To the editor: Jon Ove Hagen

We thank both reviewers for constructive comments on our manuscript, which have made the paper shorter and more clear. We hope that the editor will find the manuscript ready for publication in its revised form. Our response to every comment is listed below. When referring to the figures, we use the numbers as used in the original manuscript.

Anonymous reviewer #1

Hannesdóttir et al. investigate area, volume and mass changes of southeast Vatnajökull since the LIA. The article's strength is a well-described and thorough reconstruction of glacier changes which is a useful contribution to scientific literature. There are some methodological details I would suggest to reconsider and I have some suggestions for restructuring the article. Most of that comes in the detailed comments, however, I find 3.2. and 4.1. could be combined to one and checked for redundancy.

Answer: Thank you for this comment. Since the other reviewer had comments on the methodology section we have decided to keep the data and methods chapters separated, but have minimized redundancy between them.

General Comments:

The part where the results are related to climate change could use some refinement.

Answer: The Discussion chapter on the variable response of the outlet glaciers to similar climate forcing has been better organized and is more focused.

In my opinion, the discussion on the scaling laws does not add very much to the paper and I think it could be omitted without big loss of substance as the main outcome is that there is no trend in scaling parameters but also that the sample size is too small and probably also biased in terms of size distribution.

Answer: The discussion on the scaling law has been deleted from the paper as suggested by both reviewers.

In general, the paper is quite long and could be shortened at several locations, especially in 6. Some of them i indicate as a suggestion below.

Answer: We have focused the paper better and shorten it as suggested by both reviewers.

Specific Comments:

p4682

L12: by 164 km2...from xx km2 to xx km2
Answer: We agree and have changed this to: “the glacierized area has shrunk by 164 km^2 or from **1015 km^2 to 851 km^2**“

L14: suggest to put the numbers in meter
Answer: We prefer to keep the units in mm.

L17: most negative compared to what? Very different lengths of time periods are looked at so it is a bit arbitrary
Answer: This has been clarified and the sentence now reads: “The rate of mass loss during the post-LIA period was most negative in the years 2002-2010, …“

P4683

L11: every place on earth is ...influenced by changes in the atmospheric circulation...
Specify
Answer: This sentence is now more detailed: „Iceland is located in northern part of the storm track in the North Atlantic Ocean, at the boundary of warm and cold ocean surface currents.“

L13: mean monthly T?
Answer: “the mean temperatures are close to 0°C in winter and 11°C during the summer months in the lowlands.“

L19: the ’1’ in the units should be removed
Answer: This has been changed as suggested.

L20: reads strange after the semicolon. Not a full sentence
Answer: The sentence has been changed and after the comma reads: **„**which is among the highest in the world (De Woul and Hock, 2005).“

L21: is that also true for snow melt water? To be sure, suggest ’glacial meltwater input’L11:
Answer: We have changed this to glacial meltwater input as suggested.

P4684

L1: repetition to L20 on previous page
Answer: We have now moved this sentence to the previous page.

L4: ...’at their deepest’ as this is not true for all areas at the terminus
Answer: This has been changed as suggested: “since their beds lie even 100-300 m at their deepest below the elevation of the current terminus.“

L13: ELA from Modis images is in principle wrong. Snow line is OK, equilibrium line is also acceptable, ELA is the point where the balance profile crosses 0 and therefore not to be acquired from Modis.
Answer: We explain in the methods section that the elevation of the snowline at the end of the ablation season provides an estimate for the ELA on temperate glaciers and refer to several

papers. The autumn snowline is thus a proxy for the ELA, and we refer to it in the results section as MODIS-ELA.

L21. The hypsometry comes much later in the paper but actually it could be good if Fig 13 appears already there.
Answer: We consider Fig 13 to be part of the results, and should thus not be in the chapter on the study area. The variable hypsometry is taken out of this section.

L21-end of paragraph: very descriptive. Consider omitting this as all this is visible in the map.
Answer: This has been omitted and we agree that this is visible on Fig. 1. and some information is also found in Table 1.

P4685

L9: I agree with that until the glaciers are small enough not to touch the lakes anymore. It is therefore only partly coupled to climate. Suggest reformulating
Answer: We have reformulated this sentence, which now reads: "The lakes will continue to grow and new ones form in the troughs as the glaciers retreat, assuming current climate conditions or warming, and enhance ablation, at least until they retreat out of the lakes."

L12: numbers of significant digits?
Answer: We have added a ~1 m in this context, and further details are found in the cited reference.

P4686

L10: make location of AWS more prominent in fig 1.
Answer: The weather stations are displayed more clearly in Fig 1. now.

L20: How have the 10 yr periods been defined? Is that running average? Explain
Answer: We calculated the 10 year mean temperature of the warmest 10 year long periods.

L21: and why now 1884-1890?
Answer: Because measurements only started in 1884 and lasted for 6 years, this has been clarified in parenthesis.

L26: why undercatch only at one of the stations?
Answer: This was not clearly stated. The undercatch is a suggestion for the difference between winter and annual values, i.e. the winter precipitation is only 2 times higher on the eastern side compared to the western side, where the annual precipitation is 3 times higher. The sentence now reads:

"The records from Kvísker show more than two times higher winter precipitation than in Skaftafell (Fig. 2), wherea the annual precipitation is three times higher (not shown). This seasonal difference could be related to precipitation undercatch of the rain gauges especially during winter, which is generally more pronounced for snow than rain (e.g. Sigurðsson, 1990)."

P4687

L1-3: not entirely logical there, reformulate or specify.
Answer: The sentence has been reformulated.

L18: define where you have the knowledge from that LIA maximum was at around 1890 at some point.
Answer: We have added in parenthesis after 1890: "(the timing based on historical documents)".

L22: how has the accuracy been determined? It sounds quite optimistic to me for a reconstruction taking problems as trimline erosion etc into account.
Answer: The method and error estimates are described in Hannesdóttir et al., 2014, and we refer to that paper here for clarification.

P4688

L3: remove 'a'
Answer: This has been removed as suggested.

L15: explanation for abbreviation right after AMS
Answer: The explanation has been given as suggested: „The AMS **(Army Map Service)**"

L19: is it then valid to use them for the calculation of geodetic MB?
Answer: The surface geometry in the upper accumulation area has been reassessed by using the nunataks on the original images to adjust the contour lines- this is now more clearly explained in the methods chapter.

P4689

L25: have been...
Answer: This has been changed as suggested.

P4690

L3 and entire chapter: so i understand: the shape is assumed to be the same but some vertical displacement is subtracted from the LIDAR DEM. Where do you take this from? I assume this is the next

paragraph that explains that. However, it remains unclear how these ’upper reaches of the accumulation area’ are defined. I consider this an important point to clarify. And in this view, are the accuracies you determine for the individual DEMs realistic? How about other problems in photogrammetry like oversaturation?
Answer: This has been clarified in the following section:

“The DEMs are obtained by construcing new contour lines from each contour line of the LiDAR DEM; the new contour has the elevation of the LiDAR plus an elevation shift. The intersection point of the new contour with the valley wall is found by moving the old point up or down the wall by a vertical elevation shift along a line drawn between the old intersection points on the opposite sides of the valley.“

L11-13:unclear, specify ’available data points’
Answer: We have now detailed what the available data points are: “Between the data points retrieved from the trigonometric survey points, nunataks and the resurveyed glacier margin from the original aerial images.“

L17: how about an abbreviation for the Glaciology Group... that appears several times.
Answer: Glaciology Group at the Institute of Earth Sciences appears only here (once) in the text, but in a table too, so we will use GGIES as an abbreviation.

L28: not in the most recent DEMS... but in previous ones? Clarify.
Answer: This has now been clarified: “We do not however, account for this change in the basal topography in the surface DEMs, as it is smaller than the vertical error estimate.“

P4691

L23: bedrock or rock?
Answer: This has been clarified, it now reads: „ …shadows had incorrectly been interpreted as **rock outcrops** or snow-covered gullies…“

General with all the accuracies given: would it be a good idea to include a table specifying them to shorten the text?
Answer: The vertical point accuracy estimates are given in Table 3.

P4692

L13: not clear what mosaiced means in this context. Resampled? Which cell size?
Answer: Mosaiced in the meaning of merged or spliced together; we have changed mosaiced to spliced.

L19: what is ehf? Is that part of the name?

Answer: L19: ehf is part of the name of the company and has been clarified in the text.

L21 and paragraph: so DGPS data from 2000-2003 has been used to derive 2002? and then a seasonal adjustment? And then you get to 1-2m accuracy? How is that estimated?
Answer: The accuracy is estimated by comparing the resulting DEM with the DGPS measurements.

P4693

L5: suggest mass balance profile
Answer: We use mass balance gradient: "in their response to climate change through its link with mass-balance gradient."

chapter 4.3- additional to the points i raised before: the average and std depends on the density of points digitized. Answer on that. And how was the end of summer image defined? I guess the latest with clear sky. But how close is that really to the end of the ablation season? And what do you use it for in the end? The snow-line/ELA part does not appear to me to be crucial in the discussion.
Answer: We have indicated the dates of the MODIS images in Table 1. The snowline at the end of summer (Table 1) was manually digitized from cloud free images obtained from late summer/early autumn (21 of August to 26 of September). This is the first time that the snowline elevation has been retrieved for the southeastern outlet glaciers, and we think this should be part of the data base presented here. Mass balance is only measured on a transect on Breiðamerkurjökull and Hoffellsjökull, so the ELA is known for those glaciers. Also the change in ELA since 1890 (presented in Hannesdóttir et al., 2014) is worth comparing with the modern proxy-derived ELA.

P4694

isnt 5.2. the principle result and should be mentioned before 5.1?
Answer: The MODIS derived ELA is shown in a number of figures (including Fig. 8, now Fig.7) it will not work to make this section the last sub-chapter of the Results.

P4695

L11-13: here it is relevant how far the images are apart. Suggest table with image acuqisition dates.
Answer: The parameters of the MODIS images have been detailed, and are shown in Table 2.

L18: I dont understand how the 164 km^2 result. I assume this is for the total numbers, i.e. Öraefaj and Eastern (Tab. 2). but I get down to another number. I suggest also in Tab 2 and Tab3 to put the percentage changes in brackets for the overall numbers and not only for the individual glaciers.
Answer: Fortunately the reviewer noticed this error, and the numbers have now been corrected. We have added the percentage of the overall glaciers in brackets.

L24: would DEM differencing be a way to go to detect debris covered ice from rocks? For your multi-temporal GI with high-quality DEMs this could be a way to go?

Answer: Fig. 11b shows that the surface lowering is considerable for Hrútárjökull during the period 1945-2010, in this case the glacier snout thins even though it is covered with debris. DEM differencing could be a way to detect debris covered ice.

P4696

L4: single year data point??

Answer: single year data point refers to the only information we have on the terminus position (derived from the aerial photographs in 1979. This has been clarified: "…based on the data point **from 1979** (Fig. 7)."

Fig. 9 could be saved if an overall bar would be added to fig 10 I would say.

Answer: Fig. 9 shows both the total volume and area loss and the relative changes – we think that Fig. 10 would be too complicated if the information from Fig. 9 would be added.

L22: 'southern outlets' if that is correct?

Answer: To clarify which outlets we have added „**all** the outlets collectively lost"

L26: very confusing sentence I find...

Answer: The sentence has been clarified and now reads: „All glaciers had lost at least half of their **total** post-LIA volume loss by 1945"

P4697

L7: add here that there definitely were some yeras with positive b. It is just with the intervals you are looking at that they are negative.

Answer: This has been changed accordingly: „The **average** geodetic mass balance of all glaciers was negative during every time interval of the study period (Fig. 12 and Table 4), **however, it is likely that some years had positive balance**."

p4698

Chapter 5.5: the classification is of limited use. I suggest removing that. The few points where you argue in the discussion with them you can just name the particularities of the class. If it should be kept, I suggest to move it to the method section.

Answer: We keep the discussion on the glacier hypsometry classification as suggested by comments from Reviewer 2, but have moved the classification to the methods section.

L17-22: How does that relate to other areas in the world? The fluctuations seem to be slightly ahead of for example alpine data.
Answer: A comparison with glaciers in the Alps and Scandinavia has been added, with a reference to Zemp et al., 2011.

P4699

L11: here for example the authors should be clear and always have to add that this is compared to the periods they are investigating.
Answer: This has been clarified as suggested: "The annual rate of volume and mass loss of the periods investigated was highest in 2002-2010 for almost all the outlet glaciers."

L14: add which period you are referring to for this comparison. Generally in this discussion it would be nice to add the existing measured glaciological mb time series. For example superimposed in fig 12?
Answer: We have taken out the specific sentence on Hoffellsjökull and Breiðamerkurjökull and have added a new sentence: "The geodetic mass balance during the decade 2000-2010 is similar to the measured specific mass balance of the larger ice caps in Iceland, equal to -1.0 ±0.5 m w.e. a^{-1} (Pálsson et al., 2012; Jóhannesson et al., 2013; Björnsson et al., 2013)."

The only outlet glacier with a mb series (measured in the accumulation and ablation area) that is included for comparison with the studied outlet glaciers is Hoffellsjökull, and the recently formed proglacial lake has affected the ablation considerably, and thus a direct comparison with measurements and the geodetic mass balance for the time period 2002-2010 would require a more detailed discussion.

P4700

L1-3: the ice volume...?? equals? What equals what? Give numbers! The mb numbers that follow in L4 are not equal and if it is volume loss that equals it is not that relevant for different sizes. But maybe i misunderstand
Answer: This has now been clarified: "**The ice volume loss (in km^3)** of the outlets of southeast Vatnajökull ~1890-2010 equals the ice volume loss of Langjökull and Breiðamerkurjökull during the same time interval (references)."

L7: very easily misleading: i assume you mean 25% in terms of mass balance. But the total mass loss will be very different. Reformulate and in this context i would stick to absolute numbers
Answer: The sentence has been clarified and now reads: "For comparison glaciers in the Alps have lost on average -0.31 m w.e. a^{-1} since the end of the LIA (Huss, 2012), compared to -0.38 m w.e. a^{-1} of the southeast outlets of Vatnajökull".

L9-17: write more concise.

Answer: The paragraph has ben shortened and clarified.

L19-21: this has to be changed. In my opinion you cant compare ’after 2000’ with the ’mid-90s’. Be clearer about the periods and choose ones that are beyond the natural variability. Whatever is meant by mid-90s but a few years should not be used for such a conclusion.
Answer: Warmer temperatures after 1995, than in the preceding 2-3 decades (Fig.~2b) caused retreat of the southeast outlets, that increased after year 2000 (Björnsson and Pálsson, 2008, Björnsson et al., 2013).

L22: what would this LIA ELA mean in terms of AAR? Is that a common way to determine the ELA for the LIA? I am rather used to the AAR assuming a steady state but maybe that is just as good.
Answer: The text has been clarified and we have added a reference for this method: “the ELA during the LIA maximum has been inferred from the elevation of the highest up-valley lateral LIA moraines of the studied glaciers (Hannesdóttir et al., 2014), a method known as MELM (maximum elevation of lateral moraines, e.g. Hawkins, 1985).“

L27: ’spatial variability´
Answer: Geographical variability has been replaced with **spatial variability**.

P4701-P4702

L9: I think this part could be very much condensed. Basically you conclude that hypsometry is the governing factor for the variability in changes and not different climate.
Answer: Details of the response or the magnitude of volume loss is governed by the hypsometry (and overdeepenings and proglacial lakes), but the general response is governed by the climate. We have retwritten this section to make this point more clear.

L15, very long sentence, cut in 2.
Answer: We do not think the sentence should be divided into two and keep it unchanged.

P4703: ’deflation’ very unusual in this context to me.
Answer: The word deflation has been replaced with **downwasting**.

P4704

L29 delete ’not’
Answer: This chapter has been deleted from the paper.

P4705

L15: -1.34m
Answer: We use mass change and a negative sign -1.34 m w.e. a^{-1}.

L16: put overall relative area and volume change numbers and compare to for example the Alps.

Answer: We have added the mass loss of the European Alps and North Patagonian icefield for the same time period in the conclusion. “The glaciated area decreased by 164 km^2 (16%) in ~1890–2010, and the outlets collectively lost 60±8 km^3 (22%) of ice, contributing 0.15±0.02 mm to sea level rise in the post-LIA period“.

P4716

L13: range of the averages of all years? I dont understand that. The ela is from Modis derived, right? Which years?
Answer: The MODIS-derived ELA is now presented as the averages of the years 2007-2011 with the standard deviation.

P4717

add % for total values. Caption very long: remove for instance the sentence with the ice divides.
Answer: The % for total values have beend added and the caption has been shortened.

Fig8: could maybe be omitted? It is not referred to substantially.
Answer: Fig. 8 is now referred to more thoroughly as suggested by reviewer #2.

Fig13: is the AAR related to LIA max?
Answer: The AAR is related to 2010, but we have now also added the AAR for the LIA.

Reviewer #2 – Hester Jiskoot

This manuscript presents a novel multi-temporal analysis of length, area and volume changes of a region of non-surge-type Icelandic glaciers over more than a century. The data are unique and there are some interesting findings in terms of different retreat rates, different glacier types, and different periods of potential climate forcing. Although the results seem substantial, it is hard to judge how well they stand due to a lack of proper error analysis, both in the construction of the glacier data and the analysis. Although the methodology appears extensive, much of the needed information to assess the quality of the data collection and error analysis are missing.

Answer: We have now better stressed one of the major result, i.e. the generation of a novel multi-temporal glacier inventory, and the discussion section is better structured. We do not agree with the reviewer that the mass loss data is “insufficient“ and that it should be only presented for the whole region, we have now detailed the method more clearly.

A. The paper is too long and lacks focus. Some of the major results are not stressed (e.g. that this research generated a novel multi-temporal glacier inventory) and other sections are not justifiable with the generalisations and/or the small sample of data (e.g. the volume-area scaling; mass loss).

Answer: The paper has been shortened, the section on Volume-Area scaling chapter has been omitted, and the discussion is now more focused.

B. The methodology is defective and poorly structured. Descriptions are mainly about what is done and not how it is done. A table of data types, sources, and errors for each of the DEMs, as well as the snowline MODIS imagery would be useful. The DEM of subglacial topography is unclear: what is the horizontal resolution, where were the transects taken and what was the interpolation technique? At what scale or zoom factor were the glacier outlines digitized and what was the human and digitizing error?

Answer: We have added a table that details the datasets used. The construction of the basal topography is not the subject of this paper and thus the corresponding papers are referred to for further details. In Table 2 the error estimate for the areal extent is provided.

C. Some of the methodology is questionable, in part due to the lack of information (A). In particular:

1) The mass change calculations are based on very rough generalisations, and should only be used to give an overall estimate in geodetic mass balance change, rather than calculate changes over time, or between regions.

Answer: We present data on the basal topography and the surface DEMs at various times for 12 different outlet glaciers ranging in size and hypsometry, which warrant the detailed analysis. The glacier inventory provides both temporal (the whole post-LIA time period) and spatial (along the southeastern stretch of Vatnajökull) coverage. We also stress the importance of looking at several outlet glaciers, not just 1 or 2 when inferring the response to similar climate change (all glaciers descend from SE-Vatnajökull ice cap).

2) The different maps and DEMs should have been co-registered to perform a change analysis. If this was not done, the errors will be much larger than reported.

Answer: Maps and DEMs were co-registered, and this has now been stated more clearly in the methods section.

3) I derive from Fig 4 that the snowline elevations have similar or larger seasonal variability than interannual variability. Additionally, it is always necessary to give the exact dates of the MODIS images used for the snowline measurements, and to indicate how close this is to the end of the melt season. It is unclear how the snowline pixels were derived (e.g. by image classification, or thresholding?) and how their elevations were extracted (see e.g. Jiskoot et al., 2009 for two common methods giving quite different results).

Answer: The exact dates of the MODIS images have been added to the dataset table. The snowline was manually digitized, and this has been clarified in the methods section.

D. The error analysis is weak, and the total errors not calculated properly.

Answer: We have provided errors for areal extent, vertical accuracy and we calculated the error for the geodetic mass balance, by including the previously mentioned errors for area and volume. This is now better explained in the methods section.

E. The paper is too long for its findings, and poorly structured. Rewrite and remove all repetitions, and remove some of the non-essential self-references. Move the volume area scaling methodology and results from the discussion section to the results section (if it is concluded that this section should stay in the paper).

Answer: The volume-area scaling section has been removed from the paper. We find it important to refer to the studies carried out on other glaciers in Iceland for comparison. Only a small group of people are responsible for the glaciological research in Iceland, thus self-referencing is unavoidable.

F. The discussion is unfocussed and shallow, and it seems like the authors felt the need to discuss all the results. Pick the most important findings and focus the discussion around those.

Answer: The Discussion chapter has been focused and we have put special emphasis on the special conditions with the over-deepened basins of the SE outlet glaciers of Vatnajökull, the importance of proglacial lakes (and enhanced ablation) and the hypsometry of the different outlets.

G. Several figures and tables could be combined to strengthen the interpretation of these, and to focus the results and discussion.

Answer: Figures 2 and 7 have been combined.

H. Think critically about the usefulness of comparing relative area changes (in percentages of starting area) for different periods, given that the overall class sizes have changed over the reported years, and other regions have different glacier sizes. This difference (with often the smaller class size have the largest loss in relative area) is in part a scaling issue, rather than a result of climate forcing/response. Many glacier change studies (including my own) have really emphasized this relative (%) area change, but is it really that useful?

Answer: We are aware that % changes can be misleading, thus for example we show in Fig. 9 both absolute and relative area (and volume) changes for the whole post-LIA time period (1890-2010).

I. The use of English overall is quite good, but the use of verb tenses is confusing throughout the paper. In the manuscript the authors use the present perfect tense (has been) and past tense (was) interchangeably. I suggest using the past tense throughout, as

the present perfect tense implies it still goes on. Wherever the past perfect tense (had been) is used it should imply that something was done (by other researchers) before the present study. Correct throughout and have a native English speaker check the verb tenses.
Answer: The verb tenses have been corrected as suggested.

Specific Comments

Title is too long and detailed for the confidence in the data. Change to "Area and volume changes of southeast Vatnajökull, Iceland, between ~1890 and 2010".
Answer: The title has been shortened to: Changes of southeast Vatnajökull, Iceland, between ~1890 and 2010.

P4682 Abstract

Rewrite after the paper is updated, and tone down the second part where the wording is too strong given some of the uncertainties in the results. The 'dynamic response' of glaciers is usually separate from the mass balance response, and the term 'indirect response' may be more appropriate here. Apart from the retreat in proglacial lakes, the differences in response described in this paper are more related to the reaction time and response time, rather than dynamic factors. Rewrite and tone down the causal certainty that the changes are related to hypsometry, bedrock topo and proglacial lakes.

Answer: We have rewritten the abstract after reviewing the manuscript.

P4683

L4 ....sea level rise and water resources.
Answer: "water resources" has been added according to the suggestion.

L16-19: repetitive wording. Delete "is one of the most sensitive ice caps in the world" and reword accordingly.
Answer: The sentence has been structured as suggested and now reads: **"**Simulations with a coupled positive-degree-day and ice flow model reveal that the mass balance sensitivity of southern Vatnajökull is in the range of 0.8–1.3m w.e. a^{-1} C^{-1} (Aðalgeirsdóttir et al., 2006), which is among the highest in the world (De Woul and Hock, 2005)."

L21-24: Don't the glaciers and ice caps in the Canadian Arctic contribute too?
Answer: This sentence only expresses that the second highest input to the North Atlantic comes from the Icelandic glaciers, after Greenland, and as such does not exclude other sources of meltwater input (from Svalbard, the Canadian Arctic etc).

L27-7(next page): this section is repetitive within the intro. Move to section 2 (study area).
Answer: This section has been moved to the Study area chapter.

P4684

L3: delete 'even'
Answer: The word "even" has been deleted.

P4685

L2-5: How accurately is the bedrock topo known?
Answer: The results and details of the basal topography measurements have been published in the papers cited. We have changed the text in parenthesis to "for details see Björnsson 2009; Magnússon et al., 2012). "

L5: what is 'alpine-like'?
Answer: "alpine-like" has been deleted from the sentence.

L13: use the term ablations stakes, rather than survey stakes.
Answer: Survey stakes have been changed to ablation stakes.

L23-24: remove some references.
Answer: We do not agree, since we are referring to mass balance studies, modelling studies and satellite imagery, and these results are presented in the papers cited.

L 24: ..ELA was approximately...
Answer: the verb has been changed to "was".

L26-29: Regular monitoring of annual frontal variations... Then remove 'providing annual records of the advance and retreat of the glacier'.
Answer: This has been changed according to the suggestion and the sentence now reads: "Regular monitoring of annual frontal variations of the outlets of southeast Vatnajökull started in 1932 by Jón Eyþórsson and were later carried out by volunteers of the Icelandic Glaciological society (references)."

P4686

L15-18: shorten this to one sentence: T and P were extended back to the end of the 19th century, following the methodology of A et al (2011).
Answer: This has been changed according to the suggestion and the sentence now reads: "The temperature and precipitation records were extended back to the end of the 19th century, following the methodology of Aðalgeirsdóttir et al. (2011)."

P4687

The subsections are too short to warrant subheaders, and the glacier geometry in sections 3.2-3.2.2 is poorly explaind. What was the

resolution and scale of the datasets, were they georeferenced to each other, what scale was the outline digitized, etc.
Answer: 3.2 is only to introduce the following sub-chapters as stated. We provide the vertical and horizontal accuracy for the LiDAR DEM in chapter 3.2.1 and refer to a paper on that. The LIA DEM is detailed in the paper cited, and as such we do not go into detail on that in this paper.

L20: do you mean nunataks rather than erratics?
Answer: No "glacier erratics", left by the LIA glacier, in some places leaving a lateral trace of the previous glaciers surface.

P4688

L6-14: express as the percentage of total area not mapped.
Answer: The sentence starting in L9 has been changed to: "The 1904 maps do not cover all outlets glaciers up to their ice divides. The Öræfajökull outlets have a complete coverage except Skaftafellsjökull and Morsárjökull, leaving 28% of the total area of the Öræfajökull outlets of this study unmapped. Three of the eastern outlets (Skálafellsjökull, Heinabergsjökull and Fláajökull) were mapped in 1904, but most of the accumulation area was unmapped, resulting in 67% of their area unmapped."

L28: Need an error analysis of the influence of snow cover on the accuracy of the mapping of glacier outlines from the nunataks.
Answer: The variable snow cover around the nunataks (as seen in Fig. 4) is integrated in our error assessment for our method of recreating the glacier surface DEM in the accumulation area.

P4689

L1: explain ehf.
Answer: This has been clarified: "of the **company** Loftmyndir ehf."

3.2.4 Explain the resolution and sampling of the RES: was this along flowlines or other transects or a grid? What was the horizontal spacing of the bedrock topo, and how much of that was through interpolation techniques?
Answer: As mentioned previously, results of the radio echo sounding measurements of the basal topography are referred to in the text and we do not agree with detailing the resolution and sampling since this was not part of our study. We have added in the parenthesis: "for details see…"

Section 4.1: Separate the methodology clearly into DEM reconstruction and DEM differencing. Need a much more precise explanation of the georectification (any co-registration?), GCP orthorectification, and error analysis and quantify the errors better. Rewrite entire section into the past tense.

Answer: We have rewritten this chapter in past tense. The vertical error for each DEM is provided in Table 3. We have added a sentence on the coregistration and goereferencing: "The various DEMs were coregistered and georeferenced to be merged into a common dataset, where the LiDAR data provided the reference DEM."

L19-24: move to results
Answer: This is one of the prerequisites for the method, i.e. since little changes in the surface geometry (only elevation changes) are observed in the areas mentioned or studies referred to, we feel confident in this approach.

P4690

L11: which kriging methods?
Answer: "point kriging" has been added to the sentence.

L20: ice divide shift importance is relative to the glacier size: both ST glaciers are large, but did it do something to the smaller outlets: express as a function of area.
Answer: Only a limited number of the studied outlets are adjacent to the surging glaciers as shown in Fig. 1, and since there are no exact measurements of the area affected during the surge, thus we will not express this as a function of the area. We have exchanged the sentence with the following: " Even though there have been surges in the larger outlets of Vatnajökull (Björnsson et al., 2003), they have not affected the studied SE-outlet glaciers during the study period."

P4691

L6: is the 1890 DEM explained in H et al, 2014?
Answer: We have added in the parenthesis: "(see Hannesdóttir et al., 2014 for details of the method)."

L6: delete 'shape of the'
Answer: L8 (not L6): We have deleted "shape of the"

L12: how was this adjusted?
Answer: This has been clarified: "and their shape was adjusted to resemble the more accurate contour lines of the AMS 1945 maps."

P4692

L6: Explain how it was 'reassessed'.
Answer: This has been clarified: "The glacier outline was also revised by digitizing the glacier margin from the original aerial images in areas of misinterpretation, as on the 1945 images."

L20: need to know the dates of the Landsat images, and the potential errors associated with these.
Answer: The date of the Landsat image used to digitize the glacier margin of the eastern outlet glaciers is 28th of July 1999, with a horizontal resolution of 30 m. This information has been added to the dataset table.

L23-26: What date was the lidar and what error? Not sure if I understand the methods here.
Answers: The details of the LiDAR are found in section 3.2.1., including dates and resolution, and for further detail we provide references. The method of reconstructing a DEM from the profiles is clarified in the following sentences: "The DEM is obtained by construcing new contour lines from each contour line of the LiDAR DEM; the new contour has the elevation of the LiDAR plus an amount dh. The intersection point of the new contour with the valley wall is found by moving the old point up or down the wall by a vertical amount dh along a line drawn between the old intersection points on the opposite sides of the valley (see e.g. Echelmeyer et al., 1996) for details of reconstructing surface DEM from survey profiles)."

P4693

L2: explain what error analysis you used. For each pairwise comparison (e.e. DEMa and DEMb) of the error should be calculated as E=$\sqrt{E_a^2 + E_b^2}$.
Answer: This is now stated in the section. For each DEM we provide the vertical accuracy, and when subtracting two DEMs from each other, to calculate the geodetic mass balance, we use the square root of the sum of the two errors associated with each DEM as detailed by the reviewer.

L7: and glacier dynamics (e.g. surging: see Jiskoot et el., 2001).
Answer: "and glacier dynamics" has been added to the sentence, as well as the reference as suggested.

L8-9: irrelevant: remove sentence and Lliboutry reference.
Answer: We think it is important to refer to the pioneering work of Ahlmann, and have included a reference to his paper from 1943 together with the reference of Furbish and Andrews, 1984.

L10: were these normalized curves?
Answer: The curves were not normalized.

L15-17: Long before 'recent' the ELA or snowline was estimated from aerial photography: see World Glacier Inventory (wgms.org). This was common practice in appr. 1950s-1980s.
Answer: We have removed "in recent years" from the sentence.

L21: Give years and resolution for the MODIS used for the snowline. Any problem detecting the snowline different dates? What method did you use: manual, supervised classification, thresholding? See also Jiskoot et al., 2009: Shea et al. 2013.

Answer: A table has been added with information about dates and resolution of all the MODIS images used. To clarify the sentence it now reads: „The visible snowline was digitized **manually** …“

P4694

Reverse order of equation 1 and 2.
Answer: Equations 1 and 2 have been reversed.

L9: Remove 'Sorge's Law'. Also, 900 kg/m^3 is a very rough estimation of the average density of ice. See Cuffey and Paterson (2010) for a better range for the Iceland glaciers, and calculate associated errors in volume.

Answer: In order to facilitate the comparison with other geodetic mass balance estimates of glaciers in Iceland we decided to use the same value for ice density, 900 kg m^{-3} (Guðmundsson et al., 2011; Pálsson et al., 2012; Jóhannesson et al., 2013).We have added the following sentence: "The error estimate of the geodetic mass balance takes into account the estimated error of the DEMs and the glacier areas."

We have calculated the geodetic mass balance of the outlet glaciers using 850 kg m^{-3} for ice as recommended by Huss (2013), which is valid for periods longer than 5 years, for glaciers with stable mass balance gradients, the presence of a firn area and volume changes significantly different from zero. The difference in mass change by using 850 or 900 kg m^{-3} is much smaller than the associated errors of the DEMs and area. Sorge´s law has been removed as suggested.

L23: bring to methods.
Answer: A similar description of the average ELA and the standard deviation has been added to the methods section, but we keep the sentence here as it is referring to the results shown in Fig. 4.

P4695

L1-14: confusion between the term snowline and ELA
Answer: We explain in the methods section that the snowline on the MODIS images is used as a proxy for the ELA. We have changed the title of the section: "5.1.: Spatial and temporal variability of the MODIS derived ELA."

L15-28: Poor phrasing throughout.
Answer: This section has been rephrased and shortened.

L24: debris cover will introduce and additional error in the ice extent delineation. Was this the only glacier with some debris cover, and can you give an estimate of the associate error?
Answer: Yes, this was the only glacier, and to avoid confusion we have omitted this specific sentence on Hrútárjökull.

L25: Be more specific than 'in the following few decades'
Answer: This has been clarified, and now reads: "in the 1960´s to the 1990´s."

P4696

L6: is this rate for 'relative' (%) or absolute area loss?
Answer: We have added „high rate of **absolute** area loss" for clarification.

L10: But the lack of downwasting seems a function of you forcing this above a certain elevation. If you first force it not to change and then conclude it did not change then there is no real process interpretation possible. Also, the shape of advancing and retreating glaciers has been extensively discussed and is in part due to the interplay between dynamics and ablation (see Schwitter and Raymond, 1993: JGlac 39 (133)). Use this in the discussion.
Answer: Here we are referring to available data shown in Fig. 11a, from which negligible surface lowering in the elevation range specified is evident; hence we are not forcing the lack of downwasting. A reference to Schwitter and Raymond (1993) has been added to the discussion.

L15-21: Need to know the topography of the nunataks (steep or shallow slopes) and the variability of the snow around it. See Answers in methodology too.
Answer: We agree, this is now discussed and clarified in the methods section.

L23 and further: Be careful concluding too much from comparing rates for different length of periods.
Answer: The rate of volume loss is presented as annual changes, so the comparison should be viable.

P4697

L4-5: delete: this is obvious.
Answer: We keep this sentence, since we come back to the importance of increasing the temporal resolution of the data set in the Discussion/Conclusion.

L7-25: Simplify and perhaps only use a rough estimate for the entire region, due to large errors assuming that the density is a constant for the different glaciers and at the different elevations. Also, use a good error estimation, where the error is a function of the error in the elevation, in the area, as well as in the ice density.
Answer: We do not agree that the data do not allow the detailed analysis and we provide the geodetic mass balance changes for each outlet glacier. We have also provided a more precise definition of the error estimate in the text.

P4698

L1-14: Use the proper and accepted terminology of top-heavy, equidimensional and bottom-heavy. What are the exact boundaries of

the classes, or was this just done visually? De Angelis et al (2014) use the Hypsometric Index classification proposed by Jiskoot et al. (2000 and 2009). Also, the top-heavy class (B) is typical for ice caps, so it is not a surprise that the ice caps of iceland mostly fall into that category.

Answer: We think it is useful to compare the different classes of glaciers, since the 12 outlets of SE-Vatnajökull have different area distribution with altitude (as shown in Fig. 13). The different geometry of the Öræfajökull outlets vs. the outlets of eastern Vatnajökull is also worth to compare. The categorization into the 5 hypsometric classes was done visually, and this has been clarified in the methods section. We did follow the five idealized classes as presented by Furbish and Andrews (1984) and more recently by De Angelis (2014). The terminology presented by De Angelis (2014) we found to fit better with our data than the classes suggested by Jiskoot et al. (2009), which do not include the bimodal hypsometric curve (class E) nor the glaciers where bulk of the area lies at the ELA (class D).

L14: why 'in its greatest extent?'
Answer: We have added the year at the end of the sentence "in its greatest extent ~1890.", the hypsometric curve in 1890 and 2010 is very different as shown in Fig. 13.

L17-22: A discussion of general response time is missing.
Answer: A discussion on the response time is found later in the discussion (P4702) and we have now reorganize and focused the Discussion chapter.

P4699

L12: The geodetic mass balance of - xx m. w.e. (specify)
Answer: This now reads: " geodetic mass balance of -1.38 to -1.51 m w.e. a^{-1} of the eastern outlets (apart from Heinabergsjökull) during the time period 2002-2010 is in line with … "

L17-29: Be clear about what you discuss: this material can be deleted, as it is not new for Iceland or the world.
This information is now better incorporated in the text as a comparison of our records with other data worldwide – the glaciers of this study were not included in the data base presented in the latest IPCC report. And as a response to the comment on L3-L8 on page 4700, we focus the attention on the factors that are unique for this setting, the maritime glaciers with overdeepenings, thus we find this comparison with other glaciers around the world valid.

P4700

L1: from the 'non-surging' outlets
Answer: "non-surging" has been added to the sentence.

L3-8: The interesting comparison here would be a difference in maritime glacier mass balance curves and the response, relative to other more continental regions. Additionally, iceland glaciers may

have wider tongues and flatter topography due to the lack of (or very little) constraining surrounding topography, relative to higher alpine regions (I include Svalbard and East Greenland). Additionally, the reverse bed slope and overdeepening give rise to a larger marginal region of recent proglacial lakes, and if neighbours surge the both water and mass piracy may occur. The combination of these factors is rather unique for Iceland and should be included in any discussion.

Answer: The SE-outlet glaciers are maritime and very different from the majority of the flatter more gently sloping larger outlet glaciers of western and northern Vatnajökull, and the outlets of the other major ice caps in Iceland (including Langjökull and Hofsjökull). They are constrained by valley walls and most of them have a narrow tongue. The surging glaciers of Vatnajökull are not affecting the studied outlets as now clarified in the reviewed version.

L9-29: very repetitive.

Answer: L13-L17 have been deleted (indicated by the strike-through).
„In situ mass balance measurements of glaciers in Iceland and degree-day mass balance models of selected glaciers indicate that the mass balance is governed by variation in summer ablation (which is strongly correlated with temperature), rather than winter accumulation (Björnsson and Pálsson, 2008; Guðmundsson et al., 2009, 2011; Pálsson et al., 2012; Björnsson et al., 2013).~~ Higher than average winter precipitation at the meteorological stations south of Vatnajökull, is not correlated with more positive geodetic mass balances of the southeast outlets. However, a strong correlation (*r* = 0.94–0.98) is found between the geodetic mass balance and the average summer temperature (Table 4).~~

L17-21: So here is a hint why the Iceland glacier retreat faster? Elaborate and include if it is mb curve or in part dynamic.

Answer: The maritime glaciers are sensitive to climate change and respond fast, we will refer to other previously published papers on this subject (e.g. Björnsson et al., 2013), which discuss the increased ablation in the last decade, which is not attributed to changes in the dynamic response of the glaciers.

L22-29: delete.

Answer: There is no reason provided by the reviewer for deleting this paragraph, and we think it is important to comment on the rise of the ELA in the post-LIA time period; it sheds light on the variable response of the outlets, as the hypsometry (among other factors) affects the volume loss. This paragraph has been moved to the following sub-chapter on "Different response to similar climate forcing".

P4701-03

6.2 is a particularly general, disorganised and weak discussion. The authors have the opportunity to focus on overdeepening, proglacial lakes, and differences in flow velocity here, but do not apart from a short mention in the last sentence (P4703, L8-10). I suggest to focus and elaborate on those factors which make Icelandic glaciers unusual, and from which we can learn about process-response.

The discussion about the influence of hypsometry (and Fig. 13) should include a scatterplot figure that groups the glaciers with similar hypsometries, and contrasts their length or area change, so that it becomes clear if this is a strong patters or merely a suggestion.

Answer: A scatterplot figure with the hypsometric classes and the total volume loss was included in the manuscript in an earlier version, but when cutting down the number of figures it was omitted- as it did not add much to the discussion – the information in this type of figure can be read from the tables and the text itself.

Scatterplots of the volume loss (and mass balance) vs. the average slope of the outlets did not show a strong correlation – the average slope is not very descriptive, since many of the glaciers have flat accumulation and ablation areas connected by a steeper area (as can be seen in Fig. 8.

The discussion is now more focused and includes a more thorough analysis of the variable factors influencing the volume loss of the outlet glaciers, including hypsometry, proglacial lakes and the basal topography/overdeepenings.

L11-12: these class B glaciers are the larger ones, so the % loss is size related, and thus not particularly informing.
Answer: There are other glaciers than the larger eastern ones which belong to shape class B, including Morsárjökull and Skaftafellsjökull.

L19-24: These glaciers have different size and slope (which is not mentioned) thus the different response is not surprising and can be explained with response time theory.
Answer: The average slope of Skaftafellsjökull and of Svínafellsjökull is 4° and 9° respectively, and does not explain the difference in their retreat or volume loss, as the steeper and smaller glacier (Svínafellsjökull) would be expected to respond faster than Skaftafellsjökull, but it is the other way around.

P4703-05

6.3 I suggest removing this entire section from the paper.Volume-area scaling should be in the methodology and results, and be properly presented and discussed. The number of glaciers may be too small (as you state later), and scaling laws are generally used to estimate volume from a population of glaciers, not individual glaciers.. Additionally, most of your glaciers are ice caps or outlets and should have different parameters (see e.g. Hagen et al., 1993: Glacier Atlas of Svalbard and Jan Mayen). Also, some recent effort have not surpassed this general scaling (e.g. Adhikari and marshall; Farinotti and Huss several papers).
Answer: We have removed the chapter on Area-Volume scaling from the paper.

P4705

7 Conclusions: be much more specific and give a summary of the major findings. Really focus on your own results.
Answer: The Conclusions have been rewritten, is now more specific and focuses on our findings.

P4707

References: Quite a plethora of references, and many are only used once or in conjuction with other similar references. Thin out a bit. Why are the page numbers after the references?
Answer: We have omitted the page numbers after each references and removed a few references.

TABLES

Table 1: List what year(s) are these data based on? The ELA description is vague, and should have some standard deviation.
Answer: Table 1: The caption now reads: "Characteristics of the southeast outlet glaciers in 2010. Some glaciers have gently sloping accumulation and ablation areas, which are connected by ice falls, thus the mean slope is not representative for the entire profile. The ELA is presented as the average of the years 2007-2011 with the standard deviation. Average ice thickness and terminus elevation is presented in 2010 and 1890. The retreat is from 1890 to 2010."

Tables 2 and 3: I think it would be more effective to have the numbers in a figure, such as for length (Fig 7). Perhaps make Fig 7 underneath each other a (length), b (area), and c (volume). With error bars.
Answer: Tables 2 and 3: In our opinion the data needs to be in a table, the exact numbers can not be read from a figure, and the figure would be too crowded if the % were included, which values that are referred to in the text. Figs. 2 and 7 are recommended to be combined, and we agree on that, which would not make a good fit if the area and volume data would be included in the same figure, too chaotic in our opinion.

Table 4: Delete. I doubt if the method warrants the detail per glacier. Just give the overall geodetic mass balance for the entire region as a fogure in the text. Additionaly, the average T does not say much if the time periods are for different lengths (not taking into account the NAO and AMO).
Answer: We disagree that the method is not robust enough to warrant the geodetic mass balance to be calculated for each glacier. We omit the correlation between T and geodetic mass balance in the last column (as in the text).

Table 5: delete, or go into much more detail and group per hypsometric class.
Answer: Table 5 has been deleted.

FIGURES

Fig 2 and 7 should be combined or at least underneath each other with the same scale so that patterns can more easily be discerned. Indicate starting year on x-axis.

Answer: Figs 2 and 7 are now combined, and the starting year indicated on the x-axis.

Fig 3: Add a scale-bar, and overlay and align the four panelsbetter. This image suggests that the snow cover may cause a larger error in the glacier outline than suggested in the text. Also, the snowline delineation appears to be problematic.

Answer: A scale bar has been added. Since the different sources of aerial images vary in their extent/limits, this alignment is the best possible. The possible errors associated with snowline delineation are included in the error estimate.

Fig 4: This figure suggests that interseasonal variability is higher than interannual variability and trend. Use that in the text to calculate a netter error estimate.

Answer: In the case where there are two available MODIS images from the same year, we see that the variability in the elevation of the snowline is in the range of ±50 m.

Figs 5 and 6: nice and clear figures

Fig 7: I wonder if there are any significant volcanic eruptions that can be indicated in this figure, which may have affected the glacier mb for a year or two. The figure caption is quite wordy. An 'unbroken line' is a solid line. The Lambatungnajökull dotted line should at least have msymbols on the line for the years for which the remote sensing or mapped data is available.

Answer: The effect of the eruptions is very short lived (see e.g. Björnsson et al., 2013) and would presumably not show up in the frontal variations of these oulets. There are no volcanic eruption in this area since 1727, which had local affects in Öræfajökull. The caption has been shortened and solid line used instead of "unbroken line". The data points of Lambatungnajökull have been added.

Fig 8: This figure nicely show the scale and extent of overdeepenings in Iceland. Try to explain some of the retreat patterns in Fig 7 from the margin position in the overdeepenings and the formation of proglacial lakes.

Answer: The importance of the variable basal topography and the retreat patterns is now discussed in more detail, and compared with the data shown in Fig. 7 (now Fig. 2c) and the volume loss. We have also indicated in Table 2 when lakes formed in front of the studied outlets.

Fig 9: caption: 'in geographical order': do you mean 'from west to east'?

Answer: We have changed this to: glaciers „represented from west to east" – instead of ´geographical order´.

`Fig 12: As stated before, the assumptions for the mass calculations are so general that this figure is perhaps useful when the average for each zone is given, rather than each individual glacier.`

Answer: We do not agree, our results indicate that the different glaciers undergo variable area and volume loss in the last 120 years, and in order to interpret and discuss the possible mechanisms it is wortwhile to calculate the geodetic mass balance for each glacier.

ADDITIONAL CHANGES

Bedrock topography has been changed to basal topography.

Manuscript prepared for The Cryosphere Discuss.
with version 2014/05/30 6.91 Copernicus papers of the LaTeX class copernicus.cls.
Date: 7 February 2015

~~Area, volume and mass changes~~ Changes of southeast Vatnajökull ice cap, Iceland, ~~from the Little Ice Age maximum in the late 19th century to~~ between ∼ 1890 and 2010

H. Hannesdóttir, H. Björnsson, F. Pálsson, G. Aðalgeirsdóttir, and S. Guðmundsson

Institute of Earth Sciences, University of Iceland, 101 Reykjavík, Iceland

Correspondence to: H. Hannesdóttir (hrafnha@hi.is)

Abstract

Area and volume changes and the average geodetic mass balance of the non-surging outlet glaciers of southeast Vatnajökull ice cap, Iceland, during different time periods between ~ 1890 and 2010, are derived from a multi-temporal glacier inventory. A series of digital elevation models (DEMs) (~ 1890, 1904, 1936, 1945, 1989, 2002, 2010) ~~have been~~ are compiled from glacial geomorphological features, historical photographs, maps, aerial images, DGPS measurements and a LiDAR survey. Given the mapped ~~bedrock topographywe estimate relative~~ basal topography, we estimate volume changes since the end of the Little Ice Age (LIA) ~ 1890. The variable ~~dynamic response~~ volume loss of the outlets ~~, assumed to have experienced~~ to similar climate forcing ~~,~~ is related to their different hypsometry, ~~bedrock~~ basal topography, and the presence of proglacial lakes. In the post-LIA period the glacierized area decreased by $164\,\mathrm{km}^2$ (or from 1014 km^2 to 851 km^2) and the glaciers had lost 10–30 % of their ~ 1890 area by ~~2010.~~ 2010 (anywhere from 3 to 36 km^2). The glacier surface lowered by 150–270 m near the terminus and the outlet glaciers collectively lost $60 \pm 8\,\mathrm{km}^3$ of ice, which is equivalent to ~~0.154 ± 0.02~~0.15 ± 0.02 mm of sea level rise. The ~~relative~~ volume loss of individual glaciers was in the range of 15–50 %, corresponding to a geodetic mass balance between -0.70 and $-0.32\,\mathrm{m\,w.e.\,a^{-1}}$. The annual rate of mass ~~loss~~ change during the post-LIA period was most negative in ~~the period~~ 2002–2010, on average $-1.34 \pm 0.12\,\mathrm{m\,w.e.\,a^{-1}}$, which ~~lists~~ is among the most negative mass balance values recorded worldwide in the early 21st century. ~~From the data set of volume and area of the outlets, spanning the 120post-LIA period, we evaluate the parameters of a volume-area power law scaling relationship.~~

1 Introduction

Area changes and glacier retreat rates since the Little Ice Age (LIA) maximum are known from glacierized areas worldwide (e.g., Haeberli et al., 1989; WGMS, 2008). The majority of glaciers worldwide have been losing mass during the past century (Vaughan et al., 2013), and a ~~few~~ number of studies have estimated the volume loss and the mass balance for the post-LIA period by various methods (e.g., Rabatel et al., 2006; Bauder et al., 2007; Knoll et al., 2008; Lüthi et al., 2010; Glasser et al., 2011). Knowledge about the ice volume stored in glaciers at different times is important for past, current and future estimates of sea level rise ~~. Ice caps and glaciers outside polar areas have contributed more~~ and water resources. More than half of the land ice ~~to the global mean~~ contribution to sea level rise in the 20th century comes from ice caps and glaciers outside the polar areas (Church et al., 2013). Furthermore, glacier inventories are important to analyze and assess glacier changes at a regional scale, and they provide a basic data set for glaciological studies, for example to calibrate models simulating future glacier reponse to changes in climate.

Iceland is located in ~~a climatically variable area of the~~ the northern part of the storm track in the North Atlantic Ocean, ~~influenced by changes in the atmospheric circulation and~~ at the boundary of warm and cold ocean surface currents. The temperate maritime climate of Iceland is characterized by small seasonal variations in temperature ~~, on average~~ in the lowlands, the mean temperatures are close to 0 °C in the winter and 11 °C during the summer months~~in the lowland~~. The temperate glaciers and ice caps receive high amounts of snowfall, induced by the cyclonic westerlies crossing the North Atlantic and have mass turnover rates in the range of 1.5–3.0 $\mathrm{m\,w.e.\,a^{-1}}$ (Björnsson et al., 2013). Simulations with a coupled positive-degree-day and ice flow model reveal that ~~Vatnajkull is one of the most sensitive ice cap in the world, and~~ the mass balance sensitivity of southern Vatnajökull is in the range of 0.8–1.3 $\mathrm{m\,w.e.\,a^{-1}}$ ~~1~~$^{\circ}\mathrm{C}^{-1}$ (Aðalgeirsdóttir et al., 2006)~~;~~ , which is among the highest in the world (De Woul and Hock, 2005). Results of spatially distributed coupled models of ice dynamics and hydrology, indicate that these glaciers are the most sensitive to future warming of all outlets of Vatnajökull (Flowers et al., 2005) . Apart from Greenland, the highest rate of glacial meltwater input to the North Atlantic Ocean, comes from the Icelandic glaciers, that have contributed $\sim 0.03\,\mathrm{mm\,a^{-1}}$ on average to sea level rise since the mid-1990s (Björnsson et al., 2013). Only a few quantitative estimates on volume and mass balance changes of the entire post-LIA period are available for Icelandic glaciers (Flowers et al., 2007; Aðalgeirsdóttir et al., 2011; Pálsson et al., 2012; Guðmundsson, 2014).

~~The outlet glaciers of southeast Vatnajkull (Fig. 1) are located in the warmest and wettest area of Iceland and descend down to the lowlands. Results of spatially distributed coupled models of ice dynamics and hydrology, indicate that these glaciers are the most sensitive to future warming of all outlets of Vatnajkull (Flowers et al., 2005) . They are particularly vulnerable to warming climate conditions, since their beds lie even 100–300below the elevation of the current terminus (Björnsson and Pálsson, 2008) . The surface geometry of the outlet glaciers at the LIA maximum has been reconstructed from glacial geomorphological features and historical data (?) . The outlets were at their terminal LIA moraines around ~1890, which marked the termination of the LIA in Iceland (Thórarinsson, 1943 ; Hannesdttir et al., 2014).~~

To estimate the ~~downwasting,~~ area and volume loss and the geodetic mass balance of the outlets of southeast Vatnajökull since ~ 1890, glacier outlines ~~have been~~ were digitized from various sources, and digital elevation models (DEMs) created from contour lines of topographic maps, DGPS measurements and various airborne surveys. The snowline elevation at the end of summer, a proxy for the equilibrium line altitude (ELA)~~has been~~ , was estimated from a series of recent MODIS images. ~~We consider~~ Finally, the different response of the glaciers to similar climate forcing during the post-LIA time period ~~, and from the constructed record of area and volume changes, the scaling parameters of a power law which relates glacier area to volume are evaluated~~is analyzed.

2 Study area and previous work

The studied outlet glaciers of southeast Vatnajökull (Fig. 1) are located in the warmest and wettest area of Iceland and descend down to the lowlands. The glaciers are non-surging, less than 100 km apart and most of them reach down to 20–100 m a.s.l. (Fig. 1). The glaciers vary in size from 10–200 km^2, their average thickness range is 80–330 m (Table 1)~~, and the hypsometry (area distribution with altitude) differs considerably. Morsrjkull, the westernmost outlet, flows down from an ice divide of ~ 1350m. ræfaj~~. Öræfajökull (2100 ~~) feeds several outlet glaciers: the eastern part of Skaftafellsjkull, Svnafellsjkull, Kotrjkull, Kvrjkull, Hrtrjkull and Fjallsjkull (Fig. 1).East of Breiamerkurjkull, three outlet glaciers descend from the 1500high plateau of the~~

~~Breiabunga dome, Sklafellsjkull, Heinabergsjkull, and Flajkull.Further east is Hoffellsjkull, and its accumulation area lies between Breiabunga and the mountainous area of Goahnkar (1500) , which feeds Lambatungnajkull (Fig. 1~~m a.s.l.) the highest peak in Iceland, feeds the steeper outlet glaciers of this study. The outlet glaciers east of Breiðamerkurjökull~~are~~ , which will hereafter referred to as the eastern outlet glaciers~~. The bedrock~~ , descend down from ice divides at around 1500 m a.s.l.

The basal topography of the ~~studied~~ outlets is known from radio echo sounding measurements ~~(Björnsson, 2009; Magnússon et al., 2012)~~ (see Björnsson, 2009; Magnússon et al., 2012 for details). The glaciers terminate in glacially eroded ~~alpine-like~~ valleys and have carved into soft glacial and glacio-fluvial sediments. ~~It is unlikely that~~ The glaciers are particularly vulnerable to warming climate conditions, since their beds lie 100–300 m at their deepest below the elevation of the current terminus (Björnsson and Pálsson, 2008; Magnússon et al., 2012) , and terminate in proglacial lakes that enhance their retreat. Assuming current climate conditions or warming, the lakes will continue to grow and new ones form in the troughs as the glaciers retreat, and will cause enhanced ablation, at least until they retreat out of the lakes.

The surface geometry of the ~~troughs were only formed during the LIA, considering the present rate of sediment transport in the main glacial rivers of ræfajkull (Magnússon et al., 2012) . Many of them presently calve into proglacial lakes, which enhances ablation, and makes them vulnerable to predicted future warming (Björnsson and Pálsson, 2008; Magnússon et al., 2012)~~ outlet glaciers at the LIA maximum has been reconstructed from glacial geomorphological features and historical data (Hannesdóttir et al., 2014) . The outlets were at their terminal LIA moraines around $\sim$1890, which marked the termination of the LIA in Iceland (Thórarinsson, 1943 ; Hannesdóttir et al., 2014).

Mass balance measurements have been carried out on Vatnajökull since 1993, and the ice cap has ~~lost~~ on average lost $1\,\mathrm{m\,w.e.\,a^{-1}}$ ~~on average~~ since (Björnsson et al., 2013). The majority of the ~~survey~~ ablation stakes are located on the northern and western outlet glaciers (Fig. 1), but a number of stakes are ~~situated~~ located on Breiðamerkurjökull and a few on the eastern outlets (Björnsson and Pálsson, 2008; Aðalgeirsdóttir et al., 2011). ~~In the accumulation area~~

~~of these last-mentioned outlets,~~ On these glaciers, the annual mass balance has been measured 1–4 m w.e. a^{-1} in the accumulation area in the time period 1996–2010. Losses of up to 9 m w.e. a^{-1} have been observed during summer on Breiðamerkurjökull and Hoffellsjökull, and even negative winter balances at the terminus (Björnsson and Pálsson, 2008). The mass balance at the plateau of Öræfajökull ice cap (1750–1900 m a.s.l.) was 6–8 m w.e. a^{-1} in 1993–1998 (Guðmundsson, 2000). Based on satellite imagery, in situ mass balance measurements and model simulations, the average ELA of southeast Vatnajökull has been estimated to be around 1100–1200 m (Björnsson, 1979; Aðalgeirsdóttir et al., 2005, 2006; Björnsson and Pálsson, 2008; Aðalgeirsdóttir et al., 2011). Interannual variability of ~~the ELA has been measured~~ approximately 200–300 m of the ELA was measured in the time period 1992–2007 (Björnsson and Pálsson, 2008).

Regular monitoring of annual frontal variations of the outlets of southeast Vatnajökull started in 1932 by Jón Eyþórsson and were later carried out by volunteers of the Icelandic Glaciological Society ~~, providing annual records of the advance and retreat of the glaciers (Eyrsson, 1963; Sigursson, 2013;)~~(Eyþórsson, 1963; Sigurðsson, 2013, http://spordakost.jorfi.is) . The history of retreat and volume changes of Hoffellsjökull since the end of the LIA has been derived from numerous archives (Aðalgeirsdóttir et al., 2011; Björnsson and Pálsson, 2004). Downwasting and volume loss of Kotárjökull (Fig. 1) in $\sim$1890–2010 has been quantified by repeat photography and mapping of LIA glacial geomorphological features (Guðmundsson et al., 2012). The records of these two glaciers are integrated in our data base for comparison with the other outlets of southeast Vatnajökull.

3 Data

3.1 Meteorological records

Long temperature and precipitation records are available from two lowland weather stations (Fig. 1) south of Vatnajökull; at Fagurhólsmýri (16 m a.s.l., 8 km south of Öræfajökull) and Hólar in Hornafjörður (16 m a.s.l., 15 km south of Hoffellsjökull). The temperature record at Hólar is available for the period 1884–1890 and since 1921, whereas, the precipitation measurements started in 1931 (Fig. 2). Temperature measurements started in 1898 at Fagurhólsmýri, and the precipitation record goes back to 1921 (Fig. 2). The temperature ~~record has been~~ and precipitation records were extended back to the end of the 19th century~~by correlation with other temperature records from around the country, and the precipitation record by linear regression between temperature and precipitation of the local stations (see Aðalgeirsdóttir et al., 2011 for details)~~, following the methodology of Aðalgeirsdóttir et al. (2011) . The mean summer (June–August) temperature during the two warmest ten year periods of the measurement series at Hólar (~~1926–1936~~ 1930–1940 and 2000–2010) was ~~10.3and 10.5~~10.4 °C~~respectively~~. For comparison the mean summer temperature for the time period 1884–1890 (the only years of measurements in the 19th century) was 8.5 °C. Winter precipitation ranges between 800 and 1400 mm, and no long term trend is observed since the start of measurements at the two stations. Precipitation has been measured at Kvísker (east of Öræfajökull) since 1963, and at Skaftafell (west of Öræfajökull) since 1964. The ~~records~~ record from Kvísker show more than two times higher winter precipitation ~~, and three times higher annual precipitation,~~ than in Skaftafell (Fig. 2)~~. This~~ , but the annual precipitation is three times higher (not shown). This seasonal difference could be related to precipitation undercatch of the rain gauges especially during winter, ~~but the underestimate~~ which is generally more pronounced for snow than rain (e.g., Sigurðsson, 1990).

3.2 Glacier geometry

The areal extent and the surface topography of the outlet glaciers at different times during the period ∼ 1890–2010, ~~has been~~ was derived from various data sets (Table 2) that are detailed in the following sub-chapters. The glacier margin ~~has been~~ was digitized from maps and aerial images at various times for different glaciers.

3.2.1 LiDAR DEM

The most accurate DEMs of southeast Vatnajökull ~~were~~ have been produced with airborne LiDAR technology in late August–September 2010 and 2011 (Icelandic Meteorological Office and Institute of Earth Sciences, 2013). The high-resolution DEMs are $5\,\mathrm{m} \times 5\,\mathrm{m}$ in pixel size with a $< 0.5\,\mathrm{m}$ vertical and horizontal accuracy (Jóhannesson et al., 2013). The LiDAR DEMs provide a reference topography, used ~~in constructing~~ to construct other glacier surface DEMs, for example in areas where corrections of contour lines from old paper maps ~~have been~~ were necessary.

3.2.2 The LIA glacier surface topography

The ~~surface topography at the~~ LIA maximum ~ 1890 surface topography (the timing based on historical documents) of the outlet glaciers of this study has previously been reconstructed from glacial geomorphological features (including lateral and terminal moraines, trimlines and glacier erratics), historical photographs, and aerial images, using the LiDAR DEM as baseline topography ~~(?)~~ (Hannesdóttir et al., 2014) . The vertical accuracy of the ~ 1890 DEM is estimated to be around ± 15–$20\,\mathrm{m}$ ~~.~~ (see Hannesdóttir et al., 2014 for details)

3.2.3 Aerial images, maps and glacier surface data

The oldest reliable maps of the outlet glaciers are from the Danish General Staff ($1:50\,000$), based on ~~a~~ trigonometrical geodetic surveys conducted in the summers of 1902–1904 (Danish General Staff, 1904). Considerable distortion was observed in the horizontal positioning, related to errors in the survey network established by the Danish Geodetic Institute (Böðvarsson, 1996; Pálsson et al., 2012). Less errors are found in the vertical component, revealed by comparison of the elevation of trigonometric points on mountain peaks and other definite landmarks between the LiDAR DEM and the 1904 maps (see also Guðmundsson et al., 2012). The 1904 maps do not cover all the outlets glaciers up to their ice divides. The Öræfajökull outlets have a complete coverage except Skaftafellsjökull and Morsárjökull, leaving 28% of the total area of the Öræfajökull outlets unmapped. Three of the eastern outlets (Skálafellsjökull, Heinabergsjökull and Fláajökull) were mapped in 1904, but most of the accumulation area was not surveyed, resulting in 67% of their area unmapped. Lambatungnajökull was not surveyed in the early 20th century, but a manuscript map exists from 1938, based on a trigonometric geodetic survey and oblique photographs of the Danish General Staff (archives of the National Land Survey of Iceland). Only a small part of the terminus of Hoffellsjökull was surveyed in 1904, but a map from 1936 covers the whole glacier.

The AMS (Army Map Service) 1 : 50 000 maps with 20 m contour lines (Army Map Service, 1950–1951) cover all the outlet glaciers up to the ice divides~~, and~~. They are based on aerial photographs taken in August–September 1945 and 1946. The geometry in the upper parts of the glaciers, above ∼ 1100 m elevation, was based on the surveys of the Danish General Staff from the 1930s and 1940s, where contour lines are only estimates, indicating shape, not accurate elevation (see also Pálsson et al., 2012). The unpublished DMA maps from 1989 (Defense Mapping Agency, 1997) include only the eastern outlet glaciers. These maps were similarly derived by standard aerial photographic methods, based on images taken in August–September 1989, with a scale of 1 : 50 000 and 20 m contour lines.

A Landsat satellite image ~~of 2000~~ from 1999 and aerial photographs from 1945, 1946, 1960, 1982 and 1989 (http://www.lmi.is/loftmyndasafn) and from 2002 (www.loftmyndir.is) were used to delineate the glacier margin ~~and~~ (Table 2). The glacier margins of the Öræfajökull outlet glaciers were digitized from the high-resolution aerial images of Loftmyndir ehf (with a horizontal resolution of 2.5 m), whereas the glacier margin of the eastern outlets were digitized from a Landsat satellite image from 28th of July 1999 (with a horizontal resolution of ±30 m, http://landsat.usgs.gov).

The aerial images were used to estimate surface elevation changes in the accumulation area from the appearance of nunataks (isolated rock outcrops within the glaciers), as they grow due to lowering of the glacier surface. A 20 m × 20 m DEM from the company Loftmyndir ehf., based on late summer aerial images from 2002, covers parts of Öræfajökull's outlet glaciers with vertical accuracy of < 5 m, excluding most of the accumulation areas. The DGPS surface elevation measurements on southeast Vatnajökull (with a vertical accuracy of ~~1–5~~ 1–2 m) have been carried out during repeated mass balance surveys and radio echo sounding profiling in spring (during the time period 2000–2003~~on southeast Vatnajkull, and~~) are used for DEM construction.

3.2.4 ~~Bedrock~~ Basal topography

The ~~bedrock~~ basal topography has been derived from radio echo sounding measurements, carried out in the last two decades ~~(Björnsson and Pálsson, 2004, 2008; Björnsson, 2009; Magnússon et al., 2007, 2012, and the data bas~~ We calculate the total ice volume from the ~~bedrock~~ bed DEMs and the ~~relative~~ ice volume changes as a fraction of the total volume. The accuracy of the ~~bedrock measurements~~ measurements of the subglacial topography is ±5–20 m, depending on location.

4 Methods

4.1 Glacier surface DEMs

~~Glacier surface DEMs are~~ The glacier surface DEMs were used to determine changes in elevation and volume, and to infer mass changes (e.g., Reinhardt and Rentsch, 1986; Kääb and Funk, 1999). Comparison of 2002 DEMs retrieved from the aerial images of Loftmyndir ehf.~~2002~~, SPOT5 HRS images ~~in autumn from~~ from autumn 2008 (Korona et al., 2009), and the 2010 LiDAR, ~~reveals~~ revealed that the surface geometry in the upper accumulation area has undergone negligible changes during the first decade of the 21st century, at a time of rapid changes in the ablation area (see also Björnsson and Pálsson, 2008). Minor changes in the surface geometry in the upper accumulation area of a western outlet of Vatnajökull in 1998–2010 ~~has~~ have similarly been observed (Auriac et al., 2014). When constructing the DEMs of 1938, 1945, 1989 and 2002, it ~~is~~ was therefore assumed that the glacier surface geometry in the upper reaches of the accumulation area ~~does~~ did not change, but the estimated vertical displacement ~~is~~ was superimposed on the LiDAR DEM. The DEMs were obtained by construcing new contour lines from each contour line of the LiDAR DEM; the new contour having the elevation of the LiDAR plus an elevation shift. The intersection point of the new contour with the valley wall is found by moving the old point up or down the wall by a vertical elevation change along a line drawn between the old intersection points on the opposite sides of the valley. We consider the average vertical bias of each DEM to be smaller than the estimated point accuracy, which is provided in Table 5.

The various DEMs were merged into a common dataset, coregistered and georeferenced, and the LiDAR data providing the reference DEM. Regular $50\,\mathrm{m} \times 50\,\mathrm{m}$ DEMs were created by digitizing the contour lines of the paper maps (1904, 1938, 1945, 1989) and interpolated using the point kriging method (e.g., Wise, 2000) . The appearance of nunataks ~~is~~ was used to determine ice surface elevation changes in the accumulation area of the southeast outlets, as has been ~~used~~ done to estimate downwasting elsewhere (Paul et al., 2007; Rivera et al., 2007; Berthier et al., 2009; Pelto, 2010). The ~~LiDAR DEMs are used as reference topography; the aerial images are~~ aerial images were laid on top of and georeferenced with a shaded relief LiDAR image ~~. This provides new estimates on~~ and the outline of the nunataks digitized. Most of the nunataks have steep slopes and the variable snow cover around them is incorporated in the error assessment. This approach provided new estimates for surface elevation changes in the upper ~~reaches~~ accumulation area of the glaciers. ~~Regular $50\,\mathrm{m} \times 50\,\mathrm{m}$ DEMs were created by digitizing the contour lines of the paper maps (1904, 1938, 1945, 1989) and interpolated using kriging method (e.g., Wise, 2000) . In upper parts of the glaciers, we extrapolated~~ The surface change data was extrapolated headward as a linear variation between ~~available data points~~ the elevation change data points - retrieved from the trigonometric survey points (1904 map) and the nunataks.

Due to lack of accurate contour lines in the highest part of the accumulation areas, we ~~assume~~ assumed that ice divides ~~are~~ were fixed in time, which may introduce an error in the ~~areal extent~~area estimate. The ice divides ~~are~~ were determined from the LiDAR DEM and the data base of the ~~Glaciology Group of the Institute of Earth Sciences University of Iceland. The neighbouring surging outlets have affected the location of ice divides following surges (Björnsson et al., 2003) . For example, the surges of Skeiarrjkull 1991 and Dyngjujkull 1999~~

~~(Fig. 1), caused ice divides to shift on the order of a few hundred m; however the area affected is small compared to the total area of each outlet .~~

~~We consider the average vertical bias of each DEM to be smaller than the estimated point accuracy. Uncertainties related to the DEM reconstruction based on a few data points in the accumulation area, lead to minor errors in the estimated total volume change, since main volume loss occurs in the ablation areas~~GGIES. Even though there have been surges in the larger outlets of Vatnajökull (Björnsson et al., 2003) , they have not affected the ice divides of the studied southeast outlet glaciers during the study period. Uplift rates around Vatnajökull in the last 20 years have been on the order of 10–30 $\mathrm{mm\,a^{-1}}$, highest around the edge of the ice cap (Árnadóttir et al., 2009; Auriac et al., 2013). We do not however, account for this change of the ~~bedrock~~ bed elevation in the ~~most recent~~ glacier surface DEMs, as it is smaller than the vertical error estimate.

4.1.1 DEMs of 1904 and 1938

The glacier margin delineated on the 1904 maps coincides with the LIA ∼ 1890 lateral moraines around an elevation of 400–500 m, thus surface lowering is assumed to only have taken place below that elevation during the ~~cold time~~ relatively cold period ∼ 1890–1904 ~~(see ?)~~ (see Hannesdóttir et al., 2014 for details of the method). A 1904 DEM of the terminus below 400–500 m was reconstructed and subtracted from the ∼ 1890 DEM ~~(?)~~ (Hannesdóttir et al., 2014) , to calculate volume changes for the ~~time interval~~ period ∼ 1890–1904. Contour lines on the 1904 map indicate ~~shape of~~ only the glacier surface geometry, not accurate elevation. The elevation of the trigonometric survey points on the glacier surface on the 1904 maps, serve as a base for generating the DEM, with an estimated vertical accuracy of 10–15 m. The contour lines of the manuscript map of 1938 of Lambatungnajökull were digitized, and their shape ~~was adjusted according to the contours~~ adjusted to resemble the more accurate contour lines of the AMS 1945 map.

4.1.2 DEMs of 1945

Due to the errors in the old trigonometric network for Iceland, parts of the 1945 maps are ~~somewhat~~ distorted horizontally. Sections of the scanned maps were thus georeferenced individually, by fitting each map segment to the surrounding valley walls, using the LiDAR as reference topography. To estimate glacier surface elevation changes in the accumulation area between 1945 and 2010, we compared the size of nunataks on the original aerial images and the LiDAR shaded relief images (an example shown in Fig. 3). No difference in surface elevation was observed above 1300–1400 m, wherefrom the LiDAR DEM was added to create a continuous 1945 DEM. The glacier margin was revised by analysing the original aerial images, for example in areas where shadows had incorrectly been interpreted as ~~bedrock~~ rock outcrops or snow-covered gullies and valley walls as glacial ice. ~~A~~For the 1945 DEM a conservative vertical error estimate ~~of~~ is 5–10 m ~~is estimated for the 1945 DEM~~was made.

4.1.3 DEMs of 1989

DEMs from the contour lines of the DMA unpublished maps of the eastern outlets have previously been created ~~at the Institute of Earth Sciences, University of Iceland. But here some~~ by the GGIES. Some adjustments were made to the glacier surface geometry in the upper accumulation area, ~~by comparing~~ based on comparison of the size of the nunataks on the original aerial images ~~with~~ and the shaded relief image of the LiDAR DEM. The glacier outline was also ~~reassessed~~ revised by digitizing the glacier margin from the original aerial images in areas of misinterpretation, as on the 1945 images. A conservative vertical error of 5 m for the 1989 DEM is estimated, based on ~~experience of interpreting~~ previous studies of Icelandic glaciers using the DMA maps ~~of Icelandic glaciers~~ (Guðmundsson et al., 2011; Pálsson et al., 2012).

4.1.4 DEMs of 2002

Negligible surface elevation changes above 1300–1400 m ~~are~~ were observed between the aerial images of the company Loftmyndir ehf. from 2002 and the shaded relief of the 2010 LiDAR

DEM; thus the high-resolution LiDAR DEM was spliced with the 2002 DEM ~~was mosaiced~~ (above that elevation) to create a complete 2002 DEM. Comparison of the altitude in ice free areas bordering the glaciers, ~~from~~ between the LiDAR and the Loftmyndir ehf. DEMs, ~~reveals~~ revealed a vertical bias of 2–5 m. The ~~glacier~~ surface elevation in the accumulation area was verified by spring DGPS measurements from radio echo sounding survey transects ~~from~~ of the same year. ~~The glacier margins of the ræfajkull outlet glaciers were digitized from the high-resolution aerial images of Loftmyndir ehf, whereas the glacier margin of the eastern outlets were digitized from Landsat satellite images from 2000 ().~~

A ~2002 DEM of the eastern outlet glaciers was constructed from a series of DGPS measurements from survey transects of radio echo sounding measurements in the time period 2000–2003. The ~~LiDAR DEM was used as topographical reference. The~~ spring DGPS elevation measurements in the accumulation area were corrected by subtracting the difference between spring and autumn elevation from the measured surface, to ~~retrieve~~ create an autumn DEM. Seasonal changes in glacier surface elevation amount to 5 m on average in the accumulation area, observed at mass balance stakes on southeast Vatnajökull every autumn and spring during the period 1996–2010. The vertical error estimate for the 2002 DEM ~~is~~ was estimated to be approximately 1–2 m.

4.2 Glacier hypsometry

The hypsometry (area distribution with altitude) of individual glaciers plays an important role ~~in~~ for their response to climate change through its link with mass-balance ~~elevation distribution (e.g., Furbish and Andrews, 1984; Oerlemans et al., 1998)~~ gradient (e.g., Ahlmann and Thorarinsson, 1943; Furbish and Andrews, 1984; Oerlemans et al., 1998) . The hypsometry is determined ~~by bedrock~~ from the basal topography, ice thickness, ~~and~~ ice volume distribution ~~(e.g., Marshall, 2008; Jiskoot et al., 2009) . One of the first people to descibe the hypsometry of glaciers and classify the hypsometric curves was Ahlmann (in ?) .~~ and glacier dynamics (e.g., Jiskoot et al., 2001; Marshall, 2008; Jiskoot et al., 2009) .

5 main hypsometric classes are presented in De Angelis (2014) , first proposed by Osmaston (1975) and also presented in Furbish and Andrews (1984) :

- (A) Glaciers with a uniform hypsometry, i.e. area is constant with elevation
- (B) Glaciers where the bulk of the area lies above the ELA
- (C) Glaciers where the bulk of the area lies below the ELA
- (D) Glaciers where the bulk of the area lies at the ELA
- (E) Glaciers with bimodal hypsometric curves, where the ELA lies approximately between two peaks

The hypsometric curves of the outlets of southeast Vatnajökull were generated from the LiDAR DEM and ~ 1890 DEM by creating histograms of the elevation data with 50 m elevation intervals.

4.3 ~~ELA~~ The snowline altitude derived from MODIS imagery and the LiDAR DEMs

The elevation of the snowline at the end of ~~summer~~ the ablation season provides an estimate for the ELA on temperate glaciers (e.g., Östrem, 1975; Cuffey and Paterson, 2010). ~~In recent years satellite~~ Satellite data have been used to estimate the ELA by this approximation in remote regions and where mass balance is not measured ~~(e.g., Barcaza et al., 2009; Mathieu et al., 2009; Mernild et al., 2013; Rabatel et al., 2013; Shea et al.,~~ Since limited mass balance measurements exist for the outlet glaciers of this study (Fig. 1, except Breiðamerkurjökull and Hoffellsjökull), the snowline retrieved from ~~the MODIS images~~ autumn MODIS images (dated to 22 of August to 26 of September 2007–2011) is a useful proxy for the present day ELA. The ~~snowline was~~ MODIS images are available on a daily basis, and only cloud-free images were selected to digitize the snowline (Table 2). The snowline was manually digitized and projected ~~over~~ on to the LiDAR DEMs to obtain ~~the~~ its elevation. The average snowline elevation and standard deviation was calculated for the glaciers from each image (Table 1). The accumulation area ratio (AAR) of the outlet glaciers was estimated from the average snowline elevation from all years and the glacier margin in 2010. The estimated MODIS snowline of 2007–2011 is at similar elevation as the

ELA derived from mass balance measurements on Hoffellsjökull and Breiðamerkurjökull Aðalgeirsdóttir et al. (2011); Guðmundsson (2014) .

4.4 Volume calculations and average geodetic mass balance

Ice volume changes for the different time periods since the end of the LIA until 2010 were obtained by subtracting the DEMs from each other. Given the ~~bedrock~~ bed DEMs, the ~~fraction of the volume loss (of the total volume)~~ total volume loss is calculated. The volume change is the average elevation change (Δh) between two years, multiplied by the area of the glacier,

$$\Delta V = \Delta h \times A \tag{1}$$

The ice volume change is converted to average annual mass balance, ~~bn~~bn, expressed in m of water equivalent per year (~~m w.e.~~ $\mathrm{m\,w.e.\,a^{-1}}$) averaged over the mean glacier area

$$\mathrm{bn} = \frac{\rho \times \Delta V}{A \times \Delta t} \tag{2}$$

where ρ is the average specific density of ice, ~~900 kg (Sorge's law),~~ ΔV the volume change, A the average of the initial and final glacier area and Δt the time difference in years between the two DEMs. ~~The volume change is the average elevation change (Δh) between two years, multiplied by the area of the glacier,~~

$$\cancel{\Delta V = \Delta h \times A}$$

Here we use ρ=900 kg $\mathrm{m^{-3}}$ in order to be consistent with the commonly used value for Icelandic glaciers (e.g., Guðmundsson et al., 2011; Pálsson et al., 2012; Jóhannesson et al., 2013) ,

The uncertainty related to the conversion of ice volume to mass change to obtain geodetic mass balances, is small for long periods (decades) of glacier retreat, and when volume loss is mainly confined to the ablation area, mostly ice is lost ~~(e.g., ?Huss, 2013)~~ (e.g., Huss, 2013) . We base our estimates of the error for the geodetic mass balance on previous assessments of errors in DEM reconstruction and geodetic mass balance calculations for ice caps in Iceland

~~(Guðmundsson et al., 2011; Pálsson et al., 2012)~~ (e.g., Guðmundsson et al., 2011) , which take into account the square root of the sum of the two errors associated with each DEM and the glacier area.

5 Results

5.1 Spatial and temporal variability of the MODIS derived ELA

Spatial variability is observed in the ~~ELA deduced from the 2007–2011 MODIS images~~autumn snowline or the MODIS derived ELA (referred to as the MODIS-ELA hereafter). The average ~~ELA~~ MODIS-ELA and the standard deviation for each year is displayed in Fig. 4. The ~~ELA~~ MODIS-ELA of the western outlet glaciers of Öræ~~fajfa~~fa jökull is approximately 170 m higher than on the eastern outlet glaciers, and the ~~ELA~~ MODIS-ELA rises eastward from Skálafellsjökull to Lambatungnajökull by ~ 200 m. Due to the low resolution of the MODIS images, the snowline on the narrow outlet glaciers of Öræfajökull (Morsárjökull, Svínafellsjökull, Kotárjökull, Kvíárjökull, and Hrútárjökull) is only discernible on a limited number of images. The snowline on the ~ 2 km wide Skaftafellsjökull and ~ 3.5 km wide Fjallsjökull is detectable on several images, allowing determination of the ~~ELA~~ MODIS-ELA in all years. The ~~ELA~~ MODIS-ELA range and AAR of the narrow outlet glaciers of Öræfajökull, is thus inferred by comparison with the neighbouring glaciers during overlapping years (Table ~~1~~2). The ~~ELA fluctuated by~~ MODIS-ELA fluctuated about 100–150 m during this 5 years period. A similar interannual trend of the ~~ELA~~ MODIS-ELA is observed; the ~~ELA~~ MODIS-ELA in 2009 is the lowest for most of the glaciers, whereas the ~~ELA in 2010~~ MODIS-ELA is usually the highest in 2010 (Fig. 4). The AAR of the outlet glaciers ~~ranges between~~ is in the range of 0.43 ~~and~~ to 0.71, but the majority of the outlets have an AAR of 0.6–0.65 (Table 1).

5.2 Frontal variations and areal change

The areal extent of the outlet glaciers at different times is shown in Figs. 5 and 6, and in Table ~~2.~~ 3. The outlets started retreating from their terminal LIA moraines ~~$\sim$ 1890, (?)~~ $\sim$ 1890, (Hannesdóttir et al., 2014) , and had retreated 1–4 km by 2010 (Figs. ~~7 and 8), corresponding~~ 2c and 7). This corresponds to an areal decrease of ~~164~~164 $\pm$ 6 km^2, equal to 16 % of the $\sim$1890 areal extent, ~~and~~ or in the range of 15–30 % for individual glaciers (Table ~~2~~ 3 and Fig. ~~9). Main area decrease occurred in the ablation area, although small glacier tongues at higher elevation did also retreat in the 20th century (Figs. 5 and 6). Most glaciershad by 1945 lost 10of their ∼1890 area (Table 2), and~~ 8). For the majority of the glaciers, the rate of area loss was ~~the~~ highest during the time period 1904–1945 ~~for majority of the glaciers~~ (Fig. ~~10a). Hrtrjkull had by that time lost 17, however its debris covered terminus on the 1945 aerial image prevents accurate interpretation of the glacier margin. In the following few decades~~ 9a). In the 1960s to the 1990s glacial retreat slowed down or halted (Fig. ~~7~~2c). During the time period 1982/1989–2002 the areal extent of the glaciers changed little (Figs. 5, 6 and ~~7~~ 2c and Table ~~2~~3). Morsárjökull, Skaftafellsjökull, Hrútárjökull, Skálafellsjökull and Fláajökull advanced in 1970–1990, others remained stagnant (Fig. ~~7~~2c). The terminus position of Skálafellsjökull, Heinabergsjökull and Fláajökull was not measured during this time period, but from aerial images of 1979, it was possible to ~~delineate the location of the~~ position their termini, and infer ~~about their slight advances based on the single year data point~~ their slight advance during this period (Fig. ~~7~~2c). The majority of the glaciers started retreating just prior to the turn of the 21st century; between 2002 and 2010 the glaciers experienced high rates of area loss, the highest for Heinabergsjökull and Hoffellsjökull during the last 120 years (Fig. ~~10a~~ 9a and Table ~~2~~3).

5.3 Thinning and volume changes

Between ~~∼1890~~ $\sim$ 1890 and 2010 the outlet glaciers lowered by 150–270 m near the terminus, but negligible downwasting was observed above $\sim$1500–1700 m elevation (Fig. ~~11a~~10a). Svínafellsjökull and Kvíárjökull underwent the smallest surface lowering during this period, ~~whereas~~ and the glaciers only retreated about 1 km in $\sim$ 1890–2010 (Fig. 2c), both terminating in overdeepened basins. Heinabergsjökull, Hoffellsjökull and Lambatungnajökull experienced the greatest downwasting (Fig. ~~11a).~~ 10a), the outlets are constrained by valley walls on both sides, and have retreated close to 3 km in the post-LIA period (Table 1).

Surface lowering between 1945 and 2010 is shown in Fig. ~~11b~~10b. The comparison of the size of nunataks in the upper reaches of the outlet glaciers, reveals negligible surface elevation change above 1300 m a.s.l. between 1945 and 2010. An example of the different appearance of nunataks ~~in the 20th century is shown in Fig. 3~~ of the outcrops of Skaftafellsjökull called “Skerið milli skarða” ~~.~~ at different times during the 20th century, is shown in Fig. 3. Across the whole southeast part of Vatnajökull, the nunataks are smaller in ~~area in~~ 1989 and 1982 than in 1945 or 2002, ~~meaning~~ indicating that the glacier was thicker at that time. A slight thickening in the accumulation area between 1945 and 1982/1989 is thus ~~inferred. The similar size of the nunataks~~ apparent. However, the nunataks were similar in size in 1945 and ~~2002 is evident.~~ 2002.

In the time period $\sim$ 1890–2010 all the outlets collectively lost $60 \pm 8\,\mathrm{km}^3$ (around 22 % of their LIA volume) and the ~~relative~~ volume loss of individual outlets was in the range of 15–50 % (Table ~~3~~ 4 and Fig. ~~9~~8). The rate of volume loss was highest between 2002 and 2010 and second highest in the time period 1904–1945 (Fig. ~~10b~~9b). All glaciers had lost at least half of their total post-LIA volume loss by 1945 (Table ~~3~~4). The eastern outlet glaciers (except Lambatungnajökull), experienced higher rates of volume loss than the majority of the smaller and steeper outlets of Öræfajökull ice cap during every period of the last 120 years (Fig. ~~10b~~9b). For example between 2002 and 2010 the volume loss of the Öræfajökull outlets was in the range of -0.34 to $-0.13\,\mathrm{km}^3\,\mathrm{a}^{-1}$ vs. -0.95 to $-0.28\,\mathrm{km}^3\,\mathrm{a}^{-1}$ of the eastern outlets (Fig. ~~10b). The lack of 1980s DEMs of~~ 9b). Since no 1980´s DEMs exist for the Öræfajökull outlets, ~~restricts~~ the comparison with the eastern ~~outlet glaciers to the time period~~ outlets is restricted to 1945–2002.

5.4 Geodetic mass balance

The average geodetic mass balance of all the studied glaciers was negative during every time interval of the study period (Fig. ~~12~~ 11 and Table ~~4)~~5), however it is likely that individual years had positive mass balance. The average mass balance of the outlets $\sim$ 1890–2010 was $-0.38\,\mathrm{m\,w.e.\,a}^{-1}$, and in the range of -0.70 to $-0.32\,\mathrm{m\,w.e.\,a}^{-1}$ for individual outlets. The mass ~~loss~~ change in $\sim$ 1890–1904 was between -0.5 and $-0.15\,\mathrm{m\,w.e.\,a}^{-1}$. In the first half of the 20th century (1904–1945), the average mass balance was in the range of -1.00 to $-0.50\,\mathrm{m\,w.e.\,a^{-1}}$. The geodetic mass balance during the warmest decade of the 20th century (1936–1945), is only available for Hoffellsjökull and Lambatungnajökull, when ~~they lost~~ the mass balance was -1.00 and $-0.75\,\mathrm{m\,w.e.\,a^{-1}}$, respectively. In 1945–2002 the mass balance returned to similar values as at the turn of the 19th century. The geodetic mass balance of the eastern outlets was similar during the periods 1945–1989 and 1989–2002. The most negative balance is estimated in 2002–2010, ranging between -1.50 and $-0.80\,\mathrm{m\,w.e.\,a^{-1}}$, except for Heinabergsjökull ~~which lost on average~~ ($-2.70\,\mathrm{m\,w.e.\,a^{-1}}$).

Of the Öræfajökull outlets, Fjallsjökull and Hrútárjökull experienced the most negative average mass balance during the majority of the time periods ~~of the ræfajkull outlets~~ (Fig. ~~12~~11). Heinabergsjökull and Hoffellsjökull sustained the highest rate of mass loss of the eastern outlets during most intervals. Skálafellsjökull and Fláajökull generally had the least negative mass balance during every time period of the post-LIA interval of the eastern outlet glaciers, and Kvíárjökull and Svínafellsjökull of the Öræfajökull outlets.

5.5 Glacier hypsometry

The ~~outlet glaciers of southeast Vatnajkull are divided into 5 hypsometric classes adopted from the categorization of De Angelis (2014) , first proposed by Osmaston (1975) and also presented in Furbish and Andrews (1984) :~~

~~(A) Glaciers with a uniform hypsometry, i.e. area is constant with elevation (B) Glaciers where the bulk of the area lies above the ELA (C) Glaciers where the bulk of the area lies below the ELA (D) Glaciers where the bulk of the area lies at the ELA (E) Glaciers with bimodal hypsometric curves, where the ELA lies approximately between two peaks~~

~~The~~ majority of the studied glaciers belong to shape class B (Table 1 and Fig. ~~13). Lambatungnaj~~12). Lambatungnajökull and Hrútárjökull belong to shape class D. Two glaciers have bimodal hypsometric curves (class E), Svínafellsjökull and Fjallsjökull, the latter could be classified as a piedmont glacier (class C) in its greatest extent ∼ 1890 (Fig. 12).

6 Discussion

6.1 Glacier changes since the end of the LIA

~~Retreat~~ The retreat of the outlet glaciers of southeast Vatnajökull from the LIA terminal moraines, that started in the last decade of the 19th century, was not continuous. The recession accelerated in the 1930s, as a result of the rapid warming beginning in the 1920s (Figs. 2b and ~~7). Glacier recession slowed down following~~ c). Similarly enhanced glacier retreat has been observed in the Alps and southern Norway in the early 20th century (Zemp et al., 2011, and references therein) . Recession of the southeast outlets of Vatnajökull slowed down due to cooler summers after the 1940s, and from the 1960s to late 1980s the glaciers remained stagnant or advanced slightly (Fig. ~~7).~~ 2c). Warmer temperatures after 1995, than in the preceding 2-3 decades (Fig. 2b), caused retreat of the southeast outlets, that increased after year 2000 (Björnsson and Pálsson, 2008; Björnsson et al., 2013) .

A mass gain in the accumulation area during ~~this cooler period was recognized~~ the cooler period 1960s to 1980s was observed on the aerial images of the 1980s, by smaller nunataks than on the 1945 aerial images (Fig. 3). The mass balance of the outlets in some years of the 1970s and 1980s may have been positive, although the geodetic mass balance of the periods 1945–1989 (~~of~~ for the eastern outlets) and 1945–2002 (for Öræfajökull outlets) was negative (Fig. 11). The mass balance of the larger ice caps in Iceland was generally close to zero in 1980–2000 ~~(e.g., Guðmundsson et al., 2009, 2011; Aðalgeirsdóttir et al., 2006, 2011) . According to in situ measurements ,~~ (e.g., Björnsson and Pálsson, 2008; Guðmundsson et al., 2009, 2011; Pálsson et al., 2(In situ measurements show that mass balance was positive on Vatnajökull 1991–1994, but negative since then (Björnsson and Pálsson, 2008; Björnsson et al., 2013). ~~Warmer temperatures after the mid-1990s (Fig. 2b) caused retreat of the southeast outlets, that increased after year 2000 (Björnsson and Pálsson, 2008; Björnsson et al., 2013) . The~~

The highest annual rate of volume and mass loss ~~was highest during the period~~ of the periods investigated was observed in 2002–2010 for almost all the ~~southeast~~ outlet glaciers (Figs. ~~10b and 12~~9b and 11, Table ~~4~~5). The geodetic mass balance ~~is in line with~~ in the range of -1.38 to -1.51 m w.e. a^{-1} (apart from Heinabergsjökull) during the time period 2002–2010 is similar to the measured specific mass balance ~~of Breiamerkurjkull and Hoffellsjkull, which was on average −1.4~~on the larger ice caps in Iceland in the first decade of the 21st century, equal to -1.0 ± 0.5 m w.e. a^{-1} ~~(Björnsson et al., 2013) . Langjkull ice cap, similarly experienced~~ (Pálsson et al., 2012; Björnsson et al., 2013; Jóhannesson et al., 2013) . The warming in Iceland since the 1990s has been 3–4 times higher than the average warming of the Northern Hemisphere during the same time interval (Jones et al., 2012; Björnsson et al., 2013) , which may explain the high rates of mass loss in the ~~period 1997–2009 (–1.26), which was however, even more negative in the warm decade of 1936–1945 (Pálsson et al., 2012)~~ first decade of the 21st century. In situ mass balance measurements of glaciers in Iceland and degree-day mass balance models of selected glaciers indicate that the mass balance is governed by variation in summer ablation (which is strongly correlated with temperature), rather than winter accumulation (Björnsson and Pálsson, 2008; Guðmundsson et al., 2009, 2011; Pálsson et al., 2012; Björnsson et al.,

Increasing negative mass balance in recent years ~~from~~ on majority of ice sheets, ice caps and glaciers worldwide ~~is reported in the latest IPCC report~~ has been reported (Vaughan et al., 2013, and references therein). Glaciers in ~~the Alps (Huss, 2012) and in Alaska (Luthcke et al., 2008) lost on average 1.0during the first decade of the 21st century, considerably smaller than the mass loss of glaciers in Iceland (Fig. 12b), which~~ Iceland experienced among the most negative mass balance worldwide in the early 21st century ~~(Vaughan et al., 2013)~~ (Vaughan et al., 2013; Gardner et al., 2013) . In this time period increased surface lowering on the southeast outlets of Vatnajökull is evidenced in emerging rock outcrops and expansion of nunataks up to an elevation of approximately 1200 m. ~~The~~ A pattern of increased downwasting in the accumulation areas in recent years has been observed in Alaska (Cox and March, 2004), the Alps (Paul et al., 2004), North Cascade glaciers (Pelto, 2010), and Svalbard (James et al., 2012).

The ~~amount of ice~~ ice volume loss (in km^3) ~~lost from the~~ of the non-surging outlets of southeast ~~Vatnaj~~Vatnajökull ~1890–2010 ~~equals the estimated ice loss of~~ corresponds to the ice volume loss of both Langjökull ~~and Breiamerkurjkull during the same time interval (Pálsson et al., 2012; Guðmundsson, 2014) . The average~~ (equal to a mass balance of ~~the outlets in this time period was -0.38, compared to~~ $-0.45\,\mathrm{m\,w.e.\,a^{-1}}$~~of Langjkull (Pálsson et al., 2012) and $-0.64$of~~) and Breiðamerkurjökull ~~(Guðmundsson, 2014)~~ (equal to $-0.64\,\mathrm{m\,w.e.\,a^{-1}}$) during the same time interval (Pálsson et al., 2012; Guðmundsson, 2014) . For comparison the glaciers in the Alps have lost ~~on average~~ $96 \pm 13\,\mathrm{km^3}$ (equal to a mass balance of $-0.31\,\mathrm{m\,w.e.\,a^{-1}}$~~since the end of the LIA (Huss, 2012) , which is 25less than the mass loss of the southeast outlets of Vatnajkull.~~

~~In situ mass balance measurements of glaciers in Iceland and degree-day mass balance models of selected glaciers indicate that the mass balance is governed by variation in summer ablation (which is strongly correlated with temperature), rather than winter accumulation (Björnsson and Pálsson, 2008; Guðmundsson et al., 2009, 2011; Pálsson et al., 2012; Björnsson et al.. Higher than average winter precipitation at the meteorological stations south of Vatnajkull, is not correlated with more positive geodetic mass balances of the southeast outlets. However, a strong correlation ($r = 0.94$–0.98) is found between the geodetic mass balance and the average summer temperature (Table 4). Temperature records in Iceland indicate a warming of approximately 1.5since the latter part of the 19th century until 2002 (Hanna et al., 2004; Jóhannesson et al., 2007) . The mean annual temperature has been $\sim$ 1higher after 2000 than in the mid-1990s, which is 3–4 times higher than the average warming of the Northern Hemisphere during the same time interval (Jones et al., 2012) .~~

~~The ELA of the outlets of southeast Vatnajkull has since the end of the LIA, risen by >300; the ELA during the LIA maximum has been inferred from the elevation of the highest up-valley lateral LIA moraines of the studied glaciers (Hannesdttir et al., 2014). Similar spatial differences in the ELA at both time periods have been observed, a 150–200difference between the western and eastern outlets of ræfajkull, and increasing ELA from Sklafellsjkull to Lambatungnajkull. The geographical variability of the ELA is likely related to orographically enhanced precipitation on the SE coast (e.g., **??**)~~) since 1900 (Huss, 2012) , similar to the mass loss of the North Patagonian Icefield since 1870 (Glasser et al., 2011) .

6.2 Different response to similar climate forcing

The meteorological records from Hólar in Hornafjörður and Fagurhólsmýri (Fig. 1) indicate similar temperature and precipitation fluctuations during the 20th and early 21st century at both stations since start of measurements (Fig. ~~2~~2a and b). We thus infer that the studied outlets ~~have experienced similar climate~~ experienced similar temperature and precipitation forcing since the end of the LIA. ~~The precipitation records from the lowland stations indicate little variation during this time period~~

Details in the response or the magnitude of volume loss of the southeast outlet glaciers of Vatnajökull is governed by the hypsometry, overdeepenings and proglacial lakes, but the general response is governed by the climate. Glaciers respond to mass balance changes by adjusting their surface elevation and area. Our results show that glaciers with different hypsometry respond ~~dynamically differently to the same~~ differently to similar climate forcing as has been reported from several studies (e.g., Kuhn et al., 1985; Oerlemans et al., 1998; Oerlemans, 2007; Jiskoot et al., 2009; Davies et al., 2012; De Angelis, 2014). ~~Glaciers of shape class B lost the smallest percentage of their ∼ 1890 volume (15–20); except Heinabergsj~~The appearing proglacial lakes modify the glacier dynamics by floating of the terminus, increasing calving and ice flow and accelerating the terminus retreat. However, the scarcity of measurements limit the possibility to assess the relative importance of the overall ice loss (see Trussel et al., 2013 and references therein). Glacier surface lowering is generally a function of elevation (Fig. 10) as detailed previously in Schwitter and Raymond (1993) , but the downwasting near the terminus of the southeast outlet glaciers of Vatnajökull ~~(30)and~~ is highly variable (Fig. 10). The outlets terminating in overdeepened basins seem to loose mass by thinning rather than retreat, as has been shown by simplified dynamical models to be the retreat pattern in over-deepened basins (Adhikari and Marshall, 2013) .

The hypsometry of a glacier controls its sensitivity to a rise in the ELA. For example, a temperature rise of 0.5–1.0 °C would raise the ELA by approximately 100 m (given a temperature lapse rate). A rise in the ELA will have more effect on the gently sloping eastern outlets, compared to the steeper Öræfajökull outlets. A 100 m rise in ELA would cause

Lambatungna jökull to loose most of its accumulation area, Hoffellsjökull ~~(25~~and Morsárjökull would loose approximately 30 and 45 %~~). Heinabergsj~~, respectively, whereas the accumulation area of Fjallsjökull would only decrease by 7%. The ELA during the LIA maximum around 1890 has been determined from the elevation of the highest up-valley lateral LIA moraines of the studied glaciers (Hannesdóttir et al., 2014, see Fig. 12), applying a method known as MELM (maximum elevation of lateral moraines, (e.g., Hawkins, 1985) . The ELA of the outlets of southeast Vatnajökull has ~~a small peak in the area distribution in the ablation area~~ risen by ≥ 300 msince the end of the LIA (Fig. ~~13), and the peak in the area distribution of Hoffellsj~~12), reducing the size of the accumulation area by 2–16 % (Table 1).

Glaciers of shape class B lost the smallest percentage of their $\sim$ 1890 volume (15–20%). The two glaciers belonging to shape class B, which terminate in proglacial lakes (Heinabergsjökull ~~is close to the modern average ELA.Lambatungnaj~~and Hoffellsjökull) lost 30% and 25% respectively, the former one has an overdeepened basin reaching 200-300 m below sea level (Fig. 7). Fjallsjökull and Hrútárjökull~~that are of shape class D, have lost 40~~, the east-facing Öræfa jökull outlets, lost the most of their $\sim$ 1890 volume, or 35 % and 50 % ~~of their $\sim$ 1890 volume, respectively. The two glaciers with bimodal hypsometric curves (class E), Sv~~respectively, and receive high amount of precipitation and have ice divides lying above 1800 m. The former one belongs to shape class E and was terminating in a proglacial lake that was formed as early as 1945, in the overdeepened basin, and the latter is of shape class D and its debris covered terminus may have increased the ablation. Hrú~~nafellsj~~tárjökull and ~~Fjallsj~~Lambatungnajökull ~~, have lost 30and 35of their $\sim$1890 volume , respectively~~(shape class D) have lost the highest percentage of their $\sim$ 1890 volume (Fig. 12).

There is a noticeable difference in the response of the neighbouring outlet glaciers, Skaftafellsjökull and Svínafellsjökull. The former ~~has~~ retreated 2.7 km and lost 20 % of its $\sim$ 1890 volume, whereas the latter ~~has~~ only retreated 0.8 km and lost 30 % of its $\sim$ 1890 volume~~although~~. However, part of the surface lowering may be due to excavation of the bed, creating an overdeepening in the terminus area of the glacier, as is well ~~known~~ observed for Breiðamerkurjökull (Björnsson, 1996). Similar difference is observed between Skálafellsjökull and Heinabergsjökull, where the former glacier lost 15 % of its $\sim$ 1890 volume and retreated 2 km, and the latter lost 30 % of its ~ 1890 volume and retreated 3 km. Their ~~bedrock~~ basal topography is different, with Heinabergsjökull terminating in an over-deepened basin (Fig. ~~8~~7), and part of the surface lowering in the ablation area of Heinabergsjökull may likewise be attributed to excavation of the bed.

~~The area-altitude distribution of a glacier controls its sensitivity to a rise in the ELA. For example, a temperature rise of 0.5–1.0would raise the ELA by approximately 100. The ablation area of the gently sloping eastern outlet glaciers will expand more than for the majority of the steeper ræfajkull outlets following a rise in the ELA. Lambatungnajkull would almost loose its accumulation area, Hoffellsjkull and Morsrjkull would loose approximately 30 and 45~~The influence of overdeepenings on the ablation and terminus retreat is clearly seen in the western and eastern arm of Hoffellsjökull (Aðalgeirsdóttir et al., 2011) , where the western arm has retreated more than 3 ~~, respectively~~km, whereas the ~~accumulation area of Fjallsjkull would only decrease by 7.~~ thicker and more escavated eastern arm has only retreated a few hundred m since ~ 1890.

A clearer distinction between the response of the Öræfajökull outlets and the eastern outlets to the post-LIA climate ~~perturbations~~ variation would perhaps be expected, as steeper glaciers generally respond faster to changes in climate (e.g., Cuffey and Paterson, 2010). The thinner Öræfajökull glaciers, with ice divides lying 400–500 m higher than ~~on~~ the eastern outlet glaciers and steep mass balance gradient, are ~~suspected~~ expected to have a shorter response time. The response time of a glacier, i.e. the time it takes for a glacier to adjust its geometry to a new steady state after a change in mass balance, is a function of its mean thickness and terminus ablation (Jóhannesson et al., 1989), and of its hypsometry and mass balance gradient (Cuffey and Paterson, 2010).

However, the geodetic mass balance records and terminus fluctuations of the outlets of south-east Vatnajökull do not indicate a distinct difference in the response of the outlets of the two glaciated regions. ~~But the~~ The temporal resolution of the geodetic mass balance records is lower than the supposed response time of 15–30 years ~~,~~ (given terminus ablation of $-10\,\mathrm{m\,w.e.\,a^{-1}}$ and average ice thicknesses of 150–300 m). In order to detect mass balance changes during the colder period following the 1960s, aerial images could be used to construct surface DEMs, and thereby increase the temporal resolution of the mass balance record for the period 1945–1989 ~~/2002.~~

~~Glacier surface lowering is influenced by the geometry and hypsometry of the outlet glaciers, and the proglacial lakes. Surface lowering is generally a function of elevation (Fig. 11), but the downwasting near the terminus is highly variable. Two of the glaciers experiencing the greatest surface lowering near the termini (Heinabergsjkull and Lambatungnajkull), are constrained by valley walls on both sides, and have retreated close to 3in the post-LIA period (Table 1). The surface elevation changes near the terminus of Svnafellsjkull and Kvrjkull are in the lower range (Fig. 11). The glaciers only retreated about 1in ~1890–2010 (Fig. 7), and they are both confined by steep valley walls and terminate in overdeepened basins. Their mass loss has been governed by thinning rather than retreat, which may be related to their bedrock topography. Using simplified dynamical models, Adhikari and Marshall (2013) found that valley glaciers with overdeepened beds were likely to withdraw through deflation more than marginal retreat.~~

6.3 ~~Volume-area scaling~~

~~Less than 0.1of the world's glacier volume is known (**?**) and observations of volume evolution are rare (e.g., Flowers and Clarke, 1999; Radic et al., 2007; Möller and Schneider, 2010) . Glacier volume change estimates of the whole post-LIA time period are limited (Vaughan et al., 2013, and references therein) , and results of model studies are often compared with calculations from other models, not with observations (e.g., Oerlemans, 2007) . Our volume-area time series of the 12 outlets of southeast Vatnajkull starts at the end of the LIA, when most of the glaciers had reached their maximum size in historical times, some even since the end of the early Holocene deglaciation (Thórarinsson, 1943) . From glacier area inventories, glacier volume has been estimated by applying scaling relations (e.g., Chen and Ohmura, 1990; **?**) and ice-dynamical considerations (e.g., Adhikari and Marshall, 2013) . Our data set provides an opportunity to evaluate the empirical and modelled volume-area scaling relation. The volume-area scaling method~~

~~assumes that the volume of a glacier is proportional to its area in a power γ~~

$V = c \times A^{\gamma}$

~~where V and A are the volume and surface area of a single glacier, and c and γ are constants. Based on statistical regression of data from 63 mountain glaciers, Chen and Ohmura (1990) found γ to be close to 1.36, whereas theoretical considerations predict a value of 1.375 for valley glaciers, supported with data from 144 glaciers (**?**) . The volume-area evolution of the last 120of each studied glacier of southeast Vatnajkull is plotted in Fig. 14. The scaling constants are estimated for the years ~1890, 1904, 1945, 2002, 2010; γ ranging from 1.357 to 1.457, and c between 0.030 and 0.048 (Table 5).~~

~~The scaling parameters are expected to evolve over time; as the glaciers retreat, γ decreases due to the fact that glaciers thin before they undergo notable area decrease (e.g., Radic et al., 2007; **?**) . **?** show how different topographic and climatic settings, glacier flow dynamics, and the degree of dis-equilibrium with climate systematically affect the volume-area relation. The magnitude of γ after 100of glacier retreat was found to be 1.377 ± 0.063, comparable with $\gamma = 1.357$ calculated for a sample of real alpine glaciers (Chen and Ohmura, 1990) . The steady state exponent was however 1.46 (**?**) . From our data set this trend is not evident, as the volume-area data set of ~1890 gives $\gamma = 1.357$, compared to 1.457 in 2002 (Table 5). As seen in Fig. 14, the volume-area relation of the individual outletsvaries. Glaciers with bulk of their area distribution above the ELA (shape class B) are in line with the slope of the classical volume-area relation of **?** and **?** as well, with a slightly higher value for the coefficient c. The majority of the outlets belonging to other hypsometric classes (Hrtrjkull, Svnafellsjkull, Lambatungnajkull, Fjallsj~~(eastern outlets) or 1945–2002 (Ö~~kull, Hoffellsj~~ræ~~kull and Heinabergsj~~fajökull ~~) experienced larger relative volume loss, have a larger exponent γ (Fig. 14), and lost volume at a faster rate than the shape class B glaciers. The increase in γ from our data set can probably be explained by the variable response of individual outlet glaciers and the glaciers not being in the same transient states at each point in time. Furthermore our data set may not be not large enough to make estimates on the change of γ. Comparison of the ice volume calculated according to the exponents of **?** and **?** with our volume estimates,~~

~~reveals an underestimate in ice volume of up to 50. The variable hypsometry, shape, size, and thickness of the outletsof southeast Vatnajkull, indicate that the coefficients of the power law relating glacier volume and area need to be adjusted to variable glaciological parameters and can only be used in a statistical way on a large number of glaciers when inferring the volume from measured area~~outlets).

7 Conclusions

~~We have compiled a series~~ Series of glacier outlines and glacier surface DEMs ~~of~~ for the outlets of southeast Vatnajökull were compiled from various sources. The multi-temporal glacier inventory of volume and area changes for the period $\sim$1890–2010 is unique. ~~We derive the~~ The mass balance history of one of the most sensitive glaciated areas in the world for the post-LIA period was derived by geodetic methods. The average mass balance during the period 1890–2010 was ~~-0.38~~ -0.38 ± 0.96 m w.e. a^{-1} ~~. The glaciers are sensitive to climate change, with high mass turnover rates, and~~ and these glaciers experienced among the highest ~~rates of mass loss~~ mass loss rates (on average 1.34 m w.e. a^{-1}) worldwide in the early 21st century (Vaughan et al., 2013). The glaciated area decreased by ~~162~~ 164 ± 6 km^2 (16 %) in $\sim$1890–2010, and the outlets collectively lost 60 ± 8 km^3 (22 %) of ice, contributing ~~0.154 ± 0.020~~ 0.15 ± 0.02 mm to sea level rise in the post-LIA period.

Each glacier lost between 15 and 50 % of their $\sim$1890 volume, the difference attributed to their variable hypsometry~~and bedrock~~, the basal topography, and the presence of proglacial lakes, that enhance melting at the terminus. The different response of glaciers experiencing similar climatic forcing, underlines the importance of a large sample of glaciers when interpreting the climate signal~~, and highlights~~. The results highlight once more the effect of glacier hypsometry and geometry on the dynamic response of glaciers to changes in mass balance. The ~~dynamically~~ different response of the glaciers show ~~,~~ that frontal variations and ~~aera~~ area changes only provide limited information on the glacier response~~to climate perturbations~~, as some experience rapid downwasting but little retreat.

~~A ~200difference of the ELA of the outlets glaciers was observed during the time period 2007–2011, presumably due to spatial differences in orographically enhanced precipitation, associated with atmospheric fronts and cyclones. The ELA has risen > 300since the end of the 19th century.~~ The steep Öræfajökull outlet glaciers are more likely to survive future warming, since their ice divides are 400–500 m higher than the eastern outlets. Furthermore, proglacial lakes will increase in size and new will form as the glaciers retreat, and ~~enhance melting~~cause enhanced melt.

~~From the data set of the variations of the outlets of southeast Vatnajkull we have assessed the power-law relation between glacier area and volume. A comparison of the ice volume between our measurements and the estimates based on the constants used by **?** and **?** , shows that the relation could underestimate the ice volume up to 50. This needs to be taken into account, since glaciers outside the polar areas are contributing to sea level rise at an accelerated rate. Furthermore, the~~ This glacier inventory provides information that can be used to calibrate mass balance-ice flow models that simulate future glacier response to climate scenarios. Work is already underway to simulate the 20th century evolution of three of the eastern outlets.

Acknowledgements. This work was funded by a doctoral grant of the Research Fund of the University of Iceland to Hrafnhildur Hannesdóttir, two additional grants from the University Research Fund to Guðfinna Aðalgeirsdóttir, the Icelandic Road Administration, The Nordic Centre of Excellence SVALI, the Kvísker Fund, the University of Iceland's Research Centre in Hornafjörður, and the Directorate of Labour. We thank Trausti Jónsson at the Icelandic Meteorological Office for access to the temperature and precipitation records. The 2010 LiDAR DEM was acquired as a part of an ongoing collective effort between the Icelandic Meteorological Office and the Institute of Earth Sciences of the University of Iceland, to map the surface topography of Icelandic ice caps, initiated in the International Polar Year 2007–2009. We thank Tómas Jóhannesson for very helpful comments on an early draft of the manuscript. This publication is contribution No. 42 of the Nordic Centre of Excellence SVALI, "Stability and Variations of Arctic Land Ice", funded by the Nordic Top-level Research Initiative (TRI).

References

Aðalgeirsdóttir, G., Guðmundsson, G. H., and Björnsson, H.: Volume sensitivity of Vatnajökull Ice Cap, Iceland, to perturbations in equilibrium line altitude, J. Geophys. Res.-Earth, 110, F04001, doi:10.1029/2005jf000289, 2005.

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

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

~~Adhikari, S. and Marshall, S. J.: Glacier volume-area relation for high-order mechanics and transient glacier states, Geophys. Res. Lett., 39, , 2012.~~

Adhikari, S. and Marshall, S. J.: Influence of high-order mechanics on simulation of glacier response to climate change: insights from Haig Glacier, Canadian Rocky Mountains, The Cryosphere, 7, 1527–1541, doi:10.5194/tc-7-1527-2013, 2013.

Ahlmann, H. W. and Thorarinsson, S.: Vatnajökull, Scientific results of the Swedish-Icelandic investigations 1936-37-38, Esselte, Stockholm, 1943.

Army Map Service, C. o. E.: Series C762, sheets: 6018-I,IV, 6019-I,II,III,IV, 6020-I,II,III, 611IV, 6120-I,II,III, US Army, Washington D.C., 1950–1951.

Árnadóttir, T., Lund, B., Jiang, W., Geirsson, H., Björnsson, H., Einarsson, P., and Sigurðsson, T.: Glacial rebound and plate spreading: results from the first countrywide GPS observations in Iceland, Geophys. J. Int., 177, 691–716, doi:10.1111/j.1365-246X.2008.04059.x, 2009.

Auriac, A., Spaans, K. H., Sigmundsson, F., Hooper, A., Schmidt, P., and Lund, B.: Iceland rising: Solid Earth response to ice retreat inferred from satellite radar interferometry and visocelastic modeling, J. Geophys. Res.-Sol. Ea., 118, 1331–1344, doi:10.1002/Jgrb.50082, 2013.

Auriac, A., Sigmundsson, F., Hooper, A., Spaans, K. H., Björnsson, H., Pálsson, F., Pinel, V., and Feigl, K. L.: InSAR observations and models of crustal deformation due to glacial surge in Iceland, Geophys. J. Int., 198, 1329–1341, doi:0.1093/gji/ggu205, 2014.

~~Bader, H.: Sorge's Law of densification of snow on high polar glaciers, J. Glaciol., 2, 319–323, 1954.~~

~~Bahr, D. B.: Global distributions of glacier properties: A stochastic scaling paradigm, Water Resour. Res., 3, 1669–1679, , 1997.~~

~~Bahr, D. B., Meier, M. F., and Peckham, S. D.: The physical basis of glacier volume-area scaling, J. Geophys. Res.-Sol. Ea., 102, 20355–20362, , 1997.~~

Barcaza, G., Aniya, M., Matsumoto, T., and Aoki, T.: Satellite-Derived Equilibrium Lines in Northern Patagonia Icefield, Chile, and Their Implications to Glacier Variations, Arct. Antarct. Alp. Res., 41, 174–182, doi:10.1657/1938-4246-41.2.174, 2009.

Bauder, A., Funk, M., and Huss, M.: Ice-volume changes of selected glaciers in the Swiss Alps since the end of the 19th century, Ann. Glaciol., 46, 145–149, 2007.

Berthier, E., Le Bris, R., Mabileau, L., Testut, L., and Remy, F.: Ice wastage on the Kerguelen Islands (49 degrees S, 69 degrees E) between 1963 and 2006, J. Geophys. Res.-Earth, 114, doi:10.1029/2008JF001192, 2009.

Björnsson, H.: Glaciers in Iceland, Jökull, 29, 74–80, 1979.

Björnsson, H.: Scales and rates of glacial sediment removal: a 20 km long and 300 m deep trench created beneath Breiðamerkurjökull during the Little Ice Age, Ann. Glaciol., 22, 141–146, 1996.

Björnsson, H.: Jöklar á Íslandi, Opna, Reykjavík, 2009.

Björnsson, H., and Pálsson, F.: Jöklar í Hornafirði, rannsóknir og saga, in: Jöklaveröld, Náttúra og Mannlíf, edited by: Björnsson, H., 125–164, Skrudda, Reykjavík, 2004.

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

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

Björnsson, H., Pálsson, F., Guðmundsson, S., Magnússon, E., Aðalgeirsdóttir, G., Jóhannesson, T., Berthier, E., Sigurðsson, O., and Thorsteinsson, T.: 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, 2013.

Böðvarsson, A.: Landmælingar og kortagerð Dana á Íslandi: Upphaf landmælinga á Íslandi, Landmælingar Íslands, Reykjavík, 1996.

Chen, J. and Ohmura, A.: Estimation of Alpine glacier water resources and their change since the 1870s, IAHS (International Association of Hydrological Sciences), 193, 127–135, 1990.

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D., and Unnikrishnan, A. S.: Sea level change, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M.: Cambridge University Press, Cambridge, UK and New York, NY, USA, 2013.

Cox, L. H. and March, R. S.: Comparison of geodetic and glaciological mass-balance techniques, Gulkana Glacier, Alaska, USA, J. Glaciol., 50, 363–370, doi:10.3189/172756504781829855, 2004.

~~Crochet, P., Jhannesson, T., Jnsson, T., Sigursson, O., Bjrnsson, H., Plsson, F., and Barstad, I.: Estimating the spatial distribution of precipitation in Iceland using a linear model of orographic precipitation, J. Hydrometeorol., 2007.~~

Cuffey, K. M. and Paterson, W. S. B.: The Physics of Glaciers, Elsevier, Burlington, 4th edn., 2010.

Danish General Staff: Sheets: 87-NV,SV,SA, 97-NV, NA, 96-NA, Generalstabens Topografiske Afdeling, Copenhagen, 1904.

Davies, B. J., Carrivick, J. L., Glasser, N. F., Hambrey, M. J., and Smellie, J. L.: Variable glacier response to atmospheric warming, northern Antarctic Peninsula, 1988–2009, The Cryosphere, 6, 1031–1048, doi:10.5194/tc-6-1031-2012, 2012.

De Angelis, H.: Hypsometry and sensitivity of the mass balance to changes in equilibrium-line-altitude: the case of the Southern Patagonia Icefield, J. Glaciol., 60, 14–28, doi:10.3189/2014JoG13J127, 2014.

De Woul, M., and Hock, R.: Static mass-balance sensitivity of Arctic glaciers and ice caps using a degree-day approach, Ann. Glaciol., 42, 217–224, doi:10.3189/172756405781813096, 2005.

Defense Mapping Agency, H. C.: Series C761, sheets: 2113-I,2213-I,III,IV,2214-II,III, National LAnd Survey of Iceland, Reykjavík, 1997.

Eyþórsson, J.: Variations of glaciers 1931–1960, Jökull, 13, 31–33, 1963.

Flowers, G. E. and Clarke, G. K. C.: Surface and bed topography of Trapridge Glacier, Yukon Territory, Canada: digital elevation models and derived hydraulic geometry, J. Glaciol., 45, 165–174, 1999.

Flowers, G. E., Marshall, S. J., Björnsson, and Clarke, G. K. C.: Sensitivity of Vatnajökull ice cap hydrology and dynamics to climate warming over the next 2 centuries, J. Geophys. Res., 110, F02011, doi:10.1029/2004JF000200, 2005.

Flowers, G. E., Björnsson, H., Geirsdóttir, A., Miller, G. H., and Clarke, G. K. C.: Glacier fluctuation and inferred climatology of Langjökull ice cap through the Little Ice Age, Quaternary Sci. Rev., 26, 2337–2353, 2007.

Furbish, D. J. and Andrews, J. T.: The use of hypsometry to indicate long-term stability and response of valley glaciers to changes in mass transfer, J. Glaciol., 30, 199–211, 1984.

Alex S. Gardner, Moholdt, G., Cogley, J. G.,Wouters, B.,Arendt, A. A.Wahr, J., Berthier, Eþ, Hock, R., Pfeffer, W. T., Kaser, G., Ligtenberg, S. R. M., Bolch, T., Sharp, M. J., Hagen, J. O. van den

Broeke, M. R. Paul, F.:A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009, Science, 340, 852–857, doi:10.1126/science.1234532, 2013.

Glasser, N. F., Harrison, S., Jansson, K. N., Anderson, K., and Cowley, A.: Global sea-level contribution from the Patagonian Icefields since the Little Ice Age maximum, Nat. Geosci., 4, 303–307, doi:10.1038/Ngeo1122, 2011.

Guðmundsson, S.: Reconstruction of late 19th century glacier extent of Kotárjökull and Breiðamerkurjökull in ~~SE-Iceland~~ southeast -Iceland and comparison with the current extent, M.Sc. thesis, University of Iceland, Reykjavík, 2014.

Guðmundsson, S., Pálsson, F., Björnsson, H., and Haraldsson, H. H.: Comparison of energy balance and degree-day models of summer ablation on the Langjökull ice cap, SW-Iceland, Jökull, 59, 1–18, 2009.

Guðmundsson, S., Björnsson, H., Magnússon, E., Berthier, E., Pálsson, F., Guðmundsson, M. T., Högnadottir, T., and Dall, J.: Response of Eyjafjallajökull, Torfajökull and Tindfjallajökull ice caps in Iceland to regional warming, deduced by remote sensing, Polar Res., 30, doi:10.3402/Polar.V30i0.7282, 2011.

Guðmundsson, S., Hannesdóttir, H., and Björnsson, H.: Post-Little Ice Age volume loss of Kotárjökull glacier, ~~SE-Iceland~~southeast Iceland, derived from historical photography, Jökull, 62, 97–110, 2012.

Haeberli, W., Muller, P., Alean, P., and Bösch, H.: Glacier changes following the Little Ice Age- a survey of the international data basis and its perspectives, in: Glacier Fluctuations and Climatic Change, edited by: Oerlemans, J., Kluwer Academic Publishers, Utrecht, 1989.

Hanna, E., Jonsson, T., and Box, J. E.: An analysis of icelandic climate since the nineteenth century, Int., 24, 1193–1210, 2004.

Hannesdóttir, H., Björnsson, H., Pálsson, F., Aðalgeirsdóttir, G., and Guðmundsson, S.: Variations of southeast Vatnajökull ice cap (Iceland) 1650–1900 and reconstruction of the glacier surface geometry at the Little Ice Age maximum, Geografiska Annaler, in press.

Hawkins, M.: Equilibrium-line altitudes and paleoenvironment in the Merchants Bay area, Baffin island, N.W.T., Canada, J. Glaciol., 31, 205–213, 1985.

Huss, M.: Extrapolating glacier mass balance to the mountain-range scale: the European Alps 1900–2100, The Cryosphere, 6, 713–727, doi:10.5194/tc-6-713-2012, 2012.

Huss, M.: Density assumptions for converting geodetic glacier volume change to mass change, The Cryosphere, 7, 877–887, doi:10.5194/tc-7-877-2013, 2013.

Icelandic Meteorological Office and Institute of Earth Sciences, University of Iceland: DEMs of Icelandic glaciers (data set), The Icelandic Meteorological Office, Reykjavík, 2013.

James, T. D., Murray, T., Barrand, N. E., Sykes, H. J., Fox, A. J., and King, M. A.: Observations of enhanced thinning in the upper reaches of Svalbard glaciers, The Cryosphere, 6, 1369–1381, doi:10.5194/tc-6-1369-2012, 2012.

Jiskoot, H., Pedersen, A. K., Murray, T.: Multi-model photogrammetric analysis of the 1990s surge of Sortebræ, East Greenland, J. Glaciol., 47, 677–687, 2001.

Jiskoot, H., Curran, C. J., Tessler, D. L., and Shenton, L. R.: Changes in Clemenceau Icefield and Chaba Group glaciers, Canada, related to hypsometry, tributary detachment, length-slope and area-aspect relations, Ann. Glaciol., 50, 133–143, 2009.

Jóhannesson, T., Raymond, C., and Waddington, E.: Time-Scale for Adjustment of Glaciers to Changes in Mass Balance, J. Glaciol., 35, 355–369, 1989.

Jóhannesson, T., Aðalgeirsdóttir, G., Björnsson, H., Crochet, P., Elíasson, E. B., Ólafsson, H., Pálsson, F., Rögnvaldsson, O., Sigurðsson, O., Snorrason, A., Blöndal Sveinsson, Ó. G., and Þorsteinsson, Þ: Effect of climate change on hydrology and hydro-resources in Iceland, Tech. Rep. OS-2007/011, Reykjavík, 2007.

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

Jóhannesson, T., Björnsson, H., Magnússon, E., Guðmundsson, S., Pálsson, F., Sigurðsson, O., Thorsteinsson, T., and Berthier, E.: Ice-volume changes, bias estimation of mass-balance measurements and changes in subglacial lakes derived by lidar mapping of the surface of Icelandic glaciers, Ann. Glaciol., 54, 63–74, doi:10.3189/2013aog63a422, 2013.

Jones, P. D., Lister, D. H., Osborn, T. J., Harpham, C., Salmon, M., and Morice, C. P.: Hemispheric and large-scale land surface air temperature variations: An extensive revision and an update to 2010, J. Geophys. Res., 35, L19502, doi:10.1029/2008GL034470, 2012.

Kääb, A., and Funk, M.: Modelling mass balance using photogrammetric and geophysical data: a pilot study at Griesgletscher, Swiss Alps, J. Glaciol., 45, 575–583, 1999.

Knoll, C., Kerschner, H., and Abermann, J.: Development of area, altitude and volume of South Tyrolean glaciers since the Little Ice Age maximum, Zeitschrift für Gletscherkunde und Glazialgeologie, 42, 19–36, 2008.

Korona, J., Berthier, E., Bernard, M., Remy, F., and Thouvenot, E.: SPIRI T. SPOT 5 stereoscopic survey of Polar Ice: Reference Images and Topographies during the fourth International Polar Year (2007-2009), Int. Soc. Photogramme., 64, 204–212, doi:10.1016/j.isprsjprs.2008.10.005, 2009.

Kuhn, M., Markel, G., Kaser, G., Nickus, U., Obleitner, F., and Schneider, H.: Fluctuations of climate and mass balances: different responses of two adjacent glaciers, Zeitschrift für Gletscherkunde und Glazialgeologie, 21, 409–416, 1985.

~~Lliboutry, L.: Nieves y Glaciares de Chile: Fundamentos de glaciologa, University of Chile, Santiago, 1956.~~

Luthcke, S. B., Arendt, A. A., Rowlands, D. D., McCarthy, J. J., and Larsen, C. F.: Recent glacier mass changes in the Gulf of Alaska region from GRACE mascon solutions, J. Glaciol., 54, 767–777, doi:10.3189/002214308787779933, 2008.

Lüthi, M. P., Bauder, A., and Funk, M.: Volume change reconstruction of Swiss glaciers from length change data, J. Geophys. Res.-Earth, 115, F04022, doi:10.1029/2010jf001695, 2010.

Magnússon, E., Björnsson, H., and Pálsson, F.: Landslag í grennd Kvískerja í fortíð og framtíð: Niðurstöður ísjármælinga á Kvíár-, Hrútár og Fjallsjökli (Radio echo sounding on Kvíárjökull, Hútárjökull and Fjallsjökull)., Jökull, 57, 83–89, 2007.

Magnússon, E., Pálsson, F., Björnsson, H., and Guðmundsson, S.: Removing the ice cap of Öraefajokull central volcano, ~~SE-Iceland~~southeast Iceland: Mapping and interpretation of ~~bedrock~~ basal topography, ice volumes, subglacial troughs and implications for hazards assessments, Jökull, 62, 131–150, 2012.

Marshall, S. J.: Modelling glacier response to climate change, in: Glacier Science and Environmental Change, edited by: Knight, P. G., Blackwell Publishing, Malden, USA, 275–292, 2008.

Mathieu, R., Chinn, T., and Fitzharris, B.: Detecting the equilibrium-line altitudes of New Zealand glaciers using ASTER satellite images, New Zealand J. Geol. Geophys., 52, 209–222, 2009.

Mernild, S. H., Pelto, M., Malmros, J. K., Yde, J. C., Knudsen, N. T., and Hanna, E.: Identification of snow ablation rate, ELA, AAR and net mass balance using transient snowline variations on two Arctic glaciers, J. Glaciol., 59, 649–659, doi:10.3189/2013jog12j221, 2013.

Möller, M., and Schneider, C.: Calibration of glacier volume-area relations from surface extent fluctuations and application to future glacier change, J. Glaciol., 56, 33–40, 2010.

Nawri, N., and Björnsson, H.: Surface Air Temperature and Precipitation Trends for Iceland in the 21st Century, Tech. Rep. VÍ 2010-005, The Icelandic Meteorological Office, Reykjavík, 2010.

Oerlemans, J.: Estimating the reponse times of Vadret da Morteratsch, Vadret da Palu, Briksdalsbreen and Nigardsbreen from their length records, J. Glaciol., 53, 357–362, 2007.

Oerlemans, J., Anderson, B., Hubbard, A., Huybrechts, P., Johannesson, T., Knap, W. H., Schmeits, M., Stroeven, A. P., van de Wal, R. S. W., Wallinga, J., and Zuo, Z.: Modelling the response of glaciers to climate warming, Clim. Dynam., 14, 267–274, 1998.

Osmaston, H. A.: Models for the estimation of firnlines of present and Pleistocene glaciers, in: Processes in physical and human geography: Bristol essays, edited by: PeeL, R. F., Chisholm, M. D. I., and Haggart, P., 218–245, Heinemann Educational Books Ltd, London, 1975.

Östrem, G.: ERTS data in glaciology- an effort to monitor glacier mass balance from satellite imagery, J. Glaciol., 15, 403–415, 1975.

Pálsson, F., Guðmundsson, S., Björnsson, H., Berthier, E., Magnússon, E., Guðmundsson, S., and Haraldsson, H. H.: Mass and volume changes of Langjokull ice cap, Iceland, similar to $\sim$1890 to 2009, deduced from old maps, satellite images and in situ mass balance measurements, Jökull, 62, 81–96, 2012.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T., and Haeberli, W.: Rapid disintegration of Alpine glaciers observed with satellite data, Geophys. Res. Lett., 31, doi:10.1029/2004gl020816, 2004.

Paul, F., Kääb, A., and Haeberli, W.: Recent glacier changes in the Alps observed by satellite: Consequences for future monitoring strategies, Global Planet. Change, 56, 111–122, doi:10.1016/j.gloplacha.2006.07.007, 2007.

Pelto, M. S.: Forecasting temperate alpine glacier survival from accumulation zone observations, The Cryosphere, 4, 67–75, doi:10.5194/tc-4-67-2010, 2010.

Rabatel, A., Machaca, A., Francou, B., and Jomelli, V.: Glacier recession on Cerro Charquini (16 degrees S), Bolivia, since the maximum of the Little Ice Age (17th century), J. Glaciol., 52, 110–118, doi:10.3189/172756506781828917, 2006.

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J. L., Basantes, R., Vuille, M., Sicart, J.-E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., Ginot, P., Maisincho, L., Mendoza, J., Ménégoz, M., Ramirez, E., Ribstein, P., Suarez, W., Villacis, M., and Wagnon, P.: Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change, The Cryosphere, 7, 81–102, doi:10.5194/tc-7-81-2013, 2013.

Radic, V., Hock, R., and Oerlemans, J.: Volume-area scaling vs flowline modelling in glacier volume projections, Ann. Glaciol., 46, 234–240, 2007.

Reinhardt, W. and Rentsch, H.: Determination of chnages in volume and elevation of glaciers using digital elevation models for the Veragtferner, Ötztal Alps, Austria, Ann. Glaciol., 8, 151–155, 1986.

Rivera, A., Benham, T., Casassa, G., Bamber, J., and Dowdeswell, J. A.: Ice elevation and areal changes of glaciers from the Northern Patagonia Icefield, Chile, Global Planet. Change, 59, 126–137, doi:10.1016/j.gloplacha.2006.11.037, 2007.

~~Rgnvaldsson, O., Jnsdttir, J. F. , and lafsson, H~~

Schwitter, M.P. and Raymond, C.F.: ~~Numerical simulations of precipitation in the complex terrain of Iceland- Comparison with glaciological and hydrological data~~Changes in the longitudinal profiles of glaciers during advance and retreat, ~~Meterol. Z., 16, 71–85, 2007.~~ J. Glaciol., 39, 582–590, 1993.

Shea, J. M., Menounos, B., Moore, R. D., and Tennant, C.: An approach to derive regional snow lines and glacier mass change from MODIS imagery, western North America, The Cryosphere, 7, 667–680, doi:10.5194/tc-7-667-2013, 2013.

Sigurðsson, F.: Vandamál við úrkomumælingar á Íslandi, in: Vatnið og landið. Vatnafræðiráðstefna, Október 1987, edited by: Sigbjarnarson, G., Orkustofnun, Reykjavík, 307, 101–110, 1990.

Sigurðsson, O.: Jöklabreytingar 1930–1970,1970–1995,1995–2011 og 2011–2012, Jökull, 63, 118–122, 2013.

Thórarinsson, S.: Oscillations of the Iceland glaciers in the last 250 years, Geogr. Ann. A, 25, 1–54, 1943.

Trussel, B. L., Motyka, R. J.,Truffer, M.,Larsen, C. F.:Rapid thinning of lake-calving Yakutat Glacier and the collapse of the Yakutat Icefield, southeast Alaska, USA, J. Glaciol., 59, 149–161, doi:10.3189/2013J0G12J081, 2013.

Vaughan, D. G., Comiso, J. C., Allison, I., Carrasco, J., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J., Rignot, E., Solomina, O., Steffen, K., and Zhang, T.: Observations: Cryosphere, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M.: Cambridge University Press, Cambridge, UK and New York, NY, USA, 317–382, 2013.

WGMS: Global Glacier Changes: Facts and Figures, Tech. rep., Zurich, Switzerland, 2008.

Wise, S.: Assessing the quality for hydrological applications of digital elevation models derived from contours, Hydrol. Process., 14, 1909–1929, doi:10.1002/1099-1085(20000815/30)14:11/12<1909::Aid-Hyp45>3.0.Co;2-6, 2000.

Zemp, M.,Zumbuhl, H. J., Nussbaumer, S. M. H. Masiokas, L. E. Espizua, and P .Pitte: Extending glacier monitoring into the Little Ice Age and beyond, PAGES, 19, 69–69, 2011.

Table 1. Characteristics of the southeast outlet glaciers ~~.~~ in 2010. Some glaciers have gently sloping accumulation and ablation areas, which are connected by ice falls, thus the mean slope is not representative for the entire profile. The ELA is presented as the ~~range of the~~ averages of ~~all~~ the years 2007-2011 with the standard deviation. Average ice thickness, the AAR and terminus elevation are presented in $\sim$1890 and 2010.

glacier	slope (°)	ice divide (m a.s.l.)	area (km^2)	volume (km^3)	thickness (m)	AAR	ELA (m a.s.l.)	length (km)	term. elev. (m a.s.l.)	retreat (km)	hypsom.
Morsárj.	6.3	1350	28.9	6.0	215/208	0.75/0.64	~~1000–1130~~ 1065 ± 65	10.8	150/170	1.8	B
Skaftafellsj.	3.8	1880	84.1	20.3	254/241	0.63/0.66	~~1000–1160~~ 1080 ± 80	19.3	80/95	2.5	B
Svínafellsj.	9.0	2030	33.2	3.6	132/108	0.63/0.66	~~1000–1120~~ 1060 ± 60	12.0	90/100	0.8	E
Kotárj.	13.3	1820	11.5	1.7	152/148	0.81/0.71	~~1000–1130~~ 1065 ± 65	6.2	220/400	1.3	B/D
Kvíárj.	6.0	2010	23.2	4.1	187/177	0.62/0.64	~~1010–1130~~ 1070 ± 60	14.1	30/30	1.5	E
Hrútárj.	12.4	1980	12.2	0.9	111/74	0.64/0.58	~~880–910~~ 895 ± 15	8.6	50/60	2.0	A/C
Fjallsj.	7.9	2030	44.6	7.0	185/157	~~0.6~~ 0.55/0.60	~~870–960~~ 915 ± 45	12.9	20/30	2.2	E/C
Skálafellsj.	3.1	1490	100.6	33.3	332/331	0.73/0.68	~~910–1020~~ 965 ± 55	24.4	40/50	2.0	B
Heinabergsj.	3.7	1490	99.7	26.7	308/268	0.64/0.61	~~990–1100~~ 1045 ± 55	22.7	60/70	2.9	B/C
Fláaj.	3.1	1480	169.8	53.9	313/317	0.76/0.59	~~1060–1120~~ 1090 ± 30	25.1	40/70	2.7	B
Hoffellsj.	3.4	1470	206.0	54.3	303/264	0.79/0.63	~~1050–1120~~ 1085 ± 35	23.6	30/50	4.0*	B/D
Lambatungnaj.	5.0	1480	36.3	3.6	135/99	0.61/0.43	~~1110–1210~~ 1160 ± 50	19.3	180/250	2.7	D

*The retreat applies to the western arm of Hoffellsjökull (named Svínafellsjökull).

Table 2. Overview of the datasets used to delineate the glacier margin, create DEMs, MODIS images to extract the late summer snowline (proxy for the ELA).

dataset	time period/details	reference/photographer
Aerial images	2002-2004	Loftmyndir ehf (www.loftmyndir.is)
Oblique photographs	2000-2012	Helgi Björnss., Snævarr Guðmundss., Víðir Reyniss.
Aerial photographs	1945, 1960, 1982, 1989	NLS (www.lmi.is/loftmyndasafn)
SPOT5	2005	SPOT5 (SpotImage©)
Landsat	2000	http://landsat.usgs.gov
MODIS	2007-2011	http://rapidfire.sci.gsfc.nasa.gov/gallery/
LiDAR	2010-2011	IMO and IES
Danish General Staff maps	1904	Danish General Staff, 1904
87 SA	Öræfajökull	Öræfajökull and the upper part of acc. area of Skaftafellsj. and Svínafellsj.
87 SV	Öræfajökull	The lower ablatoin area of Morsárj., Skaftafellsj. and Svínafellsj.
87 NV	Öræfajökull	Morsárjökull and part of the upper accumulation area of Skaftafellsjökull
96 NA	Heinaberg	Part of abl. area of Skálafellsj. and Heinabergsj., Fláaj., snout of Hoffellsj.
97 NA	Kálfafellsstaður	Sultartungnajökull, outlet of Skálafellsjökull
97 NV	Kálfafellsstaður	Part of the western rim of Skálafellsjökull
AMS maps (Series C762)	1945	Army Map Service, 1950–1951
6018-I	Kvísker	
6018-IV	Svínafell	
6019-I	Veðurárdalsfjöll	
6019-II	Breiðamerkurjökull	
6019-III	Öræfajökull	
6019-IV	Esjufjöll	
6020-I	Vatnajökull I	
6020-II	Vatnajökull II	
6020-III	Vatnajökull III	
6119-IV	Kálfafellsstaður	
6120-I	Lambatungnajökull	
6120-II	Hoffell	
6120-III	Hoffellsjökull syðri	
DMA maps (Series C761)	1989	Defense Mapping Agency, 1997
2213-I	Hornafjörður	
2213-III	Hestgerðislón	
2213-IV	Heinabergsjökull	
2214-II	Kollumúli	
2214-III	Eyjabakkajökull	
DGPS surveys	2000-2005	data base of GGIES
satelite image	date	details
MODIS	August 24 2007	Iceland.2007236.terra.250m
MODIS	August 27 2007	Iceland.2007239.terra.250m
MODIS	September 2 2007	Iceland.2007245.terra.250m
MODIS	September 11 2007	Iceland.2007254.terra.250m
MODIS	September 26 2007	Iceland.2007269.terra.250m
MODIS	August 22 2009	Iceland.2008234.terra.250m
MODIS	September 3 2008	Iceland.2008247.terra.250m
MODIS	September 26 2008	Iceland.2008269.terra.250m
MODIS	August 22 2009	Iceland.2009234.terra.250m
MODIS	August 29 2009	Iceland.2009241.terra.250m
MODIS	September 4 2009	Iceland.2009247.terra.250m
MODIS	September 12 2009	Iceland.2009255.terra.250m
MODIS	August 21 2010	Iceland.2010233.terra.250m

Table 3. Area of the outlet glaciers at different times in km^2. The estimated error of the glacier margin is shown in parenthesis in the top row. The DMA aerial photographs of Öræfajökull are from 1982, and of the eastern outlet glaciers from 1989. Glacier outlines from 2002 for Öræfajökull (obtained from images of Loftmyndir ehf.), and from 2000 for Skálafellsjökull, Heinabergsjökull, Fláajökull, Hoffellsjökull and Lambatungnajökull (digitized from Landsat satellite images). Ice divides are assumed to remain constant throughout the time period. The numbers for Hoffellsjökull are from Aðalgeirsdóttir et al. (2011). Percentages are relative to the ∼ 1890 area. *The area of Lambatungnajökull in 1904 is estimated from the relative extent of the neighbouring outlets in that year (99 %). Kotárjökull is not included in the sum of the Öræfajökull outlets, since its area is only known in ∼ 1890 and 2010.

glacier	∼ 1890 (20 m)	1904 (15 m)	1945 (10 m)	1982/1989 (10 m)	2002 (5 m)	2010 (2 m)
Morsárj.	35.3 ± 0.7	34.5 ± 0.6 (98 %)	31.6 ± 0.3 (90 %)	30.9 ± 0.4 (87 %)	30.0 ± 0.2 (85 %)	28.9 ± 0.1 (82 %)
Skaftafellsj.	97.8 ± 1.3	96.7 ± 1.0 (99 %)	90.1 ± 0.6(92 %)	89.4 ± 0.6 (91 %)	86.4 ± 0.3 (88 %)	84.1 ± 0.1 (86 %)
Svínafellsj.	39.5 ± 0.9	38.9 ± 0.7 (98 %)	36.1 ± 0.5 (91 %)	35.5 ± 0.5 (90 %)	34.8 ± 0.3 (88 %)	33.2 ± 0.1 (84 %)
Kotárj.	14.5 ± 0.4		12.3 ± 0.5 (85 %)			11.5 ± 0.04 (79 %)
Kvíárj.	27.9 ± 0.7	27.4 ± 0.5 (98 %)	25.4 ± 0.4 (91 %)	25.1 ± 0.3 (90 %)	24.4 ± 0.2 (88 %)	23.2 ± 0.1 (83 %)
Hrútárj.	17.1 ± 0.5	16.7 ± 0.4 (98 %)	14.1 ± 0.2 (83 %)	13.9 ± 0.2 (81 %)	13.2 ± 0.1 (77 %)	12.2 ± 0.04 (71 %)
Fjallsj.	57.7 ± 0.8	56.1 ± 0.6 (97 %)	51.7 ± 0.4 90 %)	49.4 ± 0.4 (86 %)	47.3 ± 0.2 (82 %)	44.6 ± 0.1 (77 %)
Öræfaj.	275.3 ± 5.3	270.3 ± 3.8 (98 %)	249.0 ± 2.4 (90 %)	244.1 ± 2.4 (89 %)	236.1 ± 1.3 (86 %)	~~181.6 ± 0.58~~226.2 ± 0.58 (82 %)
Skálafellsj.	117.9 ± 1.6	116.4 ± 1.2 (99 %)	106.6 ± 0.7 (90 %)	104.0 ± 0.7 (88 %)	102.8 ± 0.3 (87 %)	100.6 ± 0.1 (85 %)
Heinabergsj.	120.3 ± 1.3	118.2 ± 1.0 (98 %)	109.0 ± 0.6 (91 %)	102.5 ± 0.6 (85 %)	101.8 ± 0.3 (85 %)	100.6 ± 0.1 (83 %)
Fláaj.	205.6 ± 1.9	202.1 ± 1.4 (98 %)	184.1 ± 1.0 (90 %)	181.9 ± 0.9 (88 %)	177.4 ± 0.5 (86 %)	169.7 ± 0.2 (83 %)
Hoffellsj.	234.5 ± 1.9	232.3 ± 1.4 (99 %)	224.5 ± 1.1 (96 %)	215.9 ± 1.0 (92 %)	212.7 ± 0.5 (91 %)	207.5 ± 0.2 (88 %)
Lambatungnaj.	46.1 ± 0.9	45.1 ± 0.9*	40.9 ± 0.4 (89 %)	39.4 ± 0.4 (86 %)	38.8 ± 0.2 (84 %)	36.3 ± 0.1 (79 %)
Eastern	723.9 ± 7.6	714.2 ± 5.9 (99 %)	664.6 ± 3.8 (92 %)	643.8 ± 3.6 (89 %)	632.8 ± 1.8 (87 %)	612.3 ± 0.7 (85 %)

1936 area: Hoffellsjökull 227.7 ± 1.5 (97%), Lambatungnajökull 41.9 ± 0.7 (91%).

Table 4. Volume of the southeast outlet glaciers derived from glacier surface DEMs and the bedrock DEM at different times in km^3. Percentage is relative to the ~ 1890 volume. The estimated point accuracy of the elevation is in parenthesis. * The volume of Lambatungnajökull in 1904 is estimated from the relative size of the neighbouring outlets in that year (99%). Kotárjökull is not included in the sum of the Öræfajökull outlets, since its volume is only known in ~ 1890 and 2010.

glacier	~ 1890 (15–20 m)	1904 (10–15 m)	1945 (5–10 m)	1989 (5 m)	2002 (2 m)	2010 (0.5 m)
Morsárj.	7.6 ± 0.5	7.5 ± 0.4 (99 %)	6.8 ± 0.2 (89 %)		6.3 ± 0.1 (82 %)	6 ± 0.01 (79 %)
Skaftafellsj.	24.8 ± 1.5	24.5 ± 1.0 (99 %)	21.4 ± 0.6 (86 %)		20.7 ± 0.2 (83 %)	19.9 ± 0.04 (80 %)
Svínafellsj.	5.2 ± 0.6	5.1 ± 0.4 (99 %)	4.4 ± 0.3 (84 %)		4.1 ± 0.1 (78 %)	3.6 ± 0.02 (70 %)
Kotárjökull	2.2 ± 0.2					1.7 ± 0.01 (77 %)
Kvíárjökull	5.2 ± 0.4	5.15 ± 0.3 (99 %)	4.5 ± 0.2 (87 %)		4.2 ± 0.05 (81 %)	4.1 ± 0.01 (79 %)
Hrútárjökull	1.9 ± 0.3	1.8 ± 0.2 (96 %)	1.3 ± 0.1 (68 %)		1.08 ± 0.03 (57 %)	0.93 ± 0.01 (49 %)
Fjallsjökull	10.7 ± 0.9	10.3 ± 0.6 (97 %)	8.9 ± 0.4 (83 %)		7.3 ± 0.1 (69 %)	7 ± 0.02 (65 %)
Öræfajökull	55.4 ± 4.4	54.5 ± 2.9	47.2 ± 1.8		43.5 ± 0.58	41.3 ± 0.12
Skálafellsj.	39.1 ± 1.8	38.7 ± 1.2 (99 %)	35.7 ± 0.8 (91 %)	34.9 ± 0.5 (89 %)	34.6 ± 0.2 (88 %)	33.3 ± 0.05 (85 %)
Heinabergsj.	37 ± 1.8	36.6 ± 1.2 (99 %)	32.4 ± 0.8 (88 %)	29.4 ± 0.5 (80 %)	29.1 ± 0.2 (79 %)	26.7 ± 0.05 (72 %)
Fláajökull	64.3 ± 3.1	63.4 ± 2.0 (99 %)	57.7 ± 1.3 (90 %)	57.2 ± 0.9 (89 %)	56.2 ± 0.4 (87 %)	53.9 ± 0.09 (84 %)
Hoffellsj.	71 ± 4	70.4 ± 2.3 (99 %)	63 ± 2 (89 %)	57.6 ± 1.1 (81 %)	57 ± 0.4 (80 %)	54.3 ± 0.1 (76 %)
Lambatungnaj.	6.2 ± 0.7	6.1 ± 0.7 (99 %)	4.7 ± 0.3 (76 %)	4.4 ± 0.2 (76 %)	4.1 ± 0.1 (66 %)	3.6 ± 0.02(58 %)
Eastern outlets	217.6 ± 11.4	215.2 ± 7.4	193.5 ± 5.2	183.6 ± 3.2	180.9 ± 1.3	171.8 ± 0.31

1936 volume: Hoffellsjökull 65 ± 3 (92%), Lambatungnajökull 4.9 ± 0.4 (79%).

Table 5. Geodetic mass balance in m w.e. a^{-1} for outlets of Öræfajökull (upper panel) and the eastern outlet glaciers (lower panel) for different time intervals.~~The correlation of the average summer (JJA) temperature measured at Hlar in Hornafjrur (shown as ave. T) with geodetic mass balance estimates during the same time intervals is shown in the last column.~~

Öræfaj.	~ 1890–1904	1904–1945		1945–2002		2002–2010	~ 1890–2010~~corr. T (r)~~
Morsárj.	-0.18 ± 0.63	-0.48 ± 0.15		-0.26 ± 0.06		-0.99 ± 0.12	-0.37 ± 0.96~~0.98~~
Skaftaf.	-0.19 ± 0.63	-0.73 ± 0.15		-0.13 ± 0.06		-1.06 ± 0.12	-0.40 ± 0.96~~0.94~~
Svínaf.	-0.1 ± 0.63	-0.46 ± 0.15		-0.2 ± 0.06		-0.89 ± 0.12	-0.32 ± 0.96~~0.98~~
Kvíárj.	-0.12 ± 0.63	-0.54 ± 0.15		-0.17 ± 0.06		-0.8 ± 0.12	-0.34 ± 0.96~~0.96~~
Hrútárj.	-0.27 ± 0.63	-0.77 ± 0.15		-0.24 ± 0.06		-1.33 ± 0.12	-0.5 ± 0.96~~0.96~~
Fjallsj.	-0.41 ± 0.63	-0.6 ± 0.15		-0.48 ± 0.06		-1-$.27 \pm 0.12$	-0.57 ± 0.96~~0.96ave. T 9.2 9.9 9.7 10.6~~
Eastern	**~ 1890–1904**	**1904–1945**	**1936–1945**	**1945–1989**	**1989–2002**	**2002–2010**	**~ 1890–2010~~corr. T (r)~~**
Skálaf.	-0.24 ± 0.63	-0.58 ± 0.15		-0.27 ± 0.08	-0.25 ± 0.19	-1.38 ± 0.12	-0.40 ± 0.96~~0.96~~
Heinab.	-0.22 ± 0.63	-0.81 ± 0.15		-0.56 ± 0.08	-0.36 ± 0.19	-2.6 ± 0.12	-0.70 ± 0.96~~0.97~~
Fláaj.	-0.28 ± 0.63	-0.65 ± 0.15		-0.42 ± 0.08	-0.4 ± 0.19	-1.51 ± 0.12	-0.42 ± 0.96~~0.97~~
Hoff.	-0.16 ± 0.63	-0.71 ± 0.15	-0.88 ± 0.39	-0.46 ± 0.08	-0.35 ± 0.19	-1.45 ± 0.12	-0.57 ± 0.96~~0.94~~
Lambat.	-0.14 ± 0.63	-0.6 ± 0.15	-0.68 ± 0.39	-0.17 ± 0.08	-0.48 ± 0.19	-1.5 ± 0.12	-0.47 ± 0.96~~0.94ave. T 9.2 9.9 10.4 9.7 9.7 10.6~~

1904–1936 mb: Hoffellsjökull -0.66 ± 0.39, Lambatungnajökull -0.51 ± 0.39.

~~The scaling exponent γ and coefficient c derived from the best fit line of every year. year γ $c$all 1.405 0.0381890 1.357 0.0481904 1.387 0.0431945 1.430 0.0342002 1.457 0.0302010 1.391 0.040~~

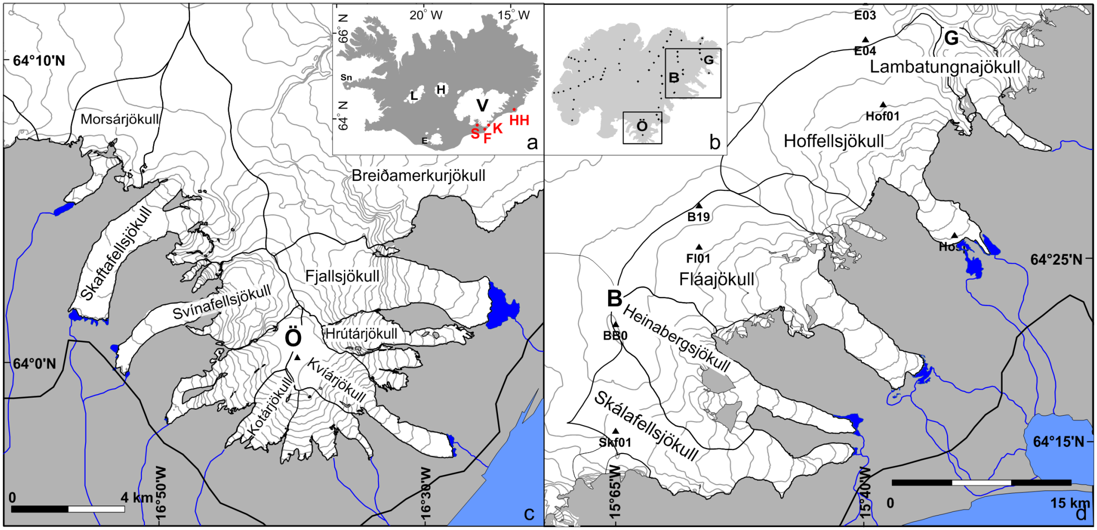


Figure 1. (a) Iceland and Vatnajökull (V) and other ice caps and glaciers mentioned in the text, Hofsjökull (H), Langjökull (L), Eyjafjallajökull (E), and Snæfellsjökull (Sn). Weather stations in Skaftafell (S), Fagurhólsmýri (F), Kvísker (K) and Hólar in Hornafjörður (HH). **(b)** Vatnajökull and mass balance stakes (black dots), the insets show the outline of figures **(c)** the outlet glaciers descending from Öræfajökull ice cap (Ö) and Morsárjökull and **(d)** the outlet glaciers east of Breiðamerkurjökull, descending from the Breiðabunga dome (B), and Goðahnúkar (G)~~, D=Dyngjujkull (mentioned later in the text)~~. The surface topography is from the 2010 LiDAR DEMs, with 100 m contour lines, and ice divides are delineated in black. The location of mass balance measurements is indicated with triangles. Note the different scale of the two figures. Proglacial lakes and rivers are shown in blue and highway 1 in black.~~(**e** and **f**) Topographic relief shading of the LiDAR DEMs of the same area as in **(a)** and **(b)**. The LIA terminal moraines are clearly visible in front of the glaciers and a number of ice-marginal lakes.~~

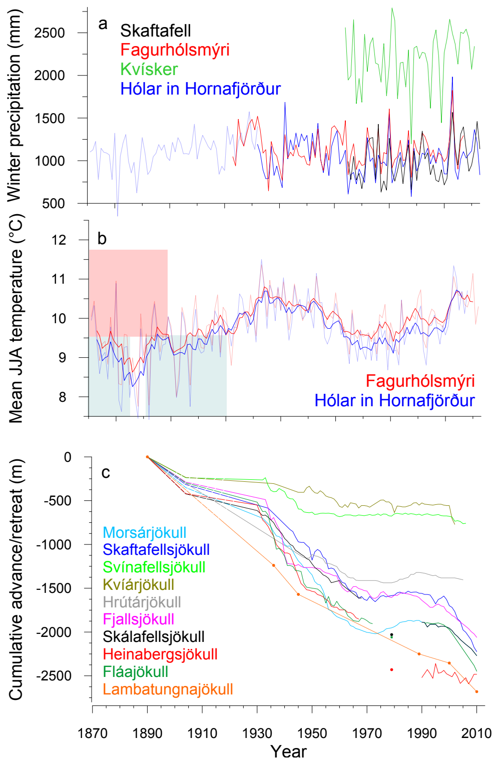

a
Skaftafell
Fagurhólsmýri
Kvísker
Hólar in Hornafjörður
Winter precipitation (mm)
b
Mean JJA temperature (°C)
Fagurhólsmýri
Hólar in Hornafjörður
c
Cumulative advance/retreat (m)
Morsárjökull
Skaftafellsjökull
Svínafellsjökull
Kvíárjökull
Hrútárjökull
Fjallsjökull
Skálafellsjökull
Heinabergsjökull
Fláajökull
Lambatungnajökull
Year

Figure 2. (a) Winter precipitation (October–April in mm) at Skaftafell (black), Fagurhólsmýri (red), Kvísker (green) and Hólar in Hornafjörður (blue), see Fig. 1a for location of stations. Reconstructed precipitation indicated with a light blue line (from Aðalgeirsdóttir et al., 2011). **(b)** Mean summer (JJA) temperature at Fagurhólsmýri (red) and Höfn in Hornafjörður (blue) and 5 years running average. Light blue and light red boxes indicate time period of reconstructed temperature (from Aðalgeirsdóttir et al., 2011). **(c)** Cumulative frontal variations of the southeast outlet glaciers relative to the ∼ 1890 terminus position determined from the terminal LIA moraines (Hannesdóttir et al., 2014) . The retreat until 1932, when measurements of volunteers of the Icelandic Glaciological Society started, is indicated by broken lines; the position in 1904 is known from the maps of the Danish General Staff; note that a linear recession is not expected in ∼ 1890–1904 or 1904–1932. Annual measurements are shown with a solid line (http://spordakost.jorfi.is). Skálafellsjökull, Heinabergsjökull and Fláajökull were not measured in the 1970s and 1980s, but their terminus position in 1979 is determined from aerial images of the National Land Survey of Iceland (indicated by dots). The terminus of Lambatungnajökull (dotted line) has not been measured, but its recession is retrieved from maps, aerial photographs and satellite images.

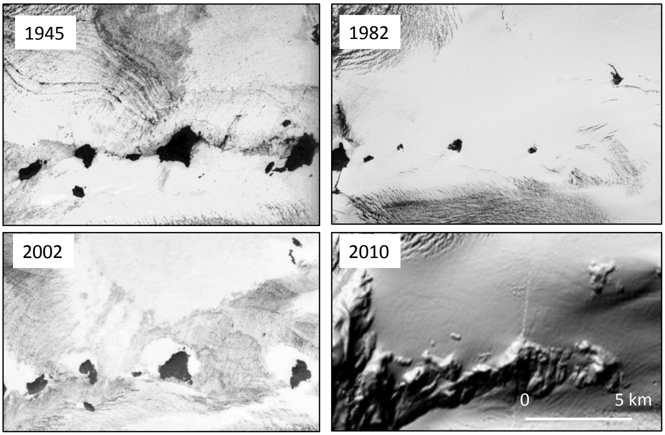


Figure 3. Small nunataks at an elevation of 950–1050 m, east of the mountain "Skerið milli skarða", which divides the main branch of Skaftafellsjökull (see Fig. 5), at different times. Aerial photograph of National Land Survey of Iceland 1945 and 1982, aerial image of Loftmyndir ehf. from 2002, LiDAR shaded relief map from 2010. Only the largest mid nuntak is visible on the 1904 map (not shown).

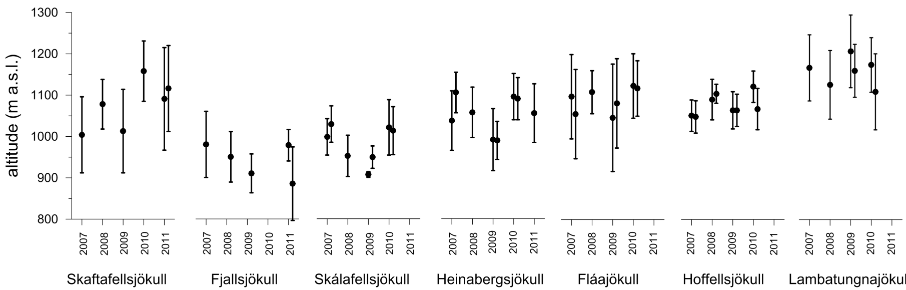


Figure 4. The elevation range (average and standard deviation) of the snowline for each glacier deduced from MODIS images (2007–2011); the elevation obtained from the LiDAR DEM.

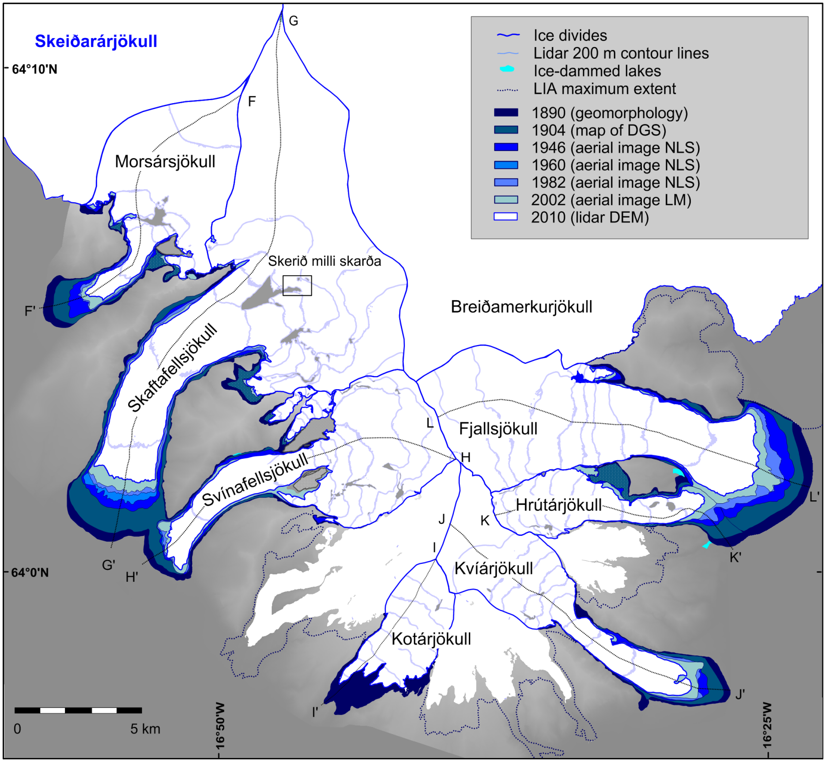


Figure 5. The extent of Öræfajökull's outlet glaciers and Morsárjökull at different times. The surface map is derived from the LiDAR DEM, showing 200 m contour lines. The locations of longitudinal profiles shown in Fig. 8 are indicated with capital letters F-F′, G-G′, etc. The area covering the nunataks east of "Skerið milli skarða", shown in Fig. 3 is outlined. The ice extent in 1904 is uncertain in the mountains surrounding Morsárjökull and Skaftafellsjökull, due to distorted topography on the old map. DGS = Danish General Staff, NLS = National Land Survey of Iceland, LM = Loftmyndir ehf. The ∼ 1890 glacier extent is from ~~?~~ Hannesdóttir et al. (2014) .

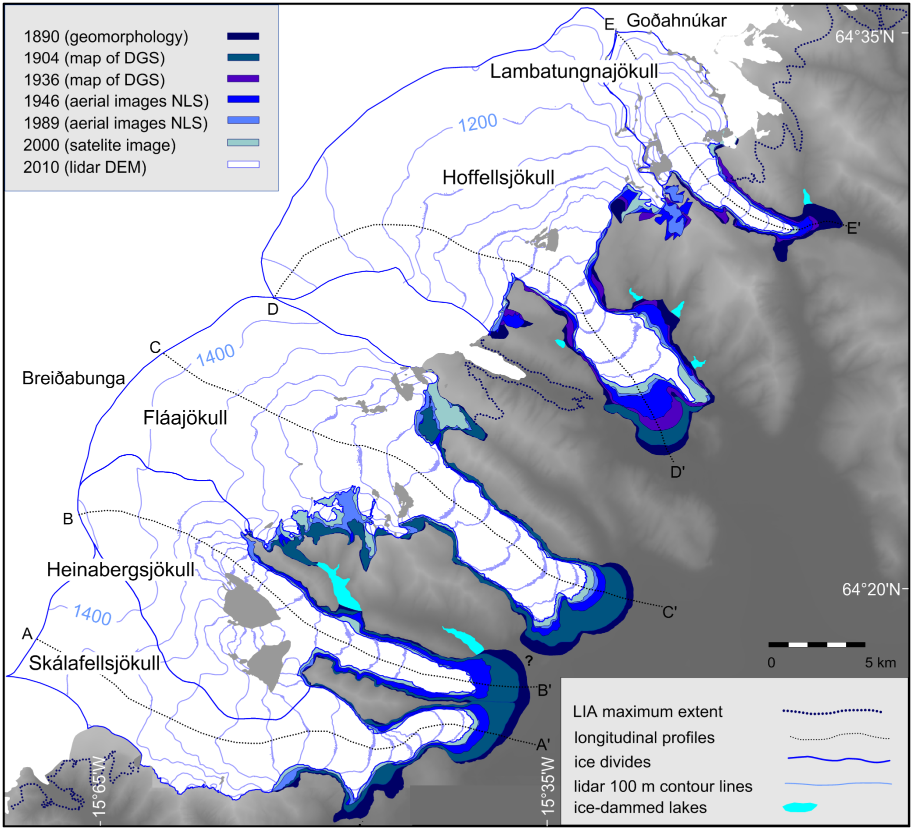


Figure 6. The extent of Skálafellsjökull, Heinabergsjökull, Fláajökull, Hoffellsjökull and Lambatungnajökull at different times. The locations of longitudinal profiles shown in Fig. 8 are indicated with capital letters (A-A′, B-B′ etc.). Surface map is derived from the LiDAR DEM, showing 100 m contour lines. (DGS = Danish General Staff, NLS = National Land Survey of Iceland). The ∼ 1890 glacier extent is from ~~?~~ Hannesdóttir et al. (2014) .

~~Cumulative frontal variations of the southeast outlet glaciers relative to the ∼ 1890 terminus position determined from the terminal LIA moraines (**?**) . The retreat until 1932, when measurements of volunteers of the Icelandic Glaciological Society started, is indicated by broken lines; the position in 1904 is known from the maps of the Danish General Staff; note that a linear recession is not expected in ∼1890–1904 or 1904–1932. Annual measurements are shown with an unbroken line (). Sklafellsjkull, Heinabergsjkull and Flajkull were not measured in the 1970s and 1980s, but their terminus position in 1979 is determined from aerial images of the National Land Survey of Iceland (indicated by dots). The terminus of Lambatungnajkull (dotted line) has not been measured, but its recession is retrieved from maps, aerial photographs and satellite images.~~

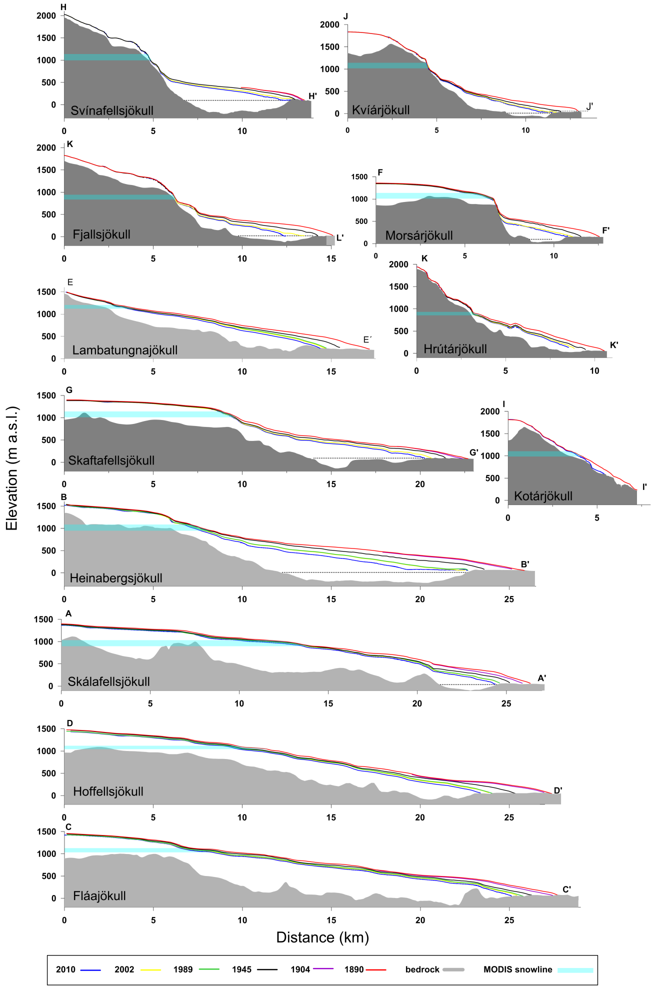

Svínafellsjökull
Kvíárjökull
Fjallsjökull
Morsárjökull
Lambatungnajökull
Hrútárjökull
Skaftafellsjökull
Kotárjökull
Heinabergsjökull
Skálafellsjökull
Hoffellsjökull
Fláajökull
Elevation (m a.s.l.)
Distance (km)
2010
2002
1989
1945
1904
1890
bedrock
MODIS snowline

Figure 7. Longitudinal profiles of the southeast outlet glaciers, showing ice thickness and location of the termini at different times. The average ELA derived from the MODIS images is shown with a light blue horizontal line. Öræfajökull outlets with dark gray colored ~~bedrock~~ basal topography and the eastern outlets with light gray colored ~~bedrock~~basal topography.

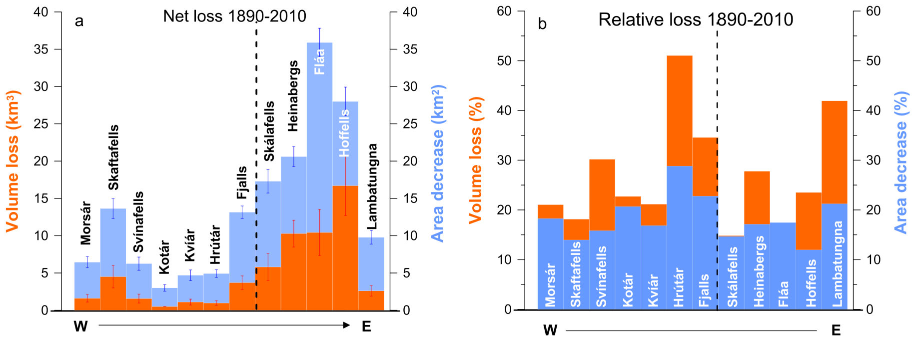


Figure 8. Total area decrease (light blue) and volume loss (orange) during the time period ∼1890–2010 **(a)** absolute values, and **(b)** relative to the LIA maximum size. Glaciers represented in geographical order and the dotted line separates the outlets of Öræfajökull and the eastern outlets.

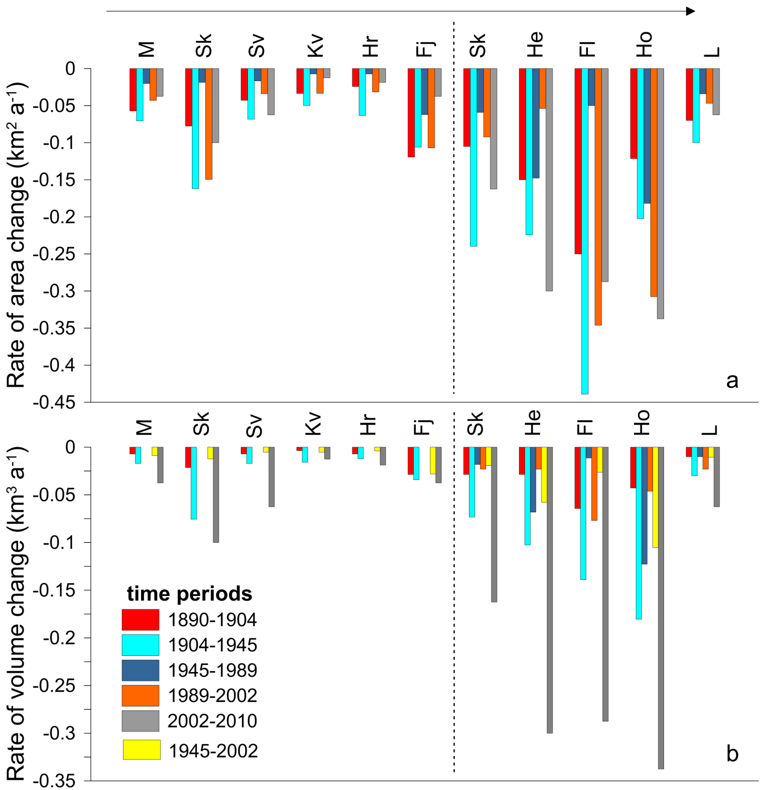


Figure 9. Rate of area **(a)** and volume **(b)** change of the outlet glaciers (from west to east) during different time periods of the last 120 years. The first few letters of each glacier name are shown at the top, glaciers represented ~~in geographical order,~~ from west to east. The dotted line separates the outlets of Öræfajökull and the eastern outlets.

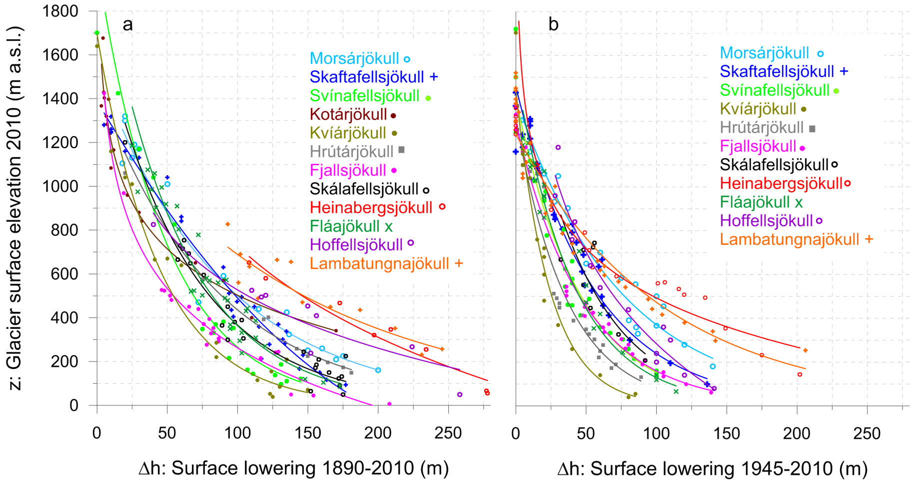


Figure 10. Average surface lowering of every 20 m altitudinal interval of the outlets of southeast Vatnajökull. **(a)** Between ∼ 1890 and 2010 ~~(modified from ?)~~ (modified from Hannesdóttir et al., 2014) . The ∼ 1890 glacier surface elevation in the accumulation area is derived from historical photographs, survey elevation points on the 1904 maps and the aerial images of Loftmyndir ehf., and in the ablation area it is mainly deduced from glacial geomorphological features. **(b)** Between 1945 and 2010. The glacier surface lowering in the accumulation area is based on comparison of the size of nunataks as observed on the original aerial images of 1945 and the LiDAR DEMs. No 1945 DEM is available for Kotárjökull.

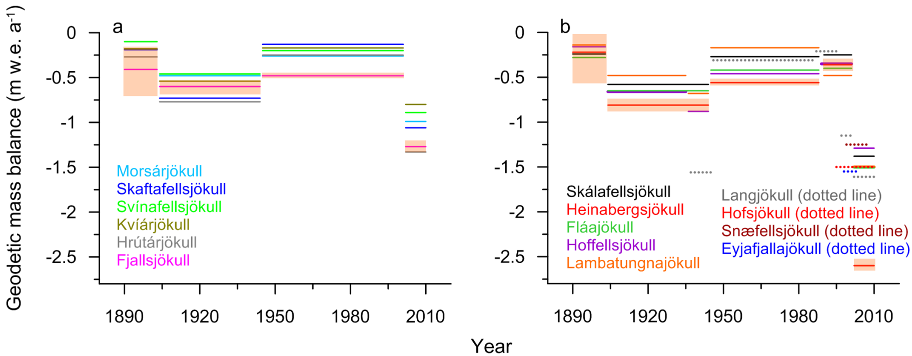
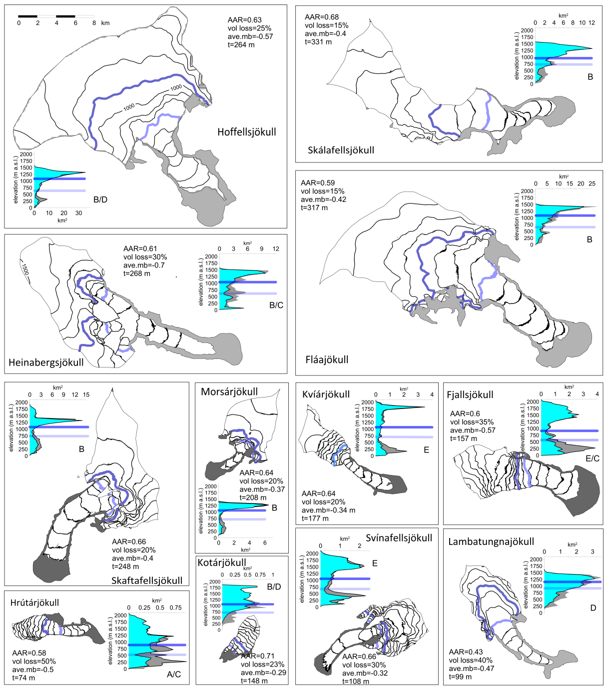


Figure 11. Geodetic mass balance rates during different time periods of the last 120 years. **(a)** The outlet glaciers of Öræfajökull and Morsárjökull. **(b)** The eastern outlet glaciers. For comparison, the geodetic mass balance of Langjökull (Pálsson et al., 2012), Eyjafjallajökull 1998–2004 (Guðmundsson et al., 2011), Snæfellsjökull 1999–2008 (Jóhannesson et al., 2011), and Hofsjökull 1995–2010 (Jóhannesson et al., 2013) is presented with dotted lines in **(b)**. The two latest time periods of Langjökull (1997–2002 and 2002–2010) are based on surface mass balance measurements (data base Glaciological group Institute of Earth Sciences, University of Iceland). For error estimates of the geodetic mass balance see Table ~~4~~5, only the error bars for Fjallsjökull and Heinabergsjökull are shown here.



Hoffellsjökull
AAR=0.63
vol loss=25%
ave.mb=-0.57
t=264 m
B/D
Skálafellsjökull
AAR=0.68
vol loss=15%
ave.mb=-0.4
t=331 m
B
Heinabergsjökull
AAR=0.61
vol loss=30%
ave.mb=-0.7
t=268 m
B/C
Fláajökull
AAR=0.59
vol loss=15%
ave.mb=-0.42
t=317 m
B
Skaftafellsjökull
AAR=0.66
vol loss=20%
ave.mb=-0.4
t=248 m
B
Morsárjökull
AAR=0.64
vol loss=20%
ave.mb=-0.37
t=208 m
B
Kotárjökull
AAR=0.71
vol loss=23%
ave.mb=-0.29
t=148 m
B/D
Hrútárjökull
AAR=0.58
vol loss=50%
ave.mb=-0.5
t=74 m
A/C
Kvíárjökull
AAR=0.64
vol loss=20%
ave.mb=-0.34 m
t=177 m
E
Fjallsjökull
AAR=0.6
vol loss=35%
ave.mb=-0.57
t=157 m
E/C
Svínafellsjökull
AAR=0.66
vol loss=30%
ave.mb=-0.32
t=108 m
E
Lambatungnajökull
AAR=0.43
vol loss=40%
ave.mb=-0.47
t=99 m
D
elevation (m a.s.l.)
km²

Figure 12. The topography of the outlet glaciers in 2010 with 100 m contour lines of the LiDAR DEM. The $\sim$1890 areal extent is shown in dark gray for the Öræfajökull outlets and in light gray for the eastern outlets. The average MODIS-derived ELA (2007–2011) is drawn in dark blue on the map, and the inferred ELA of the maximum LIA in light blue ~~(?)~~ (Hannesdóttir et al., 2014) . Inset graphs show the 2010 area-altitude distribution of the glaciers (hypsometry) in 2010 (cyan) and $\sim$1890 (gray), with the average ELA for 2010 and $\sim$1890 shown in dark blue and light blue, respectively. The AAR, the relative volume loss of their $\sim$1890 size, the average geodetic mass balance $\sim$1890–2010 is shown in m w.e. a^{-1}, as well as the average ice thickness (t) in 2010, for every glacier.

~~Volume-Area evolution of the individual outlet glaciers at ∼ 1890, 1904, 1937, 1945, 1989, 2002, and 2010. The solid red line shows a least-squares fit to all the data points of this study, the solid gray line the corresponding least-squares line derived by ? for 144 glaciers, the solid black line the least-squares line dervied by ? for synthetic glaciers in steady state, and the dashed black line for the same glaciers after 100of retreat.~~