Relation between glacier-termini variations and summer temperature in Iceland since 1930

Oddur SIGURÐSSON,[1] Trausti JÓNSSON,[2] Tómas JÓHANNESSON[2]

[1]*Hydrological Service, National Energy Authority, Grensásvegur 8, IS-108 Reykjavík, Iceland*
E-mail: osig@os.is
[2]*Icelandic Meteorological Office, Bústaðavegur 9, IS-150 Reykjavík, Iceland*

ABSTRACT. Measurements of the retreat and advance of glacier termini are simple and straightforward and in many cases give clear indications about climate history. A careful analysis of glacier type and the processes that override the climate forcing of the mass balance are important for the correct interpretation of terminus variations in terms of climate fluctuations. Regular measurements of glacier variations in Iceland were started in 1930. The Iceland Glaciological Society is now responsible for the monitoring programme. The observed front variations of non-surge-type outlet glaciers of various sizes have closely mimicked major variations of the climate in Iceland during the 20th century. Most of the glaciers retreated rapidly during the warm decades from 1930 to 1960, slowing down as the climate cooled during the following decade, and started to advance after 1970. The rate of advance peaked in the 1980s, after which it slowed down as a consequence of rapid warming of the climate that has taken place since the mid-1980s. Mass-balance measurements show alternating positive and negative mass balance of glaciers during the period 1987–95, but the mass balance has been predominantly negative since 1996. Most glaciers in Iceland began to retreat after 1990, and by 2000 all monitored non-surge-type glaciers in Iceland were retreating. A comparison of the front variations of non-surge-type glaciers and mean summer temperature shows that the major shifts in the climate were followed by a change in the rate of advance or retreat at the termini with a delay of only a few years. This delay does not seem to correlate with the size, the mass turnover or other characteristics of the glacier.

INTRODUCTION

Glaciers integrate the effects of climate over a large area. The results are recorded by variations in the position of the terminus. Annual monitoring of glacier front variations is a simple and straightforward procedure that requires relatively unsophisticated techniques and instruments. Nevertheless, such monitoring produces some of the most important information needed to understand the nature of glaciers; in many cases it reveals the history of climate in regions where little other meteorological information is available (Houghton and others, 2001).

To be able to evaluate the reaction of a glacier to climate change, each glacier must be analyzed carefully. In general, the growth and decay of glaciers depends on the climate through the surface mass balance. The main climatic factors that affect the mass balance of a glacier are radiation and air temperature during the summer or ablation season, and precipitation during the winter or accumulation season (Meier, 1965; Bamber and Payne, 2004). The reaction of the snout of a surge-type glacier to variations in mass balance is masked by advance and retreat caused by surges, and surge-type glaciers are therefore of little use as climate-change indicators. Composite outlet glaciers coming from source areas with variable characteristics may interact in such a way that their reaction at the terminus is not easily interpreted. Several factors other than climate may in some cases influence the mass balance; these factors have to be carefully considered in an analysis of glacier front variations in terms of climate history. Such factors can be geothermal or volcanic activity, debris on the glacier surface and calving in a lake or the ocean, to mention a few factors.

In Iceland the climate during the 20th century was much warmer than during at least the previous four centuries (Bergþórsson, 1969), but with a distinct cooling during the period 1965–85, particularly in an area stretching from Labrador, Canada, to Iceland (Hanna and others, 2004). Three sudden perturbations in temperature and a well-documented history of glacier variations makes Iceland a good place to investigate the relation in space and time between temperature variations and fluctuations in the length of the glacier termini.

The purpose of this paper is to give a brief overview of available data on terminus fluctuations of Icelandic glaciers since regular monitoring started in the 1930s and show examples of how they reflect variations in the climate of the country.

MONITORING OF GLACIER VARIATIONS

Regular monitoring of variations of glacier termini in Iceland was started in 1930 (Eyþórsson, 1931) (Fig. 1). Since 1951, the Iceland Glaciological Society has been responsible for the monitoring (Sigurðsson, 1998). Measurements are carried out by laypeople in the fall of each year, preferably in September or October, but occasionally at other times of the year. Benchmarks (usually two stone cairns or metal poles) have been established at a safe distance in front of a glacier terminus. The measurements of the distance from the benchmarks to the glacier margin are typically made with a tape but sometimes, particularly in previous times, with a string of known length or even by pacing the distance between the benchmark and the terminus.

During the first three to four decades, reports about terminus position were delivered in personal letters to J. Eyþórsson, meteorologist at the Icelandic Meteorological Office, who initiated the monitoring programme. Since

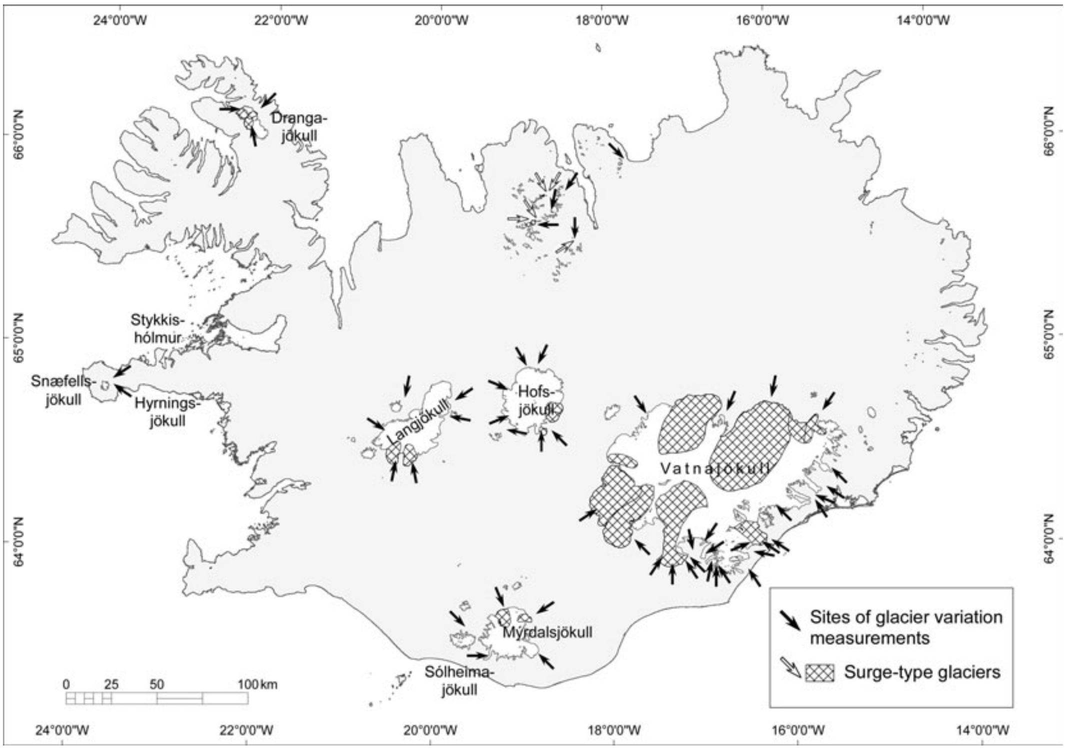

Fig. 1. Location map showing monitored glacier fronts. Known surge-type glaciers are highlighted with cross-hatching.

1967 most of the reports have been filled out on a form designed for this purpose. In most cases, the measurement is accompanied by a description and sometimes a photograph of the situation at the snout. Occasionally, the report includes a forecast of what is to be expected in the near future. Usually, the same people carry out the measurements for many years or even decades. The record is 59 consecutive visits by farmer G. Gunnarsson who started his monitoring in 1947. In some cases, the monitoring of a particular glacier has been carried out by members of the same family since the start of the monitoring programme in the 1930s. Figure 2 shows the number of glacier termini measured each year.

Most glaciers with a fairly large elevation range have a well-defined terminus, which poses no problems in identifying the margin. Occasionally the snout is covered with debris, which inhibits melting to some degree and obscures the glacier margin. Marginal lakes are sometimes obstacles in accessing the terminus. Undulating terrain may cause relatively large or small annual variations, but these tend to even out in the long run. During colder periods, the snouts of glaciers with a limited elevation range may be concealed by snow, even in late summer. Therefore, some glaciers were not measured for some period of time, and the variation records of the termini of small glaciers tend to have breaks and are often incomplete. The measurements are published annually in the periodical *Jökull*, and in *Fluctuations of glaciers* by the World Glacier Monitoring Service (WGMS) at 5 year intervals.

Monitoring of mass balance was started in 1988 (Björnsson and others, 2002; Sigurðsson and others, 2004; Sigurðsson, 2005a). Four of the major ice caps are now included in this programme which is run by the Hydrological Service of the National Energy Authority of Iceland and the Institute of Earth Sciences of the University of Iceland. The results of the mass-balance measurements are published biannually by the WGMS in the *Glacier Mass Balance Bulletin* series (Haeberli and others, 2005).

The outlines of all 276 identified glaciers in Iceland have been traced as of approximately the year 2000, using mainly satellite images but also vertical and oblique aerial photographs, and direct field observations where these were needed to correctly identify the ice margin. This dataset forms a baseline for monitoring future changes in the area covered by glaciers in the country (these outlines can be viewed at http://gullhver.os.is/website/hpf/orkustofnun_english/viewer.htm). The total area of the glaciers in 2000 was found to be 11 048 km^2.

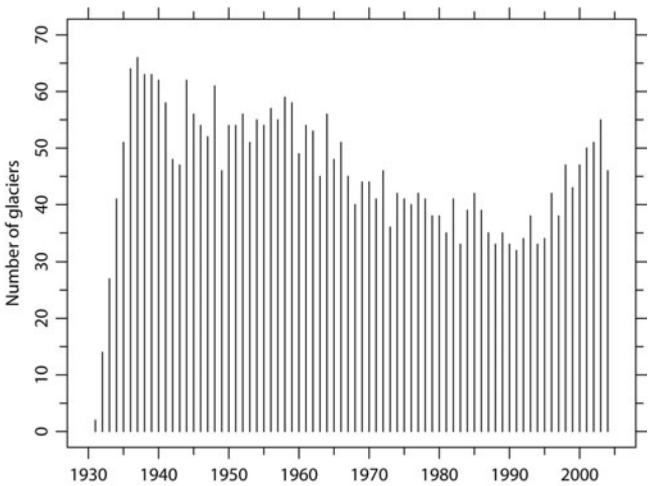

Fig. 2. Number of glacier termini where front variations have been measured, 1930–2005.

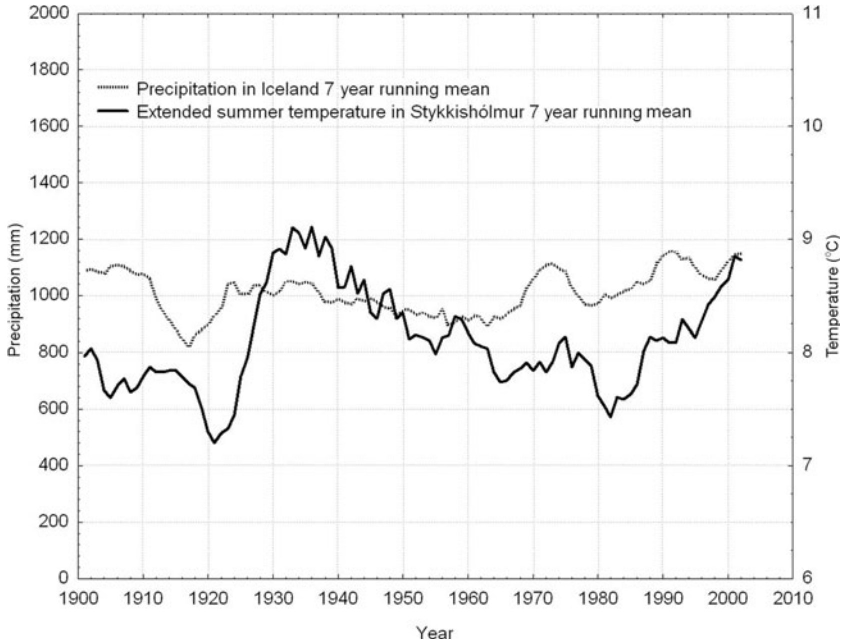

Fig. 3. Annual precipitation in Iceland (average of several available stations), and mean extended summer (May–September) temperature in Stykkishólmur, western Iceland, since 1900.

CLIMATE DURING THE 20TH CENTURY

There are large decadal variations of temperature in Iceland and these have persisted throughout the ~200 year long period of instrumental observations. The year-to-year variability and north–south temperature gradient during the last 100 years seem to have been smaller than during the colder 19th century. This can be attributed to the larger sea-ice cover in the earlier period (see, e.g., Ogilvie and Jónsson, 2001; Hanna and others, 2004). The warming from the 1920s, which was evident during the winter season from earlier in that decade and continued until reaching an abrupt end in 1965, lasted for a shorter period in the summer. The increase in the summer temperatures started later, and the summer warmth was already in decline by the late 1940s. There has been a marked warming in recent decades, during both winter and summer (Fig. 3). While the temperature variations are larger in the north than in the south, they are more or less synchronous over the entire country. The cold period from 1965, which came to an end in two steps around 1985 and 1995, abated slightly earlier in the east than in the west (Hanna and others, 2004).

Annual and decadal variations in precipitation show more local variability than the temperature. During the early 20th century, precipitation was only measured at a few stations, but a generally wet period lasting to the early 1930s seems to have been interrupted by a dry spell in the mid- to late 1910s. There was a general decrease in precipitation from the 1930s to the 1960s, but then an increase until about 1995 (Fig. 3). During the last 40 years, decadal variations have been prominent, with comparatively high precipitation in the 1970–76 period and around 1990 (Hanna and others, 2004).

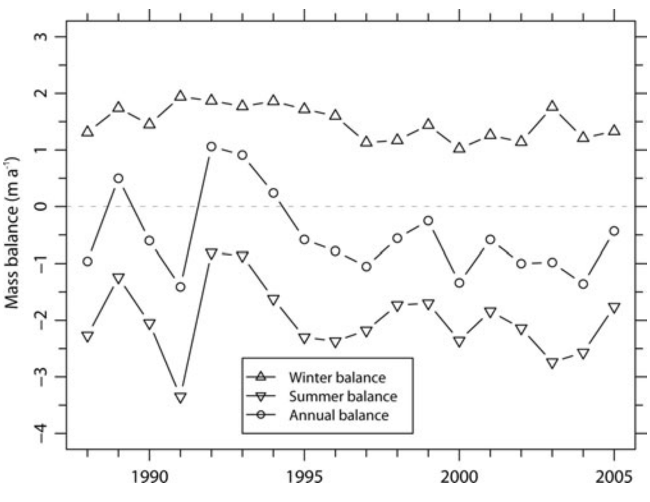

Fig. 4. Mass balance of Hofsjökull ice cap, northern side, 1987–2005.

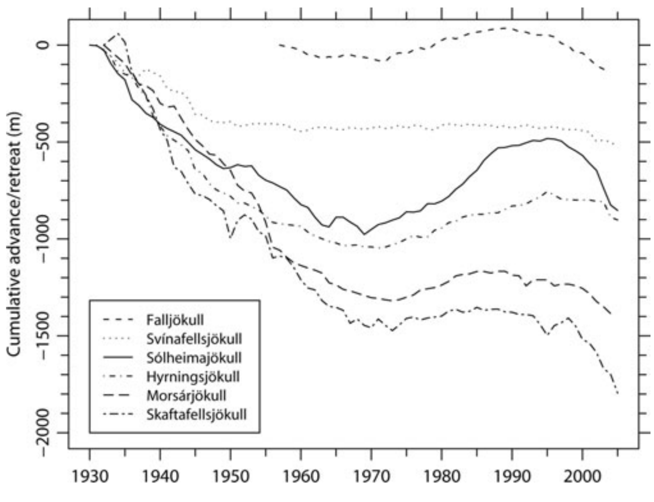

Fig. 5. Cumulative variations of the termini of six non-surge-type glaciers during the period 1930–2005.

Fig. 6. Oblique aerial photograph of Hyrningsjökull, an outlet glacier of Snæfellsjökull, western Iceland, during retreat. View to northwest on 18 October 2001. Photograph by O. Sigurðsson.

GLACIER VARIATIONS DURING THE 20TH CENTURY

Most glaciers in Iceland reached their maximum postglacial extent around 1890 (Björnsson, 1979; Sigurðsson, 2005b). During the first quarter of the 20th century, retreat was notable but not rapid (Björnsson, 1998). The abrupt increase in temperature that occurred about 1925 (Fig. 3) was accompanied by a rapid retreat of glacier fronts all over Iceland (Eyþórsson, 1931, 1963; Sigurðsson, 1998). By 1960, all monitored glaciers had retreated from their 1930 position, although typically 10–20% of the glacier termini were advancing each year (Jóhannesson and Sigurðsson, 1998). The rate of retreat slowed down as the climate cooled gradually during the 1940s and 1950s. Almost all non-surge-type glaciers advanced to a varying degree for two to three decades following the 1960s and then returned to retreating during the 1990s, particularly after 1995, as temperatures began rising rapidly (Fig. 3), with 2002–04 the warmest 3 year period during the almost 200 year long instrumental record. By 2000, all monitored non-surge-type glaciers were retreating (Sigurðsson 2005b).

The mass-balance measurements of the main ice caps show alternating positive and negative mass balance of glaciers during the period 1987–95, but the mass balance has been predominantly negative since 1996 (Fig. 4). According to the mass-balance measurements, the variations in the summer balance are much greater than in the winter balance, which indicates the importance of summer temperature in the net balance.

REACTION OF GLACIER TERMINI TO TEMPERATURE VARIATIONS

Terminus variations of about 60 different glaciers (outlet glaciers, cirque glaciers, etc.) since 1930 are documented in the glacier-variations database of the Iceland Glaciological Society. Half of those have a fairly complete record extending for several decades. They vary in area from <1 to about 1700 km^2 and in length from 1 to 50 km (Sigurðsson, 1998). Kirkbride (2002) analyzed glacier variations in Iceland and their relation to climate and correlated them with the North Atlantic Oscillation.

Figure 5 shows the cumulative variations of the termini of six non-surge-type outlet glaciers during the period 1930–2005. The main shifts in advance and retreat are more or less synchronous for all the glaciers, except for Svínafellsjökull which showed very little change in terminus position during the entire period 1950–2000. It is possible that Svínafellsjökull is somewhat anomalous because of large terminal moraines that hamper its movements back and forth. Two outlet glaciers of different size are chosen here for comparison of front variations with summer temperature. These are Hyrningsjökull (Fig. 6) in the Snæfellsjökull ice cap and Sólheimajökull (Fig. 7) in the Mýrdalsjökull ice cap (Table 1).

It has previously been shown that front variations of Sólheimajökull (Fig. 5) follow very closely a snow-budget index derived from temperature and precipitation records from meteorological stations in Iceland (Sigurðsson and Jónsson, 1995). In Figures 8–10, annual front variations of Hyrningsjökull and Sólheimajökull are compared with the mean extended summer temperature (May–September) at the meteorological station in Stykkishólmur in 7 year running means. The 7 year running mean is somewhat arbitrarily chosen based on trial and error, to reduce interannual scatter

Table 1. Characteristics of the two outlet glaciers as of about the year 2000

	Hyrningsjökull	Sólheimajökull
Length (km)	2	15
Area (km^2)	2	47
Mean thickness (m)	60	270
Volume (km^3)	0.1	12.5
Elevation range (m)	700–1450	110–1450
Average slope (°)	22	5

Notes: The thickness and volume are derived from radio-echo sounding. Sources: Sigurðsson (1998); Björnsson and others (2000); Davíðsdóttir (2003).

Fig. 7. Oblique aerial photograph of Sólheimajökull, an outlet glacier of Mýrdalsjökull, southern Iceland, during advance. View to northeast on 30 October 1985. Photograph by O. Sigurðsson.

but at the same time maintain the amplitude of fluctuations in the climate and terminus position that last longer than a few years. In a few cases in the initial decades of the series, missing annual values have been estimated by annual averages for measurements spanning 2–3 year periods. The coefficient of determination of annual variations in terminus position with temperature is very good for Sólheimajökull ($r^2 = 0.66$) and slightly lower for Hyrningsjökull ($r^2 = 0.55$). This high coefficient of determination indicates that variations of the two non-surge-type glaciers are strongly correlated in time with mass balance, which in turn is predominantly dependent on summer temperature. Most other non-surge-type glaciers in Iceland start their retreat or advance more or less contemporaneously (Fig. 5). This indicates that glacier termini react to (sufficiently large) mass-balance changes quite promptly, with a delay of only a few years. It is notable that the variations of the two glaciers are qualitatively quite similar, in particular the timing of the reversal from advance to retreat during the 1990s, in spite of their very different size and geometry. This relationship is likely to improve if the effect of precipitation variations is included, for example by using a mass-balance model (Greuell, 1992). Also, more detailed considerations of the response time of the glaciers (Jóhannesson and others, 1989; Harrison and others, 2001) are needed in order to interpret the terminus variations quantitatively in terms of climate history (Oerlemans, 2005).

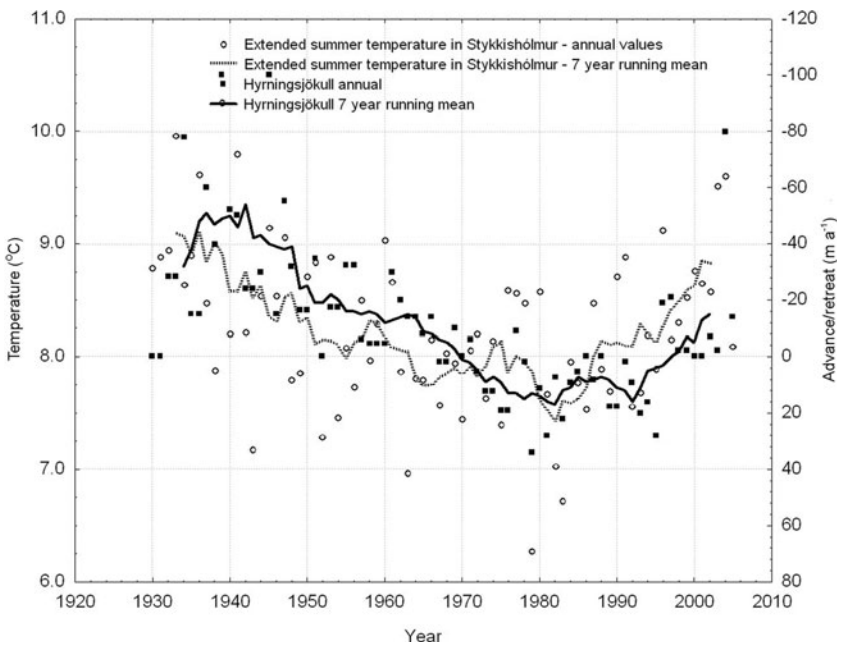

Fig. 8. Annual variations (symbols) of the terminus of Hyrningsjökull (on the righthand scale retreat is up and advance is downward) and mean summer temperature (May–September) in Stykkishólmur (on the lefthand scale). The vertical scale is adjusted to facilitate comparison. Thick curves show 7 year running means.

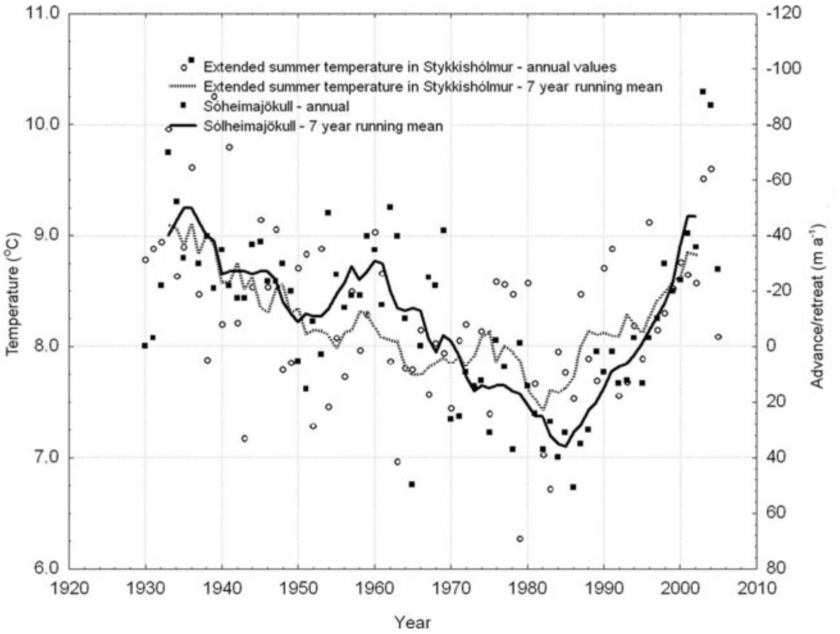

Fig. 9. Same as Figure 8, but for the terminus of Sólheimajökull.

It should be noted that the high correlation between temperature and annual advance or retreat evident in Figure 10 may be expected to depend crucially on the rather rapid climate changes in Iceland during the 20th century. If, for example, the glaciers started to approach a new equilibrium corresponding to a warmer climate, the annual retreat would approach zero for a constant temperature change, which would obviously not agree with the statistical relationship indicated by the distribution of data points in the figure. Such a departure from a simple linear relation may be the cause of the systematic deviation of data points from different periods from the regression lines. For example, the data points for Hyrningsjökull from the early part of the monitoring period, when the glacier was comparatively large, cluster below the regression line, but the more recent data points, when the glacier had become smaller, tend to be located above the line. Thus, the statistical relationships shown by the regression lines in Figure 10 should not be interpreted as a general physical relation between summer temperature and annual advance or retreat, but simply as a graphical representation of these particular data, which interestingly shows a nearly linear distribution for this period. It should also be noted that the fast *reaction* of the glacier terminus to a change in climate does not mean that the glacier has fully adjusted to the change. Thus, the rather fast *reaction time* indicated by Figures 8–10 does not imply a short *response time*, because the response time measures the length of time over which a change in climate affects the position of the terminus, not the length of time until it can first be detected at the terminus (Jóhannesson and others, 1989; Haeberli, 1995).

CONCLUSIONS

During the 20th century, substantial decadal variations of temperature have resulted in distinct variations of glacier termini in Iceland. Changes in summer temperature have been the predominant driving factor in variations of the mass balance of the glaciers. Perturbations in mass balance have caused a reaction of the terminus of non-surge-type glaciers within a few years, a time delay that does not seem to depend much on the size of the glacier.

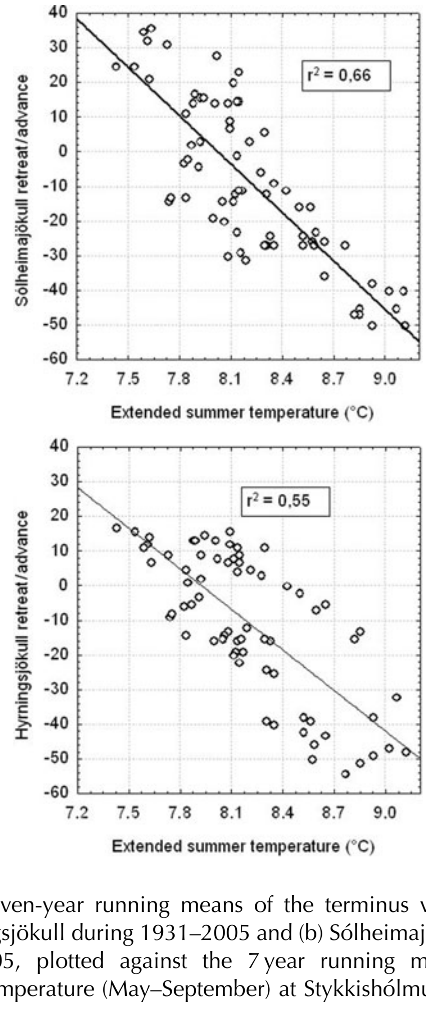

Fig. 10. Seven-year running means of the terminus variations of (a) Hyrningsjökull during 1931–2005 and (b) Sólheimajökull during x1930–2005, plotted against the 7 year running mean of the summer temperature (May–September) at Stykkishólmur.

ACKNOWLEDGEMENTS

Thanks are due to the numerous observers who have carried out the glacier-monitoring programme of the Iceland Glaciological Society during a period of 75 years. Without their work and interest in the nature of glaciers, the extensive dataset of glacier termini variations in Iceland would not exist. Reviews by A. Kääb, M.P. Kirkbride and M. Zemp are appreciated.

REFERENCES

Bamber, J.L. and A.J. Payne, *eds*. 2004. *Mass balance of the cryosphere: observations and modelling of contemporary and future changes.* Cambridge, etc., Cambridge University Press.

Bergþórsson, P. 1969. An estimate of drift ice and temperature in Iceland in 1000 years. *Jökull,* **19**, 94–101.

Björnsson, F. 1998. Samtíningur um jökla milli Fells og Stadherfjalls. *Jökull,* **46**, 49–61.

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

Björnsson, H., F. Pálsson and M.T. Guðmundsson. 2000. Surface and bedrock topography of Mýrdalsjökull, Iceland: the Katla caldera, eruption sites and routes of jökulhlaups. *Jökull,* **49**, 29–46.

Björnsson, H., F. Pálsson and H. Haraldsson. 2002. Mass balance of Vatnajökull (1991–2001) and Langjökull (1996–2001), Iceland. *Jökull,* **51**, 75–78.

Davíðsdóttir, M. 2003. Íssjármæling Snæfellsjökuls. (BS thesis, University of Iceland.)

Eyþórsson, J. 1931. On the present position of the glaciers in Iceland: some preliminary studies and investigations in the summer 1930. *Vísindafélag Isl. Rit.* 10.

Eythórsson, J. 1963. Variations of Iceland glaciers, 1931–1960. *Jökull,* **13**, 31–33.

Greuell, W. 1992. Hintereisferner, Austria: mass-balance reconstruction and numerical modelling of the historical length variations. *J. Glaciol.,* **38**(129), 233–244.

Haeberli, W. 1995. Glacier fluctuations and climate change detection: operational elements of a worldwide monitoring strategy. *WMO Bull.,* **44**(1), 23–31.

Haeberli, W., J. Noetzli, M. Zemp, S. Baumann, R. Frauenfelder and M. Hoelzle, *eds*. 2005. *Glacier Mass Balance Bulletin No. 8 (2002–2003).* Zürich, IAHS (ICSI), World Glacier Monitoring Service; Nairobi, UNEP; Paris, UNESCO.

Hanna, E., T. Jónsson and J.E. Box. 2004. An analysis of Icelandic climate since the nineteenth century. *Int. J. Climatol.,* **24**(10), 1193–1210.

Harrison, W.D., D.H. Elsberg, K.A. Echelmeyer and R.M. Krimmel. 2001. On the characterization of glacier response by a single time-scale. *J. Glaciol.,* **47**(159), 659–664.

Houghton, J.T. *and 7 others*. 2001. *Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, etc., Cambridge University Press.

Jóhannesson, T. and O. Sigurðsson. 1998. Interpretation of glacier variations in Iceland 1930–1995. *Jökull,* **45**, 27–33.

Jóhannesson, T., C. Raymond and E. Waddington. 1989. Time-scale for adjustment of glaciers to changes in mass balance. *J. Glaciol.,* **35**(121), 355–369.

Kirkbride, M.P. 2002. Icelandic climate and glacier fluctuations through the termination of the 'Little Ice Age'. *Polar Geogr.,* **26**(2), 116–133.

Meier, M.F. 1965. Glaciers and climate. *In* Wright, H.E., Jr and D.G. Frey, *eds. The Quaternary of the United States: a review volume for the VII Congress of the International Association for Quaternary Research.* Princeton, NJ, Princeton University Press, 795–805.

Oerlemans, J. 2005. Extracting a climate signal from 169 glacier records. *Science,* **308**(5722), 675–677.

Ogilvie, A.E.J. and T. Jónsson. 2001. 'Little Ice Age' research: a perspective from Iceland. *Climatic Change,* **48**(1), 9–52.

Sigurðsson, O. 1998. Glacier variations in Iceland 1930–1995: from the database of the Iceland Glaciological Society. *Jökull,* **45**, 3–25.

Sigurðsson, O. 2005a. Jöklabreytingar 1930–1960, 1960–1990 og 2003–2004. *Jökull,* **55**, 163–170.

Sigurðsson, O. 2005b. Variations of termini of glaciers in Iceland in recent centuries and their connection with climate. *In* Caseldine, C., A. Russell, J. Harðardóttir and Ó. Knudsen, *eds. Iceland – modern processes and past environments.* Amsterdam, etc., Elsevier, 241–255, 408.

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

Sigurðsson, O., þ. þorsteinsson, S.M. Ágústsson and B. Einarsson. 2004. *Afkoma Hofsjökuls 1997–2004.* Reykjavík, Orkustofnun.