# Climate Induced Twentieth-Century Glacier Fluctuations in Southeast Iceland

## Veðurlagselvdar jøkulbroytingar í tjúgundu øld á Suðurlandinum í Íslandi

*Tom Bradwell*

Department of Geography, Drummond Street, The University of Edinburgh, Edinburgh, UK, EH8 9XP.
Phone: +44 131 650 1000, Fax: +44 131 650 2524, e-mail: tb@geo.ed.ac.uk

## Úrtak

Í hesi grein verður kannað sambandið millum, hvussu Virkisjökull-Falljökull, ein ósajøkul úr Öræfajökulli í Íslandi, tekur seg aftur, og broytingar í miðallufttemperaturi. Jøkulmarkið er broytt tey seinastu 120 árini. Har sum ísurin er bráðnaður, er eitt vítt øki við proglasialum strandarlendi. Stakir *arcuate* kambar og 'ósløtt' avlættingingarmorena eru varðveitt á strandarlendinum og endurspegla mynstur á tí ójavna fremsta partinum av ísinum. Við at brúka likenometriskt tilfar og geomorfisk sambond á staðnum hevur borið til at gera rættiliga neyvar relativar tíðarfestingar. Søguligar heimildir og loftmyndir hava verið brúkt fyri at staðfesta tíðarrøðina seinnu helvt av øldini. Jøkulin hevur ikki tikið seg aftur á ein samlíkan hátt síðan endan á kalda skeiðnum nevnt 'tann lítla ístíðin'. Afturtøkan av tí fremsta á ísinum hevur verið órógvað av *re-advance events* á ymiskum stigum. Eitt uppskot hevur verið, at mynstrið á broytingunum av ísmarkinum samsvarar við gongdina í miðallufttemperaturi í fleiri ár. Heitari tíðarskeið høvdu við sær skjóta lækking í 1900-árunum, 1940-árunum og 1970-árunum; kaldari skeið høvdu ábyrgdina av *re-advances* í 1920-árunum, 1950-árunum og seint í 1970-árunum. Tað sæst, at reaktiónin hjá ísmarkinum til temperaturbroytingar er seinkað umleið sjey til níggju ár.

## Abstract

This paper examines the link between the recession of Virkisjökull-Falljökull, an outlet glacier from the Öraefajökull ice-cap in Iceland, and variations in mean air temperature. The glacier margin has fluctuated in response to climatic change over the past one-hundred and twenty years. Recession of the ice has revealed an extensive area of proglacial foreland. Discrete, arcuate ridges and 'hummocky' ablation moraine are preserved on the foreland reflecting the pattern of ice-front fluctuations. Approximate relative dating of these features has been achieved using lichenometric data combined with geomorphic relationships observed in the field. Historical documentation and aerial photography have been used to construct the chronology for the latter half of the century. The glacier has not retreated in a uniform manner since the end of the 'Little Ice Age' cold phase. Recession of the ice-front has been interrupted by re-advance events on various scales. It is suggested that the twentieth century pattern of ice-marginal fluctuations corresponds with multi-annual trends of mean air temperature. Warmer periods resulting in rapid recession during the 1900's, 1940's and early 1970's; colder spells being responsible for re-advances in the 1920's, 1950's and mid to late 1970's. A lag in the response of the ice margin to temperature variation is seen to be approximately seven to nine years.

## Introduction

This study employs documentary, cartographic, photographic, lichenometric and geomorphological evidence to chronicle the fluctuation of a temperate valley glacier and examine the relationship between frontal movements and local climatic conditions.

Iceland is a uniquely important location for the study of glacial fluctuations owing

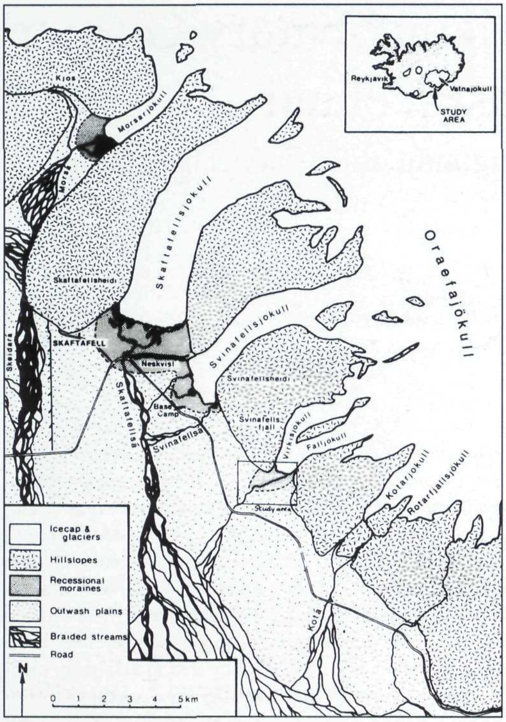

***Figure1**: Location map showing the study area and neighbouring glaciers (modified from Thompson, 1988).*

**Mynd 1:** Støðukort, sum vísir rannsóknarøkið og grannajøklar (broytt úr Thompson, 1988).

to its position in the north-eastern Atlantic Ocean. The warm North Atlantic surface waters and Norwegian Sea deepwater currents strongly influence the location of both the atmospheric and oceanic polar fronts. Studies have shown (Boyle and Keigwin, 1987; Broecker *et al.*, 1988; Veum *et al.*, 1992; Björck *et al.*, 1997; Hald and Aspeli, 1997) that ocean currents around Iceland and the Faeroe Islands may hold the key to climatic change in this area since the Last Glacial Maximum (LGM). Evidence is mounting to suggest a causal link between ocean circulation patterns and climatic change.

It has been shown that temperate glaciers and small ice-caps are sensitive indicators of climatic change (Nye, 1965; Rosqvist and Østrem, 1989; Grudd, 1990). Particular ice-bodies can be seen to reflect the pattern of climate change over relatively short timescales (Suggate, 1950; Björnsson, 1979; Gordon, 1981; Woo and Fitzharris, 1992; Bickerton and Matthews, 1993; Nesje *et al.*, 1995).

Short-term fluctuations of glacier termini are essentially a climatically dependent phenomenon (Hoinkes, 1968; Oerlemans, 1989; Nesje, 1989; Paterson, 1994). However, due to glacier dynamics, the response of the glacier margin to any such climatic change may be delayed or become diffuse (Nye, 1960; Johannesson *et al.*, 1989; Paterson, 1994). It is proposed that rates of snout movement during the last century or so are seen largely as a direct response to fluctuations in local air temperature rather than the product of more complex mass-balance adjustments. A comparison between the known record of mean air temperature over the last ninety years in southeast Iceland and the nearby glacier front fluctuations, should allow the validity of this relationship to be tested.

## *Aims*

This study aims to test two main hypotheses:

1. That glacier-front movements can be viewed as a direct response to local climatic change, in particular variations in mean air temperature.

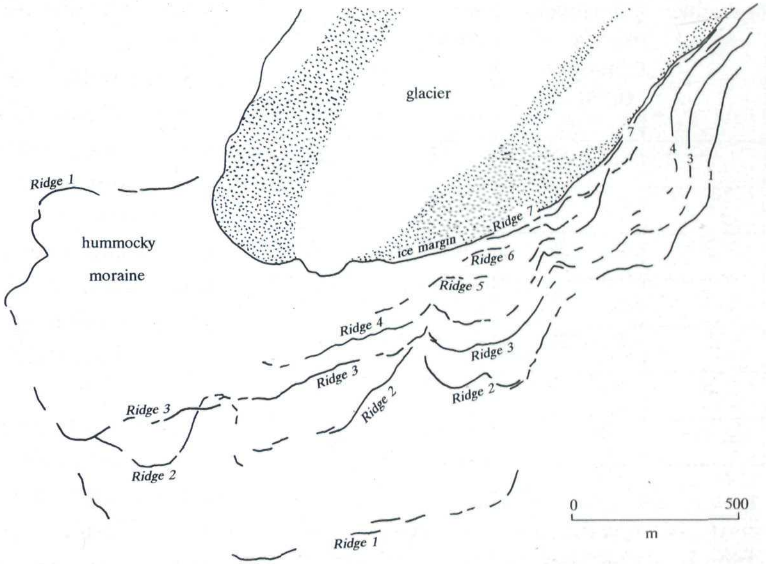

*Figure 2: Moraine systems on the foreland at Virkisjökull-Falljökull (surveyed: T. Bradwell, 1996).*
**Mynd 2:** Morenukervi á strandarlendinum við Virkisjökull-Falljökull (uppmáting: T. Bradwell, 1996).

2. That lichenometry can be used as a valid relative dating technique in glacial geomorphology over a pre-determined timescale.

### *The Study Area*

The study concerns the twin valley glaciers of Virkisjökull and Falljökull and their respective, shared proglacial foreland (fig.1). The two ice-flows are around five kilometres in length with a collective catchment area of approximately 16.2 km$^2$. They converge to form a single snout 1000 metres in width, confined to the east and west by steep, basalt cliffs. Recession of the ice has revealed an area of moraine-covered proglacial foreland. The foreland has been subjected to deposition from the melting ice-margin and dissection from the high-energy streams that issue. Discrete, arcuate ridges and hummocky ablation moraine are preserved on the foreland reflecting the pattern of ice front fluctuations. These features can be relatively dated using lichenometry and geomorphic relationships observed in the field.

### Methodology

At the time of study no maps greater than 1:50,000 scale had been published of the glacier and its surrounding foreland. In order to successfully interpret the recent glacial history of Virkisjökull-Falljökull an accurate large-scale map was created (fig.2). Onto this map all morphological and respective lichenometric data were applied whereby a complete picture of the recent glacial fluctuations could be generated.

In order to date accurately the formation of the glacio-genic landforms at Virkisjökull, a lichenometric assessment was em-

| moraine ridge | maximum lichen diameter (mm) | age (years) | date (AD) |
|---|---|---|---|
| 1 | 65 | 116 | 1880 |
| 2 | 43 | *78* | *1918* |
| 3 | 38 | *68* | *1928* |
| 4 | 36 | 62 | 1934 |
| 5 | 29 | 52 | 1944 |
| 6 | 24 | 42 | 1954 |
| 7 | 17 | 30 | 1966 |

***Table 1**: Lichenometric data collected from the proglacial foreland at Virkisjökull-Falljökull.*
**Talva 1:** Likenometriskt tilfar savnað úr tí proglasiala strandarlendinum við Virkisjökull-Falljökull.

ployed. *Rhizocarpon geographicum* agg. species was chosen to calibrate the age of the various substrates. The maximum diameter of the twenty largest lichens on the ice-proximal slope of each discrete morainic feature was measured to an accuracy of +/- 0.5mm. These values were then averaged, to eradicate possible sampling errors, and applied to a linear growth curve. Similar lichenometric studies carried out in this area of Iceland (Gordon and Sharp, 1983; Thompson and Jones, 1986; Thompson, 1988) have proved relatively successful. This study aims to show the feasibility of lichenometric dating in decoding a complex glacial history over the last century.

Glaciers have been monitored in Iceland since the first settlers arrived in the tenth century. This record of glacier fluctuations makes Iceland an ideal location to test the validity of dating techniques. Observed limits supported by lichen measurements can be used to calibrate relative growth curves for a specific environmental regime. Assuming growth rates to be linear allows ages of various substrates to be interpolated. Several studies have reported a linear relationship between lichen size and age, at least over the first two centuries of growth (Anderson and Sollid, 1971; Burrows and Orwin, 1971; Gordon and Sharp, 1983; Kugelmann, 1991). This would correspond with the 'Great Period' of growth observed by Beschel (1950) and supported by later workers (Benedict, 1967; Calkin and Ellis, 1980; Caseldine, 1991). However, some argument surrounds precisely the validity of this relationship, particularly in the first 15 years following colonization (Beschel, 1961; Mottershead and White, 1972; Jochimsen, 1973). Any discrepancies between the calculated and subsequently observed landform ages would give an indication of the shortcomings of this particular method.

Virkisjökull-Falljökull has been observed only sporadically since 1880, with annual observations beginning in 1932. Prior to this time, documentation is rather scarce and therefore less reliable. However, a good impression can be gathered from the data compiled and published by Thorarinsson (1943), Eythorsson (1963, 1966), Rist (1970-1987) and Sigurdsson (1989, 1994). Further lines of evidence can be drawn from neighbouring valley glaciers whose chronologies have been documented and in some instances extended by various dating techniques (Thompson, 1988).

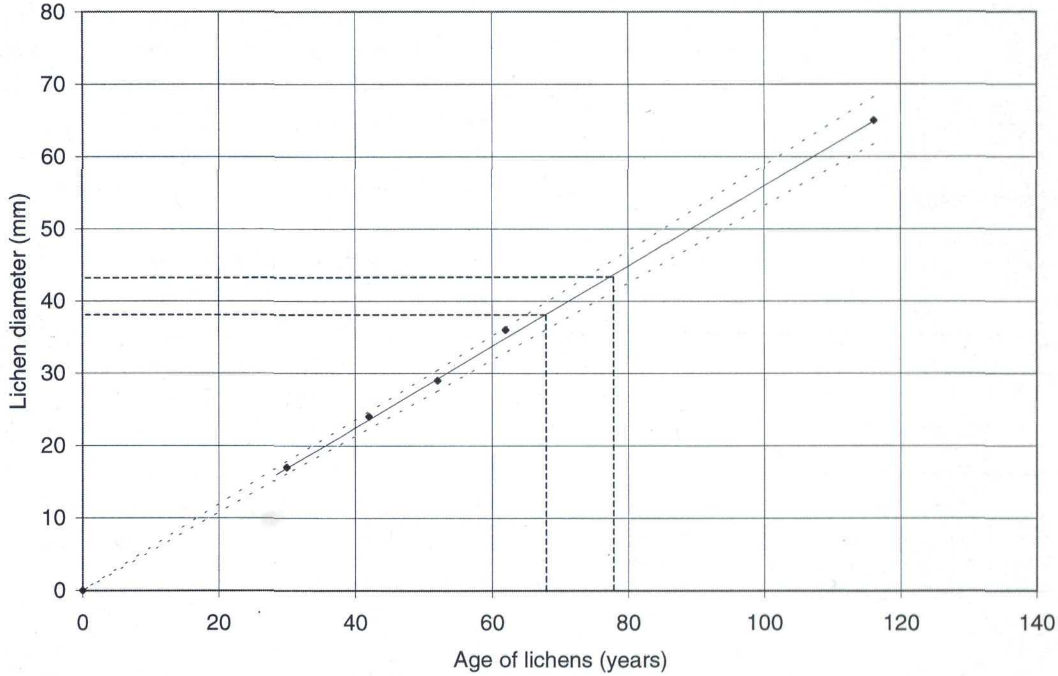

*Figure 3: Lichen growth curve for Virkisjökull-Falljökull, assuming a linear growth rate.*
**Mynd 3:** Farmynd av skónvøkstri fyri Virkisjökull-Falljökull; gingið verður út frá linjurøttum vakstrartali.

### *Field evidence*

Data collected from lichens has enabled the date of various moraine ridges to be estimated with reasonable accuracy. Assuming a linear relationship between largest lichen diameter and age, over the initial 120-year growth period, it is possible to determine the age of proglacial features formed during this time. Lichen data from moraine ridges at Virkisjökull of known age (1880, 1934, 1944, 1954 and 1966) can be used to calibrate a linear growth curve (fig.3). Using this simple relationship it is possible to extract the ages of the two undated moraines through a process of interpolation.

Along with those moraine ridges dating from 1880, 1934, 1944, 1954 and 1966, interpolation from lichenometric data has revealed the ages of two further moraine systems as 1928 and 1918. The oldest ridge (1880) represents the maximum extension of the glacier during the Little Ice Age cold period (1200-1900 AD; Grove, 1988) and possibly in historical time (Eythorsson, 1935). This terminal moraine is dated from historical documentation in 1881 by Helland who stated that the ice was fronted by a 137-foot-high moraine (Grove, 1988: 49). By 1904 the ice margin had retreated some 600 metres (Thorarinsson, 1943) although

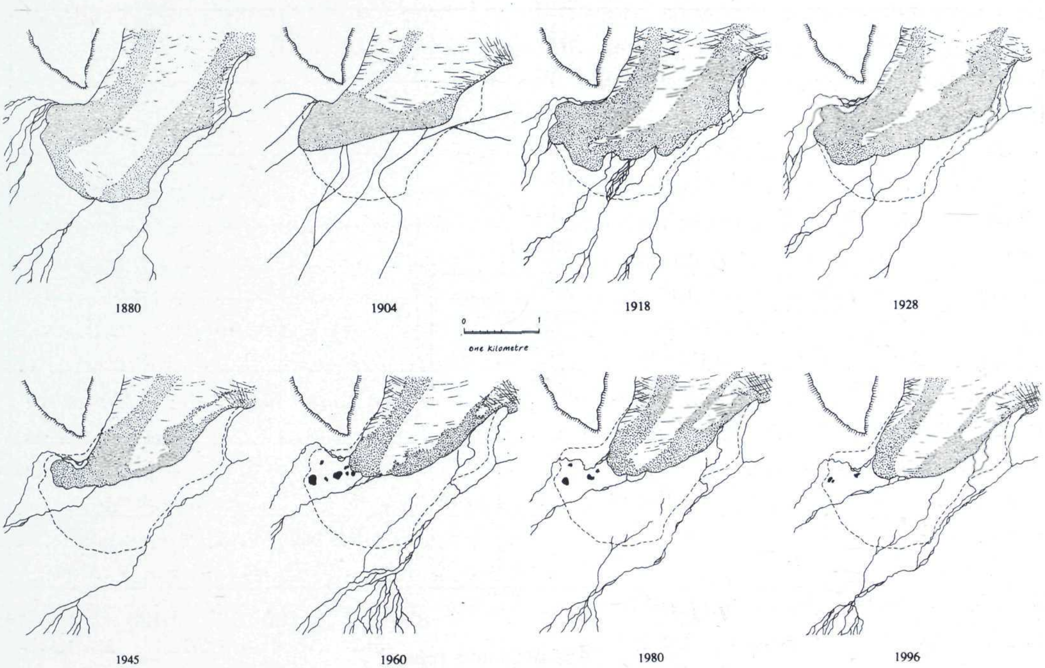

*Figure 4: Reconstructed ice-front positions for Virkisjökull-Falljökull (1880-1996).*
*1880, 1918, 1928 - derived from lichenometric data*
*1904 - taken from published map (Danish General Staff survey, 1904)*
*1996 - established from field survey (August, 1996)*
**Mynd 4:** Endurgerð av jøkulsmarki á Virkisjökull-Falljökull (1880-1996).
1880, 1918, 1928 - merkir aldur út frá likenometriskum tilfari
1904 - tikið úr útgivnum kortum (Danish General Staff survey, 1904)
1996 - fingið við uppmátingum á staðnum (august 1996)

doubt surrounds whether this represented the active ice-front or merely a body of stagnant ice formed by the rapid retreat during the late nineteenth century. Lichenometry can give a fair impression of the time taken for such a stagnant ice-mass to decay. Thalli measurements from the floor of depressions within the hummocky dead-ice topography confirm that ice, probably buried under a thick mantle of supraglacial debris, was still downmelting until the mid 1950's. Several sediment-rich meltwater pools have persisted up until the present day.

With knowledge of the glacier terminus position since the time of maximum extent (1880), the sequence of front position fluctuations can be extended back beyond the existing documented observations. The time period from 1881 to 1932 has only three data points relating to the snout position at Virkisjökull (Thorarinsson, 1943).

However, this record can now be completed with relative confidence given the lichenometric evidence collected from the foreland in 1996.

The following maps (fig.4) show the position of the ice margin at Virkisjökull-Falljökull at eight time intervals during the last 115 years. Evidence has been compiled from aerial photographs in the case of 1945, 1960, and 1980, lichenometric data in the case of 1880, 1918 and 1928, cartographic data in 1904 and by direct field observation in the case of 1996. These time slice reconstructions enable a complete picture of the recent chronology of the glacier to be generated.

## Results: A glacial chronology 1880-1996

The dating of the landforms on the proglacial foreland at Virkisjökull-Falljökull has allowed a detailed chronology of the glacier's movement over the last 115 years to be compiled. The use of lichenometry as a relative dating technique has enabled any gaps in the glacier's history to be restored with relative confidence.

The 50-year period following the glacier's retreat from the limits of maximum recent glaciation in 1880, appear to have been one of complex ice-marginal fluctuations. Evidence gathered by Thorarinsson (1943, 1956) suggests this period was punctuated by three episodes of stillstand or advance. The geomorphology at Virkisjökull-Falljökull is complex and requires careful study, but good evidence can be found on the eastern half of the foreland for two such advance events. The story on the western section of the margin is more complicated and throws some doubt on the lichenometric dating method adopted. A plausible explanation for the source of misinterpretation may be due to the presence of a large body of un-nourished or 'dead ice' which was still connected to the active margin. The absence of any discrete, recessional, moraine ridges and the presence of a large area of hummocky, ablation moraine on the western half of the foreland suggest that the snout dynamics were greatly influenced by the dead-ice mass. The later 1928 re-advance is manifest in the imposing terminal moraine complex with its oversteepened proximal slope. It is probable that both early twentieth-century re-advances returned successively to occupy the same position on the western foreland. This scenario would explain the lichenometry anomaly encountered when surveying ice-proximal slopes in this region of hummocky topography. Reactivation of the moraine flank but not the crest would lead to unrepresentatively young dates being returned for this slope. A secondary break of slope was observed on the proximal side of the terminal moraine, which may represent the height of re-activation by later episodes of advancing ice. The impressive height of this moraine ridge may also be due in part to the occupation of this position by numerous ice fluctuations. Increased dumping of supraglacial debris caused by successive margin occupations may have given this moraine complex a constructional and depositional element to its formation. The lichenometric data confirms the multiphase construction of moraine complex 1. However, the exact age of the feature is hidden by downwasting processes which almost certainly affected the surface debris.

Lichenometric data has determined the age of the prominent moraine systems on the foreland at Virkisjökull-Falljökull. Arguably the most interesting of these ridges is ascribed a date of 1928 yet occupies a more advanced position than some apparently older moraines. This evidence is not contradictory but points towards the ice margin re-advancing beyond the 1918 position in 1928. The date of moraine formation is fixed as 1928 although the re-advance probably began around 1923-4 and ended abruptly with the marked recession of 1929 and 1930. After the resurgence that culminated in 1928, the eastern margin retreated nearly 250 metres in the next 18 years, with a slight interruption in 1934-6. By 1945, the date of the first aerial reconnaissance, the ice margin was approximately halfway through this period of prolonged recession. A small still-stand during the previous two years created a low-elevation ridge that is just visible in the 1945 photograph. This feature can be used to aid calibration of the lichen growth curve.

Recession decreased to zero during the early 1950's and in 1952 the glacier advanced marginally for two whole seasons, producing a small push moraine. Retreat continued intermittently during the 1960's until in 1969 the ice margin seemed to diminish with remarkable rapidity, shifting up-valley 190m in only four years (maximum rate = -70m/yr). In 1973 the ice margin was at its most retarded position since at least 1830 AD and possibly since the start of the Little Ice Age, over 800 years ago (Thorarinsson, 1943). Any geomorphological trace of the ice margin's former position has since been obliterated by subsequent re-advances.

The recession history of Virkisjökull-Falljökull does bear remarkable resemblance to the local climatic record, represented by a 5 year-running temperature mean. The fluctuations of the glacier margin although seemingly similar to the air temperature record are not statistically significant if unsupported. In order to prove a causal link, further studies must be carried out on glaciers in the area. If other nearby valley glacier margins could be shown to exhibit sufficiently similar trends to that of Virkisjökull-Falljökull, the link between ice and climate could be strengthened.

Measurements of the nearest valley glacier to Virkisjökull, which terminates on a broad, level outwash plain, have been similarly chronicled since 1932 and extended using lichenometry back to 1900 AD, (Thompson, 1988). Although there are small discrepancies between the two, the retreat history of this glacier, Skaftafellsjökull, follows the general pattern displayed by Virkisjökull. Marked re-advances are seen to culminate in 1917, 1930, 1934, 1953 and 1982 at Skaftafellsjökull; these can be compared with 1918, 1928, 1934, 1954 and 1983 for Virkisjökull-Falljökull. Similarly, recession is strongest during the 1940's and early 1970's at Skaftafellsjökull, with the minimum front position being recorded in 1973.

## Discussion

It is possible to demonstrate the general,

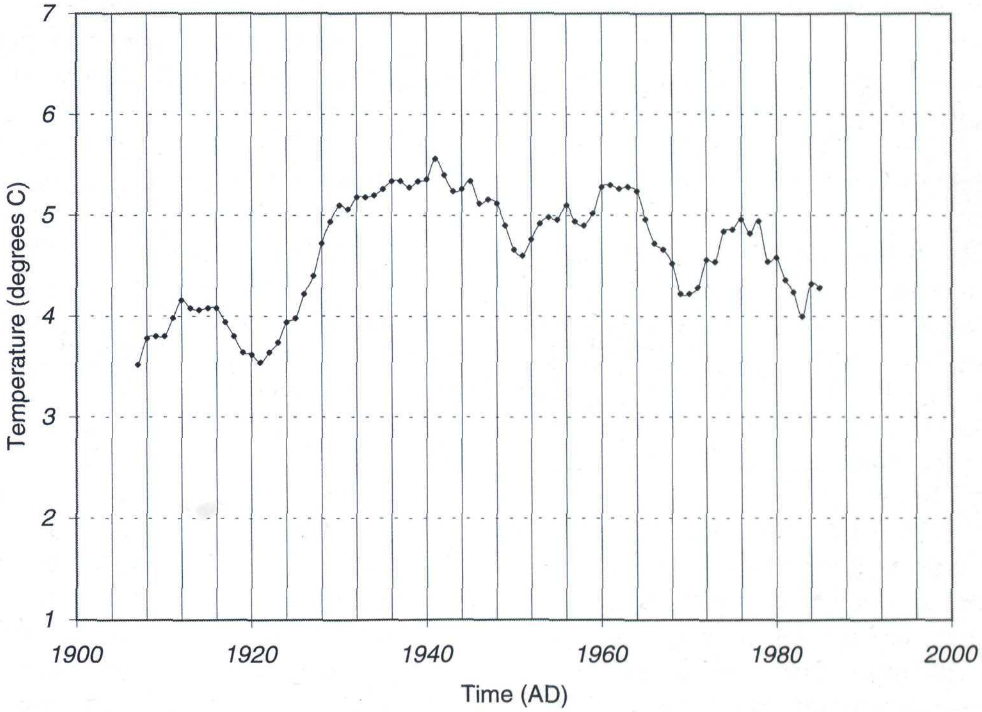

***Figure 5a**: Mean annual air temperature at Fagurholsmyri (5-year running mean). [Data from Iceland Meteorological Office]*

**Mynd 5a:** Árligur lufttemperaturur í miðal við Fagurholsmýri (miðal fyri 5 ár upp í slag). [Tilfar frá Iceland Meteorological Office]

sometimes striking, relationship between climatic trends and ice-margin fluctuations (fig.5b). Evidence from research carried out at Virkisjökull-Falljökull, southeast Iceland has pointed towards a correlation between glacier margin fluctuation and mean annual air temperature trends. The general relationship was first proposed by Finsterwalder and Schunck (1887) who noticed that melting at the glacier snout increased as a result of rising air temperatures. Although seemingly obvious this relationship has never been fully supported from field evidence alone. A validation of this relationship would be invaluable for the study of palaeo-glaciology and palaeo-climatology.

On the basis of the evidence presented in this study a good correlation can be made between the local air temperature trend and the retreat history of the glacier terminus at Virkisjökull-Falljökull, southeastern Iceland. The record of glacier front fluctuations has been compared with temperature data from the nearby meteorological station (fig.5b). An optimal fit was found by visu-

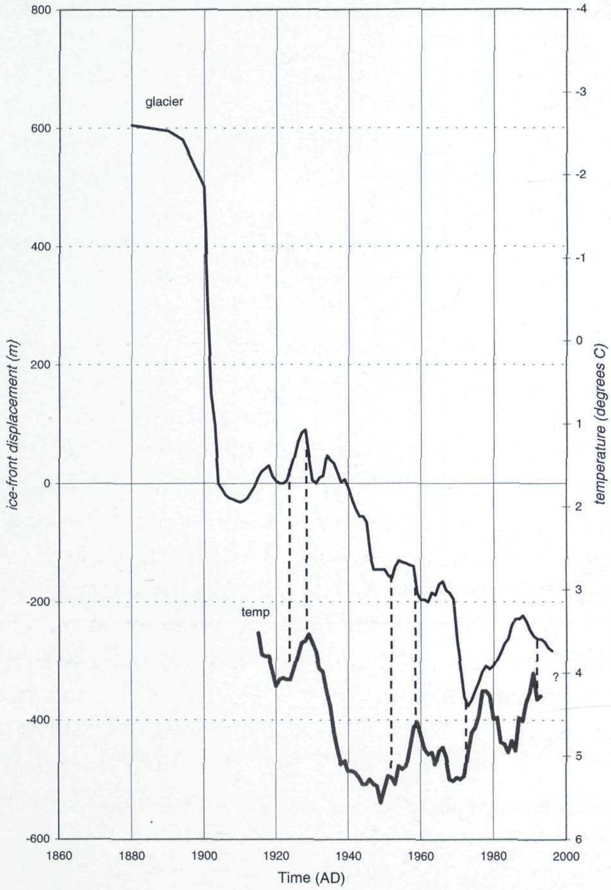

***Figure 5b:*** *Cumulative glacier-front variations of Virkisjökull-Falljökull, between 1880 and 1996, compared with local air temperature (displaced by +8 years to compensate for lag-time).*
**Mynd 5b:** Kumulativ frávik á jøkulsmarki á Virkisjökull-Falljökull, millum 1880 og 1996, samanborin við lufttemperaturin á staðnum (broytt +8 ár fyri at viga upp ímóti seinkingartíð).

al inspection of the two curves. The strongest cross-correlation was observed with an air temperature displacement of 7 to 9 years. This demonstrates that the glacier snout is seen to fluctuate in response to multi-annual variations in temperature, exhibiting a lag-time of some 7, 8 or 9 years. The timing of the glacier's response to air temperature variation appears generally constant through the period of available data (1908-1988) with both positive and negative responses to temperature change being of a very similar order (7-9 years).

Use of the 5-year running mean for air temperature records is a recognised method in glacier mass balance studies. Huybrechts *et al.* (1989) use this method along with ten and fifteen year running means when modelling an alpine glacier in France. They state that the mass balances of alpine glaciers are to a large extent controlled by meteorological conditions in summer, in particular summer temperature. Similarly, Nesje *et al.* (1995) chose to use a 5-year running mean when attempting to correlate glacier-front fluctuations with summer temperatures and winter precipitation in western Norway. A smoother curve, such as the one presented in fig.5a, will act to filter out extreme or anomalous values therefore allowing a more representative temperature trend to be depicted.

Many studies of mass balance in temperate valley glaciers have pointed to the importance of mean air temperature and precipitation in determining volume changes, and in turn snout fluctuations (Liestøl, 1967; Hoinkes, 1968; Björnsson, 1971; Oerlemans, 1989). This study has concentrated on only one of these factors in an attempt to establish the link between ice-front fluctuations and mean air temperature. The meteorological data used in this study is taken from Fagurholsmyri weather station (lat., 63’50’ N ; long., 16’45’ W) located 15 kilometres south-east of the study site.

If the relationship observed at Virkisjökull, and supported at Skaftafellsjökull, can be deemed a valid one, interesting opportunities are presented for the study of glaciology and palaeo-climatology. The possibility of reconstructing former air temperature trends from known short-term ice-margin fluctuations becomes a realistic one. Conversely, knowledge of a long-term temperature regime may yield important evidence as to the rates of ice front movement over a similar time period. This study has highlighted the general, and at times distinct, correlation between glacial snout fluctuations and annual air temperature variability. An important notion to have emerged from the research is the glacier’s delayed response to changes in air temperature conditions. Contrary to those views expressed by Nye (1963a, 1963b) and Lliboutry (1971) regarding the response time of valley glaciers, ice-front fluctuations ranging from 1 to 200 metres per year are seen to take effect in less than ten years. The time-lag observed in this study (7-9 years) is slightly longer than those inferred previously by Bickerton and Matthews (1993) [5 years] and Nesje *et al.*, (1995) [3-4 years] for similar sized Norwegian valley glaciers. Possible reasons for this small discrepancy may be related to the specific glacier dynamics at Virkisjökull-Falljökull and, consequently, the sensitivity of the terminus to climatic forcing. However, the rapidity of the response observed at the ice-front implies that these short-term snout fluctuations are predominantly a function of local climatic conditions, in particular air temperature and precipitation, and not due to more complex mass balance dynamics travelling through the glacier.

Some difficulty arises when trying to explain the positive fluctuations or advance events seen at the study site. These advances are unlikely to be the result of purely temperature change. One possible explanation may stem from the fact that the glacier is not in a steady state and has a natural tendency to advance. A short-term rise in air temperature would instigate recession of the ice margin yet falling temperatures would result in lower melting rates, effectively leading to advance. This relationship would not interfere with the overall balance of the glacier yet would explain the apparent link between falling air temperatures and glacial expansion. A further explanation may be related to increased precipitation levels during these times of falling temperature, such as those that were experienced during the late nineteenth-century (Eythorsson and Sigtryggsson, 1971). This is unlikely over such short time periods (1-10 years) although cannot be ruled out for some of the longer changes. It can be seen from this preliminary research that further work is needed on this topic.

Unfortunately, precipitation records from the weather station at Fagurholsmyri are deemed to be unreliable and could therefore not be used to complement this work. This is regrettable as variations in precipitation may partly explain periods of ice-front advance not seen to correlate directly with temperature variations, for example between 1980 and 1988. However, this does not detract from the overall relationship observed between ice-marginal movement and mean air temperature trends at Virkisjökull-Falljökull. Further work is currently examining the exact role of mean summer temperatures and the length of the ablation season in forcing ice-margin fluctuations.

## Conclusion

The twin valley glacier of Virkisjökull-Falljökull retreated from its Nineteenth-Century maximum between 1885 and 1910 AD, with the rate of ice-front retreat being most rapid during the first five years of the twentieth century. After a brief positive fluctuation in the late 1920's, recession continued from the mid 1930's up until 1973. As the climate became cooler after 1960, the retreat of the glacier margin slowed down and subsequently a period of advance occurred in the 1970's and 1980's. This observation is in agreement with those findings of Björnsson (1979) and Sigurdsson (1989) who have evidence from the majority of glaciers in Iceland. Since about 1985 the climate in Iceland, and on Earth as a whole, has become warmer. As a direct consequence of this most recent temperature rise, Virkisjökull-Falljökull gradually began retreating again around 1993. Interestingly, allowing for the inferred lag-time of between 7 and 9 years, Virkisjökull-Falljökull may continue to retreat indefinitely in response to the warmer conditions currently being experienced. A qualitative prediction of this nature, if supported, could be of great scientific and socio-economic value.

In general, it can be concluded that frontal fluctuations of Virkisjökull-Falljökull have been in sympathy with climatic trends over the last century. The ice-margin has shown a relatively coherent, lagged response to air temperature variations on a multi-annual scale over the last one hundred years. A good correlation is seen between phases of glacial retreat and periods of elevated local air temperature, particularly between 1920 and 1980. The time lag between the onset of one such warming phase and the subsequent glacial recession is seen to be in the region of 7 to 9 years. A similar correlation is observed between phases of glacial advance and periods of falling or depressed temperature. Although the response time is of a similar magnitude

(7-9 years), the scale of transgressive ice-front movement is of a lower order than that of regression. These observations can be supported by evidence from a nearby valley glacier and are in general agreement with similar twentieth century studies (Rogstad, 1951; Nesje, 1989; Nesje *et al.*, 1995), making these findings of statistical significance.

## Acknowledgements

This paper is based on fieldwork carried out whilst on the Liverpool University Iceland Expedition 1996. I would like to thank Chris Hunt and Dr. Geoff Thomas for organising the expedition. I am also indebted to Dr. Andrew Dugmore and Professor David Sugden for comments and advice on the manuscript.

## References

Anderson, J.L. and Sollid, J.L. 1971. Glacial chronology and glacial geomorphology in the marginal zones of the glaciers Mitdalsbreen and Nigardsbreen, south Norway. *Norsk Geografisk Tidsskrift*, 25: 1-38.

Benedict, J.B. 1967. Recent glacial history of an alpine area in the Colorado Front Range, USA. I: Establishing a new lichen-growth curve. *Journal of Glaciology*, 6: 817-832.

Beschel, R. 1950. Flechten als Alstermasstab rezenter Flachten. *Zeitschrift fur Gletscherkunde und Glazialgeologie*, 1: 303-309.

Beschel, R. 1961. Dating rock surfaces by lichen growth and its application to glaciology and physiography (lichenometry). In: G.O. Raasch (ed.) *Geology of the Arctic*, vol.2: 1044-1062.

Bickerton, R.W. and Matthews, J.A. 1993. 'Little Ice Age' variations of outlet glaciers from the Jostedalsbreen ice-cap, southern Norway: a regional lichenometric-dating study of ice marginal moraine sequences and their climatic significance. *Journal of Quaternary Science*, 8: 45-80.

Björck, S., Rundgren, M., Ingolfsson, O., and Funder, S. 1997. The Preboreal oscillation around the Nordic Seas: terrestrial and lacustrine responses. *Journal of Quaternary Science*, 12 (6): 455-465.

Björnsson, H. 1971. Baegisarjökull, North Iceland. Results of glaciological investigations 1967-1968: Part I. Mass balance and general meteorology. *Jökull*, 21: 1-26.

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

Boyle, E.A. and Keigwin, L.D. 1987. North Atlantic thermohaline circulation during the past 20,000 years linked to high latitude surface temperatures. *Nature*, 330: 35-40.

Broecker, W.S., Andree, M., Wolfli, M., Oeschger, H., Bonani, G., Kennett, J., and Peteet, D. 1988. The chronology of the last deglaciation: implications to the cause of the Younger Dryas event. *Paleoceanography*, 3: 1-19.

Burrows, C.J. and Orwin, J. 1971. Studies on some glacial moraines in New Zealand. 1.- The establishment of lichen growth curves in the Mount Cook area. *New Zealand Journal of Science*, 14: 327-335.

Calkin, P.E. and Ellis, J.M. 1980. A lichenometric dating curve and its applications to Holocene glacier studies in the Central Brooks Range, Alaska. *Arctic and Alpine Research*, 12: 245-264.

Caseldine, C.J. 1991. Lichenometric dating, lichen population studies and Holocene glacial history in Trollaskagi, northern Iceland. *In:* Maizels, J.K. and Caseldine, C.J. (eds.). *Environmental change in Iceland: past and present*. Dordrecht: 219-233.

Eythorsson, J. 1935. On the variation of glaciers in Iceland: some studies made in 1931. *Geografiska Annaler*, 17: 121-137.

Eythorsson, J. 1963. Variations of Icelandic Glaciers, 1931-1960. *Jökull*, 13: 31-33.

Eythorsson, J. 1964,1965,1966. Jöklabreytingar. *Jökull*, 14,15,16.

Eythorsson, J. and Sigtryggsson, H. 1971. *The Zoology of Iceland*, Reykjavik.

Finsterwalder, S. and Schunck, H. 1887. Der Suldenferner. *Zeitschrift des Deutschen und Oesterreichischen Alpenvereins*, 18: 72-89.

Gordon, J.E. 1981. Glacier margin fluctuations during the 19th and 20th centuries in the Ikamiut Kangerdluarssuat area, west Greenland. *Arctic and Alpine Research*, 13, 1: 47-62.

Gordon, J.E. and Sharp, M. 1983. Lichenometry in dating recent glacial landforms and deposits, southeast Iceland. *Boreas*, 12: 191-200.

Grove, J.M. 1988. *The Little Ice Age*. London: Methuen.

Grudd, H. 1990. Small glaciers as sensitive indicators of climatic fluctuations. *Geografiska Annaler*, 72A, 1: 119-123.

Hald, M. and Aspeli, R. 1997. Rapid climatic shifts of the northern Norwegian Sea during the last deglaciation and the Holocene. *Boreas*, 26: 15-28.

Hoinkes, H.C. 1968. Glacier variation and weather. *Journal of Glaciology*, 7, (49): 3-17.

Huybrechts, Ph., de Nooze, P. and Decleir, H. 1989. Numerical modelling of Glacier d'Argentiere and its historic front variations. *In:* Oerlemans (ed.). *Glacier Fluctuations and Climatic Change*. Kluwer Academic Press: 373-389.

Jochimsen, M. 1973. Does the size of lichen thalli really constitute a valid measure for dating glacial deposits. *Arctic and Alpine Research*, 5: 417-424.

Johannesson, T., Raymond, C.F., and Waddington, E.D. 1989. A simple method for determining the response time of glaciers. *In*: Oerlemans (ed.). *Glacier Fluctuations and Climatic Change*. Kluwer Academic Press: 343-352.

Kugelmann, O. 1991. Dating recent glacier advances in the Svarfadardalur/ Skidadalur area of northern Iceland by means of a new lichen curve. *In:* Maizels, J.K. and Caseldine, C.J., (eds.) *Environmental change in Iceland: past and present.* Dordrecht, Kluwer: 203-217.

Liestøl, O. 1967. Storbreen glacier in Jotunheimen. *Norsk Polarinstitutts Skrifter*, 141: 1-63.

Lliboutry, L.A. 1971. The glacier theory. *In:* Ven Te Chow (ed.). *Advances in Hydrodynamics*, New York, Academic Press, 7: 81-167.

Mottershead, D.N. and White, J.D. 1972. The lichenometric dating of glacier recession, Tunsbergdal, Southern Norway. *Geografiska Annaler*, 54A: 47-52.

Nesje, A. 1989. Glacier-front variations of outlet glaciers from Jostedalsbreen and climate in the Jostedalsbre region of Western Norway in the period 1901-1980. *Norsk Geografisk Tidsskrift*, 43: 3-17.

Nesje, A., Johannessen, T., and Birks, H.J.B. 1995. Brikdalsbreen, western Norway: climatic effects on the terminal response of a temperate glacier between AD 1901 and 1994. *The Holocene*, 5 (3): 343-347.

Nye, J.F. 1960. The response of glaciers and ice sheets to seasonal and climatic changes. *Proceedings of the Royal Society of London*, A256: 559-584.

Nye, J.F. 1963a. On the theory of the advance and retreat of glaciers. *Geophysical Journal of the Royal Astronomical Society*, 7 (4): 431-456.

Nye, J.F. 1963b. The response of a glacier to changes in the rate of nourishment and wastage. *Proceedings of the Royal Society*, A275: 87-112.

Nye, J.F. 1965. The frequency response of glaciers. *Journal of Glaciology*, 5 (41): 567-587.

Oerlemans, J. 1989. On the response of valley glaciers to climatic change. *In:* Oerlemans (ed.). *Glacier Fluctuations and Climatic Change*. Kluwer Academic Press: 353-371.

Ogilvie, A. 1992. Documentary evidence for changes in the climate of Iceland, AD 1500 to 1880. *In:* Bradley, R.S. and Jones, P.D. (eds.). *Climate since AD 1500.* London: 92-117.

Paterson, W.S.B. 1994. *The physics of glaciers*. Oxford: Pergamon Press.

Rist, S. 1970-1987. Joklabreytingar. *Jökull*, 20-37.

Rogstad, O. 1951. Variation in the glacier mass of Jostedalsbreen. *Journal of Glaciology*, 1: 551-556.

Rosqvist, G. and Østrem, G. 1989. The sensitivity of a small ice-cap to climatic fluctuations. *Geografiska Annaler*, 71A: 99-103.

Sigurdsson, O. 1989. Jöklabreytingar 1930-1960, 1960-1980, 1980-1986 og 1987-1988. *Jökull*, 38: 91-97.

Sigurdsson, O. 1994. Jöklabreytingar 1988-94. *Jökull*, 44.

Suggate, R.P. 1950. Franz-Josef and other glaciers of the Southern Alps, New Zealand. *Journal of Glaciology*, 1: 422-429.

Thompson, A. 1988. Historical development of the Proglacial landforms of Svinafellsjökull and Skaftafellsjökull, southeast Iceland. *Jökull*, 38: 17-30.

Thompson, A. and Jones, A. 1986. Rates and causes of proglacial river terrace formation in southeast Iceland: an application of lichenometric dating techniques. *Boreas*, 15: 231-246.

Thorarinsson, S. 1943. Oscillations of the Icelandic glaciers in the last 250 years. *Geografiska Annaler*, 25: 1-54.

Thorarinsson, S. 1956. On the variations of Svinafellsjökull, Skaftafellsjökull and Kviarjökull, in ÷raefi. *Jökull*, 6: 1-15.

Veum, T.E., Jansen, M., Arnold, I., Beyer, I. and Duplessy, J.C. 1992. Water mass exchange in the North Atlantic and the Norwegian Sea during the past 28 000 years. *Nature*, 356: 783-785.

Woo, M.K. and Fitzharris, B.B. 1992. Reconstruction of mass balance variations for Franz-Josef glacier, New Zealand, 1913-1989. *Arctic and Alpine Research*, 24: 281-290.