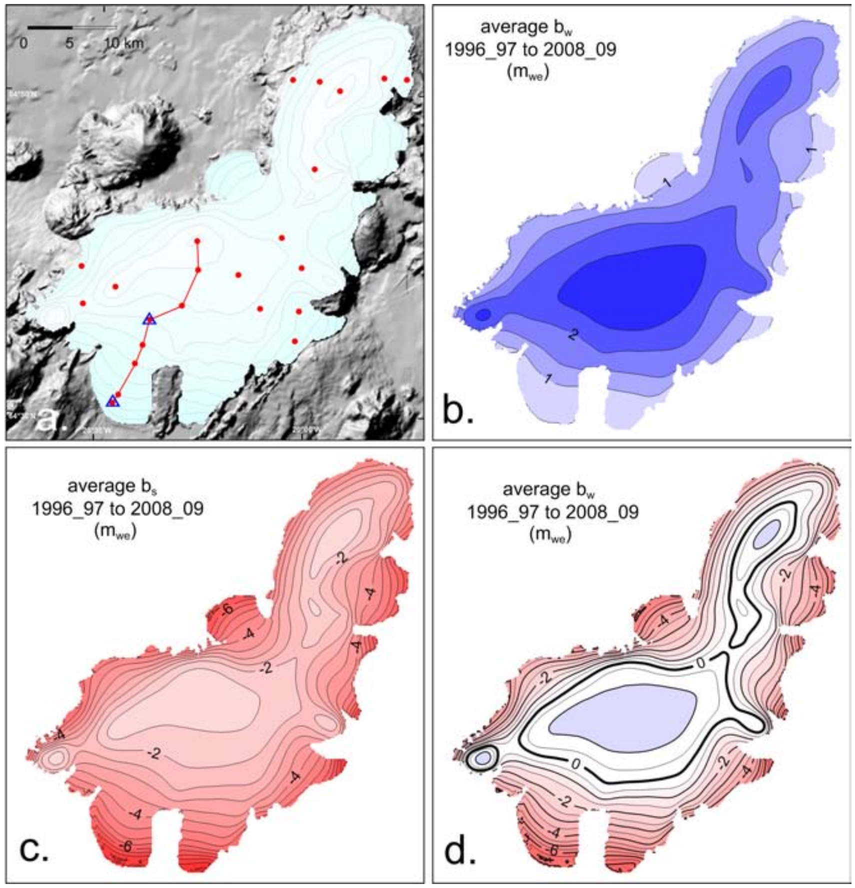

Figure 4. Location of the 23 mass balance sites on Langjökull and the two AWS's (blue triangles), the red line is an approximate central flow line down W-Hagafellsjökull outlet. b-d) Maps of the average winter- (b_w), summer- (b_s) and net balance (b_n) 1996–1997 to 2008–2009. – *a) Lega 23 afkomumælistaða (punktar) og tveggja sjálfvirkra veðurstöðva á Langjökli (þríhyrningar). b-c) Kort sem sýna meðal vetrar-, sumar- og ársafkomu Langjökuls jökulárin 1996–1997 til 2008–2009.*

tour lines of elevation) for elevations above ~1100 m. Considerable differences in the shape and elevation of the accumulation zone were revealed when comparing those maps to the 1997 and 2004 DEMs (a difference of over 100 m at the north-dome summit). Comparison of the maps and the 2004 DEM, however, indicates the contour lines to be fairly accurate below 1100 m elevation.

In a joint effort by the U.S. Army and Iceland's Energy Authority, an elevation of 10 points in the upper part of Langjökull was surveyed in the summer of 1985 using an inertia positioning system in a gravity survey campaign (accuracy ~1 m). The elevation of these points and the shape of the contours of the 1997 and 2004 DEMs, were used to control the reconstruction of the upper part of Langjökull in 1986, i.e. by assuming only small changes in the shape of the upper glacier. The lower part was based on digitized contour lines and co-registration with the 2004 DEM to correct for lateral shifts. The accuracy of the reconstructed 1986 DEM is estimated <5 m, vertically.

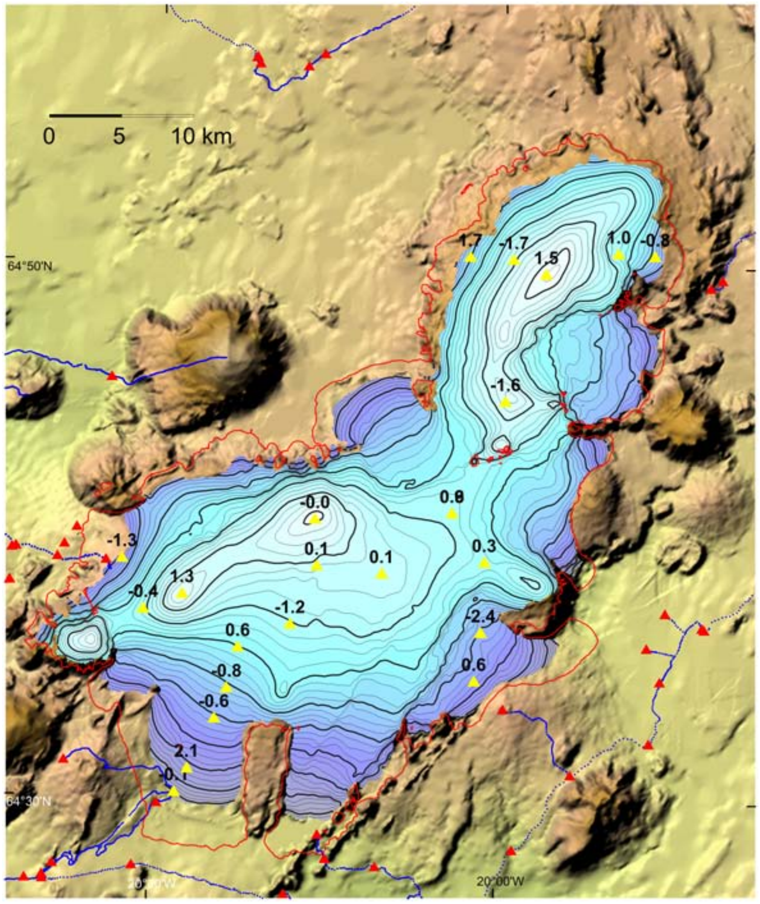

Figure 5. The surface of Langjökull constructed from SPOT5 HRG stereo image pairs (acquired on August 12th, 14th, 17th and 19th 2004). The red triangles are static or kinematic GPS surveyed control points, the blue lines kinematic GPS profiles. The yellow triangles are sites on the glacier surface surveyed in October 2004 with DGPS. The numbers are the residue between the DEM and GPS surveyed elevation. The LIA$_{max}$ outline is shown in red. – *Yfirborð Langjökuls reiknað út frá þrívíddar-myndpörum sem tekin voru með SPOT5 gervitunglinu dagana 12., 14., 17. og 19. ágúst 2004. Lega jökuljaðars við lok litlu ísaldar (um 1890) er sýnd með rauðri línu.*

The older maps (1937 and 1945) were somewhat distorted laterally, due to errors in the old trigonometric network for Iceland, used as the original reference (surveyed by the Danish Geodetic Institute in 1904–1937). To overcome this, the maps were scanned and the contour lines digitized. During the digitizing process, the maps were shifted locally using the 2004 DEM as a reference, and the rugged landforms at the glacier margin and nunataks as controls. The upper parts of both maps were reconstructed, based on the 1997 map. We assumed only small changes in the landforms (shape of contour lines) and that the elevation difference to decay linearly over the accumulation zone. The elevation difference at the highest peaks was estimated from model run, applying the coupled ice-flow mass balance model given in Gudmundsson *et al.* (2009a). This yielded in only a few metres elevation difference at the highest ridges. The above assumptions are in good agreement with the elevation difference obtained between both the 1986 and 1997 DEMs, and 1997 and 2004 DEMs at the highest areas of the glacier. Furthermore, the uncertainty due to this 'ad hoc' method yields only minor errors in total volume change estimates as the elevation changes in the lower regions are by far larger. Comparison of the elevation maps at mountain tops and other prominent features did not suggest significant vertical shift. We assume the accuracy of the 1945 DEM to be ~5 m and ~7 m for the 1937 map. We believe, however, that the average vertical bias is much smaller, less than a few metres in all the reconstructed maps. In error estimates of volume change based on DEM difference we assume possible bias as half of the random error.

Mapping of the LIA maximum margin

The LIA maximum extent of Langjökull was delineated from geomorphological field evidence such as lateral or terminal moraines, ice cored hummocky moraines, fluted terrain and trimlines and mapped from high resolution aerial photographs using remote sensing software ArcGis. Historical documents, maps and photographs from the 19th century to the early 20th century, along with field observations, detailed oblique and aerial photographs support the estimated LIA maximum extent (e.g. Wright, 1935; Sigbjarnarson, 1967; Geirsdóttir *et al.*, 2009; Kirkbride and Dugmore, 2006; Larsen *et al.*, 2010)

Meteorological observations

In this study we primarily investigate the sensitivity of the mass balance to temperature changes, using data from the meteorological station Hveravellir in central Iceland (location in Figure 1). The meteorological data from Hveravellir reach back to the year 1966. Hence, this data is supplemented with observations from a meteorological station at Stykkishólmur in W-Iceland (the longest temperature record in Iceland, reaching back to the year 1822; location in Figure 1, e.g. Sigurðsson and Jónsson, 1995; Hanna *et al.*, 2004). The climate record from Stykkishólmur is however damped due to the proximity to the ocean, while the station at Hveravellir reflects inland temperatures (Björnsson *et al.*, 2005).

RESULTS AND DISCUSSION

Mass balance from in situ observations

The average measured 1996–1997 to 2008–2009 mass balance at sites along an approximate central flow line down a south outlet of Langjökull is shown in Figure 6. The winter and summer balance is highly variable; the standard deviation of measured balance at each survey site is between 0.25 and 0.70 m_{we} yr^{-1} for both the winter and the summer balance, higher in the accumulation zone for the winter balance and in the ablation area for the summer balance. The b_w gradient (db_w/dz) is roughly linear by 0.4 m_{we} yr^{-1} per 100 m in elevation until reaching the highest peaks where some of the winter snow is blown off. The overall summer balance gradient (db_s/dz) is ~0.7 m_{we} yr^{-1} per 100 m in elevation, somewhat higher in the lowest part and significantly lower in the upper accumulation area; the gradient is mostly controlled by the surface albedo (Gudmundsson *et al.*, 2009b). The net balance has a gradient (almost linear) of 1.1 m_{we} yr^{-1} per 100 m in elevation (the deviating net balance at the highest elevation is excluded). The average ELA of 1996–1997 to 2008–2009 is ~1090 m on Langjökull southern dome, but about 1300 m on the north dome (Figures 4d and 7). In Figure 7, the zero net balance contour of the 2008–2009 b_n-grid mostly coincides with the dark/light boundary of an ENVISAT image from 20 October 2009. The dark/light boundary is interpreted as the boundary between ice or old firn and the last winter snow residue.

The specific winter-, summer- and net balances have varied between 1.1 and 2.1 (mean 1.74, std. dev. 0.33), -2.1 and -4.0 (mean -3.00, std. dev. 0.55), -0.4 and -1.9 (mean -1.26, std. dev. 0.48) in m_{we} yr^{-1}, respectively, from 1996–1997 to 2008–2009 (Table 1; Figure 8). During these 13 years, the net balance has always been negative and the total cumulative mass loss 16.4 m_{we} yr^{-1} (Figure 9). Hence, the glacier has lost 8.6% of its mass during this 13 year survey period. Scatter plots, demonstrating the relationship of b_n to both b_w and b_s (Figure 10), indicate the zero mass balance turnover b_{0-bal} (b_w = -b_s) for the current topography of Langjökull to be ~1.8 m_{we} yr^{-1}. The average winter balance has been 1.73 m_{we} yr^{-1} or 96% of b_{0-bal} while the summer balance average is

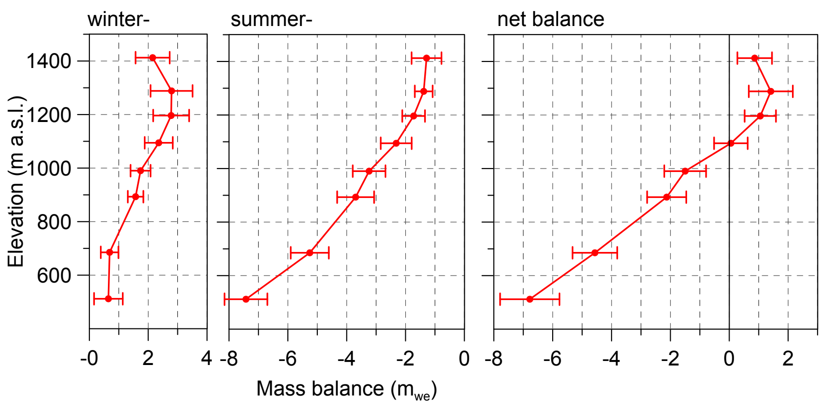

Figure 6. The average measured mass balance 1996–1997 to 2008–2009 at sites on an approximate central flow line on south Langjökull (Figure 4a). The horizontal bars indicate the standard deviation of measured balance at each site over the survey period. – *Meðalafkoma Langjökuls jökulárin 1996–1997 til 2008–2009 í mælipunktum á hæðarsniði upp Vestari-Hagafellsjökul.*

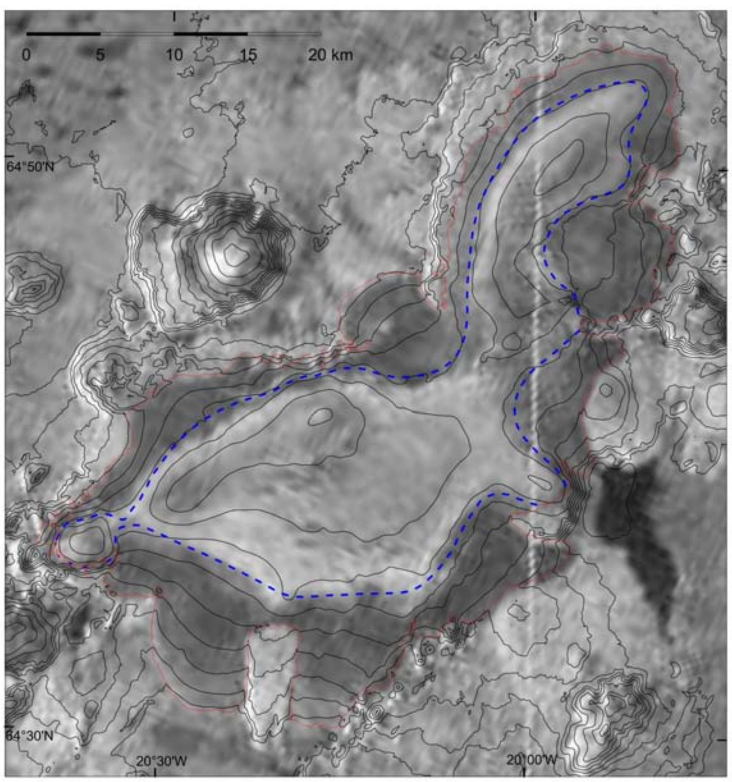

Figure 7. ENVISAT radar image of Langjökull of October 20th 2009 (100 m surface contour lines are shown in black). The blue line is the zero net balance contour from the 2008–2009 net balance digital map, deduced from mass balance survey. – *Ratsjármynd tekin með ENVISAT gervitunglinu 20. október 2009. Blá lína sýnir hjarnmörk jökulársins 2008–2009, metna eftir afkomumælingum.*

Table 1. Specific winter (b_w), summer (b_s) and net balance (b_n) for Langjökull. A conservative error estimate is on the order of 15% for both b_w and b_s. – *Meðal vetrar-, sumar- og ársafkoma Langjökuls.*

Year	b_w (m yr^{-1}) (w.e.)	b_s (m yr^{-1}) (w.e.)	b_n (m yr^{-1}) (w.e.)
1996–1997	1.9	-3.2	-1.3
1997–1998	1.12	-2.82	-1.7
1998–1999	1.39	-2.11	-0.71
1999–2000	2.13	-2.88	-0.75
2000–2001	1.28	-2.55	-1.27
2001–2002	1.57	-3.22	-1.66
2002–2003	2.11	-4.05	-1.95
2003–2004	1.79	-3.28	-1.49
2004–2005	1.62	-2.51	-0.89
2005–2006	2	-3.08	-1.08
2006–2007	1.65	-3.06	-1.41
2007–2008	2	-3.84	-1.84
2008–2009	2.02	-2.39	-0.36

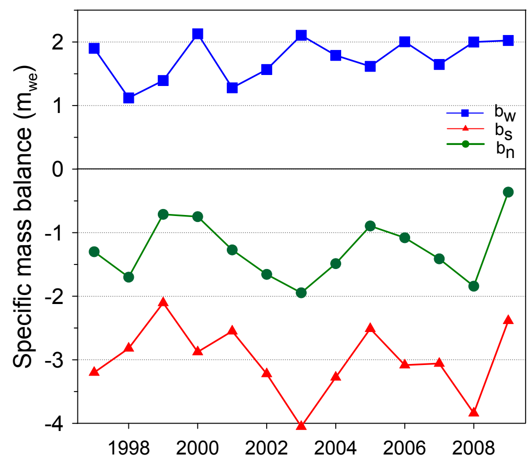

Figure 8. Langjökull mass balance record: winter- (b_w), summer- (b_s) and net- (b_n) specific balance. – *Mæld meðal vetrar-, sumar og ársafkoma Langjökuls.*

-3.0 m_{we} yr^{-1}, or 1.7 times b_{0-bal}; the negative balance of those 13 years is due to extreme summer ablation. Scatter plots of b_n against equilibrium line altitude (ELA) and accumulation area ratio (AAR) (Figure 11) suggest zero mass balance ELA at ∼1000 m on the southern dome and ∼1200 m on the northern dome, and a zero mass balance AAR of 56% (intersection between the straight line and zero b_n in Figure 11); AAR has however varied between 20 to 45% from the years 1996–1997 to 2008–2009.

In this paper we do not include the mass balance survey results for 2009–2010 and 2010–2011, both years the summer melting was greatly enhanced (∼threefold in 2010) by tephra spread over the glacier surface from eruptions, in Eyjafjallajökull in April 2010 and Grímsvötn (center of Vatnajökull) in May 2011. Hence, both those years are outliers and beyond the scope of the present study. The winter precipitation at Hveravellir and the winter balance of Langjökull are correlated (in spite of high scatter), and the summer balance is strongly correlated to the average summer temperatures (Figure 12).

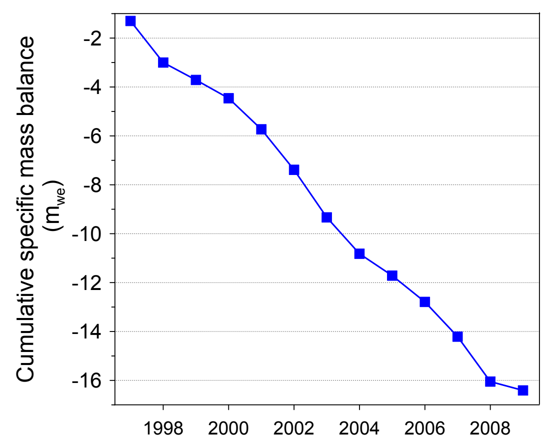

Figure 9. Langjökull cumulative mass balance 1996–1997 to 2008–2009. – *Uppsöfnuð afkoma Langjökuls jökulárin 1996–1997 til 2008–2009.*

Mass balance and volume changes from differential DEMs

When volume change is used to estimate mass balance (especially over short time spans) care must be taken to calculate the estimates over a number of glacier years (i.e. from autumn to autumn). The different specific density of the volume gained or lost (ice, snow

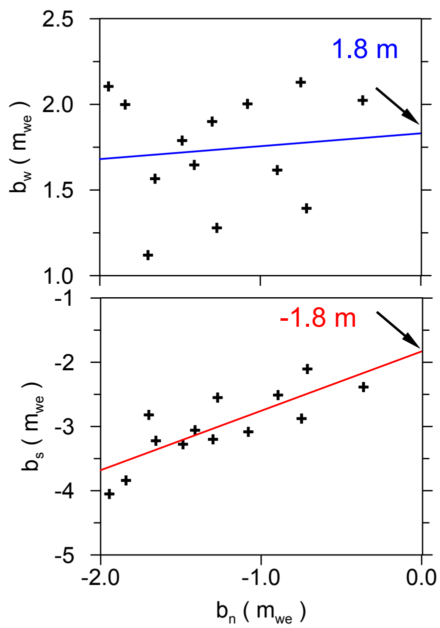

Figure 10. Langjökull: measured bn plotted against b_s and b_w both suggest zero balance turnover of 1.8 m_{we}. – *Samband ársafkomu við sumar- og vetrarafkomu. Það bendir til að jökullinn yrði í massajafnvægi við vetrarákomu og sumarleysingu sem næmi 1.8 m að vatnsgildi.*

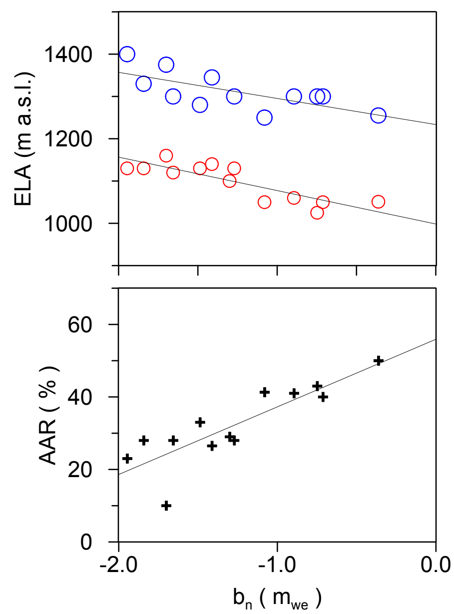

Figure 11. Langjökull: measured b_n plotted against ELA (red on the south mass balance profile, blue - western profile on the north dome) and AAR. – *Vensl ársafkomu og hæðar hjarnmarka hvers árs (efri) og hlutfalls safnsvæðis af heildarflatarmáli (neðri).*

firn) must also be considered. Over long periods of mass loss, most of the mass lost is ice and hence the specific density can be assumed 900 kg m^{-3}.

The volume change of Langjökull from autumn 1997 to autumn 2004 was calculated by integrating over the elevation difference of the surface DEMs of spring 1997 and autumn 2004 (Figure 13), correcting for the summer balance of 1997 (-2.98 $km^3{}_{we}$), yields the total volume difference 8.5 $km^3{}_{we}$. The mass loss by summing the annual mass balance DEMs (derived by *in situ* field measurements) yields 8.8 $km^3{}_{we}$. The difference between the two estimates is only in total 0.3 $km^3{}_{we}$ or $\sim$0.05 m_{we} yr^{-1} (in terms of specific balance), two orders of magnitude less than the zero mass balance turnover ($\sim$1.8 m_{we} yr^{-1}). Considering our estimate of 15% accuracy in the mass measurements the agreement is remarkable, and indicates that the methodology used to create the mass balance maps from the *in situ* measurements is random for each year rather than creating a bias.

The glacier area and ice volume estimates, derived from available surface maps, are given in Table 2 and Figure 14. The glacier area extent has decreased from $\sim$1029 km^2 in 1937 to 906 km^2 in 2004 ($\sim$12%) and the corresponding volume from 229 km^3 to 188 km^3 ($\sim$18%). According to our observation, the LIA maximum area extent was 1093 km^2. Area-volume scaling relationship of $V = cA^\gamma$ has been suggested by Bahr (1997). The observed volume change of Langjökull during the study period (1937–2004) is however too small compared to the present ice volume, to quantify the equation coefficients. Furthermore, the coefficients are extremely sensitive to only small (or negligible) changes in our data. Over a narrow band of

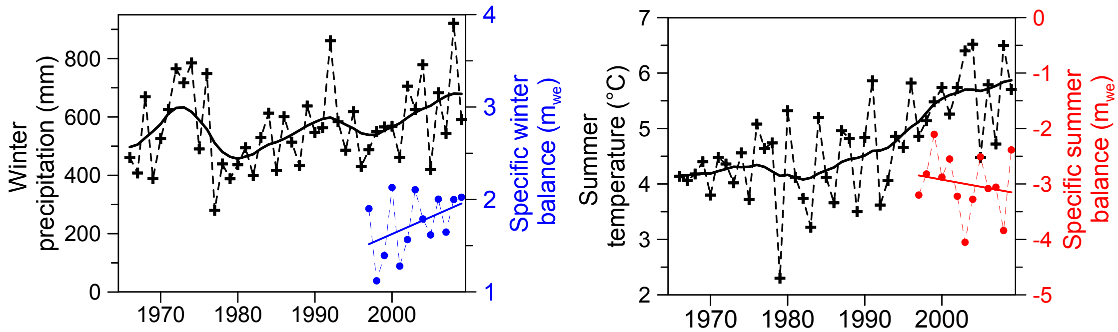

Figure 12. a) Variation of the measured specific winter mass balance of Langjökull 1996–1997 to 2008–2009, and winter prcipitation since 1966. b) Variation of the specific summer balance of Langjökull 1996–1997 to 2008–2009 and summer temperture since 1966. Linear trends in b_w and b_s are shown. The temperature and precipitation data are from a meteorological station Hveravellir ∼10 km east of Langjökull. (The precipitation and temperature trends shown are from 11 year running averages with triangular weight, 5 year filter). – *Vetrarafkoma Langjökuls og vetrarúrkoma á Hveravöllum (vinstri) og sumarafkoma Langjökuls og meðalsumarhiti á Hveravöllum (hægri).*

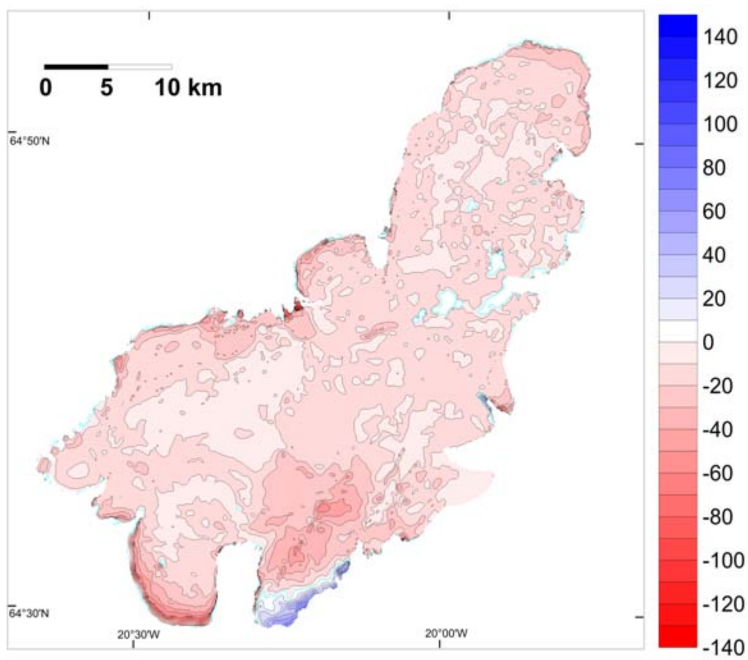

Figure 13. The change in surface elevation from April 1997 to August 2004 (10 m contour lines). The thickening of the terminus of the southeast outlet is due to a surge in 1998–1999 (Björnsson *et al.*, 2003). – *Hæðarbreytingar á Langjökli frá apríl 1997 til ágúst 2004. Þykknun neðst á Eystri-Hagafellsjökli er vegna framhlaups jökulsins 1998 til 1999.*

Table 2. Volume (km^3) and area (km^2) estimated from available maps. All the numbers correspond to the autumn. The ~1890 LIA$_{max}$ volume is predicted (see Figure 14).– *Vensl flatarmáls og rúmmáls jökulíss í Langjökli. Gögn frá tímabilinu 1937–2004 eru notuð til að áætla rúmmál um 1890 eftir að flatarmál var metið út frá ystu stöðu jökulsins við lok litlu ísaldar.*

Year	LIA$_{max}$	1937	1945	1986	1997	2004
V (km^3 ice)	248	229 ± 3.5	215 ± 2.5	202 ± 2.5	198 ± 1	188 ± 1
A (km^2)	1093 ± 20	1029 ± 15	991 ± 5	937 ± 15	924 ± 15	906 ± 2

volume change the equation results in an approximate linear segment (Figure 14), yielding a LIA maximum volume of Langjökull of 248 km^3 (Table 2).

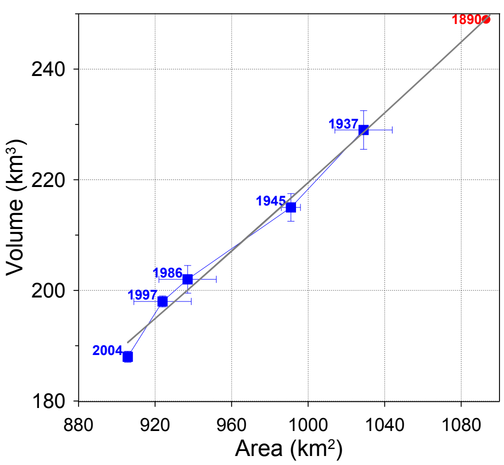

Figure 14. Scatter plot of volume and area (from Table 2). The volume for 1890 is predicted from LIA$_{max}$ area. – *Vensl flatarmáls og rúmmáls jökulíss í Langjökli. Gögn frá tímabilinu 1937–2004 eru notuð til að áætla rúmmál um 1890 eftir að flatarmál var metið út frá ystu stöðu jökulsins við lok litlu ísaldar.*

Relationship with climate fluctuations

The observed volume reduction of Langjökull and the average mass balance deduced from the volume change are compared to the annual mean temperature and precipitation at Stykkishólmur and Hveravellir (Figure 15; Table 3). The mass balance estimates are in accord with the annual mean temperature at Stykkishólmur averaged over the same time intervals (Table 3a, c; correlation r = 0.90). The relationship obtained between the average mass balance and the total precipitation is much less (r = 0.36). The first 40 years (from LIA$_{max}$ to 1937) can be roughly divided into three climatic intervals: 1890–1920 slightly warmer (~0.3°C at Stykkishólmur) than the latter half of the 19th century (1860–1890), warming up from 1920 to 1925 (by ~1.5°C at Stykkishólmur), staying there to 1937 (in fact to ~1960). Hence from inspection of Figure 14b and c, we suggest that the mass balance was close to zero from 1890 to the first years of the 1920s. The mass balance estimate between 1937 and 1945 is most likely representative for most of the time up to ~1960 (however, little less negative than the 1937 to 1945 average). It is known that during the cold period of the mid-1960s, the fronts of many outlets of the ice caps in Iceland were at a standstill or advanced slightly (measurements of the Iceland Glaciological Society since the 1930s, semi-annual reports in the society journal, *Jökull*). In the 1980s and into the 1990s the mass balance was close to zero for the major ice caps in Iceland (e.g. Gudmundsson *et al.*, 2009a, 2011; Adalgeirsdóttir *et al.*, 2006, 2011). Currently Langjökull is losing mass at a fast rate (Table 1; Figures 8, 9 and 15). This is consistent with the warming in Iceland that has taken place since mid 1990s (Figure 15; Björnsson *et al.*, 2005; Jóhannesson *et al.*, 2007).

The mass balance sensitivity to temperature is calculated for different time intervals (Table 4), using both annual averages as well as summer averages of temperature from Stykkishólmur and Hveravellir. Although the estimates are quite variable, the general conclusion is that the sensitivity is close to -2 m$_{we}$ yr^{-1}K^{-1} for the coastal station and -1 m$_{we}$ yr^{-1} K^{-1} for the inland station in both cases, slightly higher for

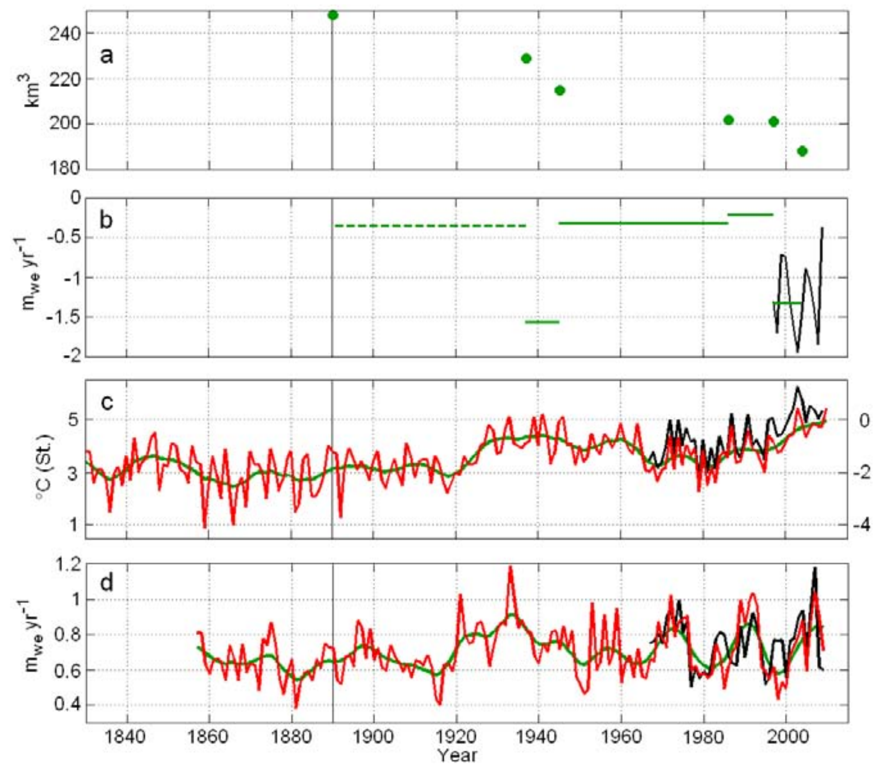

Figure 15. a) Ice volume (see Table 2). b) Mass balance of Langjökull deduced from available DEMs (green) and in situ observations (black). The dashed line is calculated assuming the predicted volume for LIA$_{max}$ and the 1937 volume of the ice cap. c-d) Annual temperature and precipitation, respectively, at Hveravellir (black) in mid-central Iceland and Stykkishólmur (red) in west-Iceland; location in Figure 1. The vertical line shows the year 1890 (appr. LIA$_{max}$). (The precipitation and temperature trends shown are from 11 year running averages with triangular weight, 5 year filter). – *Langjökull: Rúmmál jökulíss (a), meðalafkoma (b) á ýmsum tímabilum frá lokum litlu ísaldar til nútíðar metin út frá mismuni yfirborðskorta og afkomumælingum, ásamt hita- (c) og úrkomumælingum (d) í Stykkishólmi (rautt) og á Hveravöllum (svart).*

Table 3. Average specific net balance (b$_n$), at Langjökull, estimated from i) the mean difference between available elevation maps (dDEM) and ii) the surface mass balance in Table 1 (SMB). b-c) Corresponding temperature (T) and precipitation (P) at Hv and St, averaged over the same time intervals as b$_n$. Locations are in Figure 1. – *Meðalafkoma Langjökuls, 1937 til 2009, metin út frá mismuni hæðarkorta og afkomumælingum á jökli. Einnig er sýndur meðalhiti og úrkoma í Stykkishólmi og á Hveravöllum á sama tímabil.*

Time interval	(a)	(b) Hv: Hveravellir		(c) St: Stykkishólmur	
	b$_n$ (m_{we} yr^{-1})	T (°C)	P (m)	T (°C)	P (m)
August 1937 – August 1945 (dDEM)	-1.56 ± 0.50	-	-	4.29	0.74
August 1945 – August 1986 (dDEM)	-0.31 ± 0.10	-	-	3.71	0.69
August 1986 – September 1997 (dDEM)	-0.21 ± 0.20	-0.70	0.72	3.88	0.79
September 1997 – August 2004 (dDEM)	-1.32 ± 0.20	0.14	0.77	4.37	0.63
September 1997 – August 2004 (SMB)	-1.36 ± 0.20	0.14	0.77	4.37	0.63
September 1997 – August 2009 (SMB)	-1.26 ± 0.15	0.21	0.80	4.53	0.72

Table 4. Estimated mass balance sensitivity of Langjökull to 1°C temperature rise (e.g. Jóhannesson, 1997) at both Hveravellir and Stykkishólmur, using averages over i) all days in the time interval and ii) using only the corresponding summer months (June-August). Changes in precipitation are ignored in the error estimations (locations in Figure 1). – *Næmni afkomu Langjökuls fyrir breytileika meðalárshita og meðalsumarhita í Stykkishólmi og á Hveravöllum.*

Reference periods Δt_1 and Δt_2	All seasons $\delta b_n/\delta T$ (m_{we} yr^{-1} $^\circ$ C^{-1})	Summer $\delta b_n/\delta T$ (m_{we} yr^{-1} $^\circ$ C^{-1})
(a) Using temperature at Hv: Hveravellir		
Δt_1: 1986 – 1997; Δt_2: 1997 – 2004	-1.35 $\pm$ 0.35	-0.90 $\pm$ 0.20
Δt_1: 1986 – 1997; Δt_2: 1997 – 2009	-1.15 $\pm$ 0.25	-0.90 $\pm$ 0.20
(b) Using temperature at St: Stykkishólmur		
Δt_1: 1937 – 1945; Δt_2: 1945 – 1986	-2.15 $\pm$ 0.90	-2.20 $\pm$ 0.90
Δt_1: 1986 – 1997; Δt_2: 1997 – 2004	-2.35 $\pm$ 0.55	-1.70 $\pm$ 0.40
Δt_1: 1986 – 1997; Δt_2: 1997 – 2009	-1.60 $\pm$ 0.40	-0.85 $\pm$ 0.20

the annual averages. Precipitation and temperature records from the Stykkishólmur and Hveravellir stations are highly correlated (Figure 15). However, the higher mass balance sensitivity to uniform temperature rise at the coastal station Stykkishólmur than of the inland Hveravellir is explained with oceanic constraint of the coastal temperatures, demonstrating that the mass balance sensitivity calculations may strongly depend on the location of a meteorological reference station. In a model simulation study for Langjökull, Guðmundsson *et al.* (2009a) obtained mass balance sensitivity of -1.15 m_{we} yr^{-1} to an annual 1 K temperature rise at Hveravellir, which is in a good agreement with our results in Table 4.

In another study, Gudmundsson *et al.* (2011) used the Hveravellir meteorological station to investigate the mass balance sensitivity of the small Eyjafjallajökull, Tindfjallajökull and Torfajökull ice caps (Figure 1) to uniform temperature rise. Their highest sensitivity number was obtained for the maritime ice cap Eyjafjallajökull, or -2.80 m_{we} yr^{-1} K^{-1} compared to -1.37 to -1.15 m_{we} yr^{-1}K^{-1} (using all season average) found in the present study for the inland Langjökull ice cap. The mass balance sensitivity for the neighbouring Hofsjökull ice cap (location in Figure 1) is however around 75% that of Langjökull, explained by the 200–300 m higher elevation range of Hofsjökull (Gudmundsson *et al.*, 2009a). Jóhannesson *et al.* (2011) found -1.90 m_{we} yr^{-1} K^{-1} (using Stykkishólmur) for Snæfellsjökull an ice cap in W-Iceland (Figure 1), an ice cap with similar elevation range as Langjökull but much smaller. Anderson *et al.* (2010) obtained a mass balance sensitivity of -2 m_{we} yr^{-1} K^{-1} for the maritime Brewster Glacier in New Zealand. Their number is comparable to the mass balance sensitivity obtained for Icelandic ice caps.

CONCLUSION

Although old surface elevation maps of glaciers may be distorted laterally and shifted vertically due to erroneous triangulation sites and sparse or incomplete survey, some may be corrected sufficiently and used to realistically deduce volume change estimates and average mass balance. This is particularly the case for differential DEMs representing long time spans. Average specific mass balance derived from low error surface DEMs (7 years apart), produced from dense GPS profiles and SPOT5 HRG images, is in close agreement with the average specific mass balance observed with *in situ* measurements. This indicates that the set of 23 mass balance site are successfully selected to describe both the lateral and vertical mass balance variability on the ~900 km^2 Langjökull ice cap. The observations of average mass balance presented in this paper, span more than 110 years with intervals of distinctly different climate conditions, and are thus valuable for further studies of glacier response to climate variations. During the first two decades of the 20th century, the mass balance of Langjökull was close to zero, then highly negative ~1925–1950 (-1.6 m_{we} yr^{-1}), and close to zero again in the 1970s and 1980s. From 1997–2009, Langjökull has been losing mass at a high rate of -1.3 m_{we} yr^{-1}, which is in accord with the ~1.4°C warmer average summer temperature than in the close to zero mass balance period in the 1980s. The mass balance sensitivity of Langjökull is high; -2 m_{we} $yr^{-1}K^{-1}$ estimated from a coastal meteorological station and -1 m_{we} $yr^{-1}K^{-1}$ derived from an inland station. This is lower than obtained in previous studies of the mass balance sensitivity of the more maritime (higher precipitation) south coast glacier, Eyjafjallajökull (-2.8 m_{we} $yr^{-1}K^{-1}$).

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ÁGRIP

Afkoma Langjökuls hefur verið mæld á 22 til 23 mælistöðvum á jöklinum frá jökulárinu 1996–1997 og eftir mælingunum unnin stafræn kort af afkomu jökulsins. Nákvæm hæðarkort voru unnin eftir þéttum GPS-sniðmælingum frá apríl 1997 og þrívíddarmyndum teknum með SPOT5 gervitunglinu í ágúst 2004. Þessi kort voru notið til viðmiðunar við leiðréttingu á bjögunum og villum í eldri yfirborðskortum (1937, 1945–1946, 1986) og nákvæmni þeirra þannig bætt. Breyting ísrúmmáls á árabilunum milli kortanna var metin með því að draga eitt kort frá öðru. Lega ysta jaðars Langjökuls (í lok litlu ísaldar um 1890) var dregin upp eftir gervitunglamyndum, ljósmyndum og ýmsum rituðum heimildum; þannig fékkst mat á flatarmál jökulsins við lok litlu ísaldar. Þetta flatarmál og samhengið milli flatarmáls og ísrúmmáls árin sem hæðarkort eru til var notað til að áætla ísrúmmál við lok litlu ísaldar. Langtímabreyting afkomu öll þessi tímabil er metin út frá rúmmálsbreytingum. Rýrnum metin eftir yfirborðshæðarbreytingum áranna 1997–2004 reynist sú sama og samanlögð afkoma einstakra ára sem metin eftir afkomumælingunum á jöklinum. Það bendir til að vel hafi tekist við staðsetningu afkomumælistaða, mælingar og túlkun þeirra. Gögn sem ná frá um 1890 til fyrsta áratugar 21. aldar sýna að jökullinn hafi rýrnað mjög hratt á hlýju tímabili 1936 til 1946, þegar meðalársafkoman var neikvæð um 1,6 m vatns að jafnaði, og aftur á árunum eftir 1997, með neikvæða meðalársafkomu um 1,3 m vatns. Á kaldari tímabilunum frá 1946 til 1986 og 1986 til 1997 var afkoma jökulsins mun nær því að vera í jafnvægi eða - 0,3 til - 0,2 m vatns að jafnaði. Ísrúmmál Langjökuls minnkaði frá um 250 km^3 við lok litlu ísaldar í 188 km^3 árið 2004, sem er um 24% heildarrýrnun, en 40% þeirrar rýrnunar varð á hlýju árunum 1936 til 1946 og eftir 1997.

REFERENCES

Aðalgeirsdóttir, G., T. Jóhannesson, H. Björnsson, F. Pálsson and O. Sigurðsson 2006. Response of Hofsjökull and southern Vatnajökull, Iceland, to climate change. *J. Geophys. Res.* 111, F03001, doi:10.1029/2005JF000388.

Aðalgeirsdóttir, G., S. Guðmundsson, H. Björnsson, F. Pálsson, T. Jóhannesson, H. Hannesdóttir, S. Þ. Sigurðsson and E. Berthier 2011. Modelling the 20th and 21st century evolution of Hoffellsjökull glacier, SE-Vatnajökull, Iceland. *Cryosphere* 5, 961–975, doi:10.5194/tc-5-961-2011

Anderson, B., A. Mackintosh, D. Stumm, L. George, T. Kerr, A. Winter-Billington and S. Fitzsimons 2010. Climate sensitivity of a high-precipitation glacier in New Zealand. *J. Glaciol.* 56, 114–126.

Bahr, D. B. 1997. Width and length scaling of glaciers. *J. Glaciol.* 43, 557–562.

Berthier, E., Y. Arnaud, D. Baratoux, C. Vincent and F. Rémy 2004. Recent rapid thinning of the "Mer de Glace" glacier derived from satellite optical images. *Geophys. Res. Lett.* 31, L17401, doi:10.1029/2004GL020706.

Berthier, E., H. Björnsson, F. Pálsson, K. L. Feigl, M. Llubes and F. Rémy 2006. The level of the Grimsvötn subglacial lake, Vatnajökull, Iceland, monitored with SPOT5 images. *Earth Planet. Sci. Lett.* 243, 293–302, doi:10.1016/j.epsl.2005.12.027.

Björnsson, H., F. Pálsson, O. Sigurðsson and G. E. Flowers 2003a. Surges of glaciers in Iceland. *Ann. Glaciol.* 36, 82–90.

Björnsson, H., F. Pálsson and H. H. Haraldsson 2003b. Mass balance of Vatnajökull (1991–2001) and Langjökull (1996–2001), Iceland. *Jökull* 53, 75–78.

Björnsson, H. and F. Pálsson 2008. Icelandic glaciers. *Jökull* 58, 365–386.

Björnsson, H., T. Jónsson and T. Jóhannesson 2005. Comment on ”Iceland as a heat island” by D. H. Douglass *et al. Geophys. Res. Lett.* 3, L24714, doi:10.1029/2005GL023793.

de Woul, M. and R. Hock 2005. Static mass balance sensitivity of Arctic glaciers and ice caps using degree-day approach. *Ann. Glaciol.* 42, 217–244.

Einarsson, M. Á. 1984. Climate of Iceland. In: *Climates of the Oceans*, H. van Loon (ed.), Elsevier, Amsterdam, 673–697.

Flowers, G.E., H. Björnsson, Á. Geirsdóttir, G. H. Miller and G. K. C. Clarke 2007. Glacier fluctuation and inferred climatology of Langjökull ice cap through the Little Ice Age. *Quat. Sci. Rev.* 22, 2337–2353.

Geirsdóttir, Á, G. H. Miller, Y. Axford and S. Ólafsdóttir 2009. Holocene and latest Pleistocene climate and glacier fluctuations in Iceland. *Quat. Sci. Rev.* 28, 2107–2118.

Gudmundsson, S., H. Björnsson, T. Jóhannesson, G. Adalgeirsdóttir, F. Pálsson and S. Sigurðsson 2009a. Similarities and differences in the response of two ice caps in Iceland to climate warming. *Hydrol. Res.* 40, 495–502.

Gudmundsson, S., H. Björnsson, F. Pálsson and H. H. Haraldsson 2009b. Energy balance and degree-day models of summer ablation on the Langjökull ice cap, SW Iceland. *Jökull* 59, 1–18.

Gudmundsson, S., H. Björnsson, E. Magnússon, E. Berthier, F. Pálsson, M. T. Gudmundsson, Th. Högnadóttir and J. Dall 2011. Response of Eyjafjallajökull, Torfajökull and Tindfjallajökull ice caps in Iceland to regional warming, deduced by remote sensing. *Polar Res.* 30, 72–82.

Hanna, E., T. Jónsson and J. E. Box 2004. An analysis of Icelandic climate since the nineteenth century. *Int. J. Climatol.* 24, 1193–2004.

Hock, R., M. de Woul, V. Radic and M. Dyurgerov 2009. Mountain glaciers and ice caps around Antarctica make a large sea-level rise contribution. *Geophys. Res. Lett.* 36, L07501, doi:10.1029/2008GL037020.

Jóhannesson, T. 1997. The response of two Icelandic glaciers to climatic warming computed with a degree-day glacier mass balance model coupled to a dynamic glacier model. *J. Glaciol.* 43, 321–327.

Jóhannesson, T., G. Adalgeirsdóttir, H. Björnsson, P. Crochet, E. B. Elíasson, S. Gudmundsson, J. F. Jónsdóttir, H. Ólafsson, F. Pálsson, Ó. Rögnvaldsson, O. Sigurdsson, Á. Snorrason, Ó. G. B. Sveinsson and Th. Thorsteinsson 2007. *Effect of climate change on hydrology and hydro-resources in Iceland.* OS-2007/011. National Energy Authority, Hydrological Service, Reykjavík.

Jóhannesson, T., H. Björnsson, F. Pálsson, O. Sigurðsson and Th. Thorsteinsson 2011. LiDAR mapping of the Snæfellsjökull ice cap, western Iceland. *Jökull* 61, 19–32.

Kirkbride, M. P. and Dugmore, A. J. 2006. Responses of mountain ice caps in central Iceland Holocene climate change. *Quaternary Sci. Rev.* 25, 1692–1707.

Larsen, D. J., G. H. Miller, Á. Geirsdóttir and Th. Thordarson 2010. A 3000-year varved record of glacier activity and climate change from the proglacial lake Hvítárvatn, Iceland. *Quat. Sci. Rev.* 30, 2715–2731.

Palmer, S., A. Shepherd, H. Björnsson and F. Pálsson 2009. Ice velocity measurements of Langjökull, Iceland, from interferometric synthetic aperture radar (InSAR). *J. Glaciol.* 55, 834–838.

Paterson, W. S. B. 1994. *The Physics of Glaciers*, 3rd edition. Elsevier, Oxford.

Sigbjarnarson, G. 1967. The changing level of Hagavatn and glacial recession in this century. *Jökull* 17, 263–279.

Sigurðsson, O. and T. Jónsson 1995. Relation of glacier variation to climate changes in Iceland. *Ann. Glaciol.* 21, 263–270.

Toutin, T. 2006. Generation of DSMs from SPOT-5 intrack HRS and across-track HRG stereo data using spatiotriangulation and autocalibration. *ISPRS J. Photogrammetry and Remote Sensing* 60, 170–181.

Wright, J. 1935. The Hagavatn gorge. *Geograph. J.* 86, 218–234.