Modelling Holocene Glacier Fluctuations and Climatic Change in Iceland

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ABSTRACT. The aim of this paper is to use a coupled energy balance/glacier flow model to understand the climatic significance of Holocene fluctuations of Sólheimajökull, an outlet glacier in southern Iceland. Sólheimajökull has the longest geomorphic and historic record of glacier fluctuations in Iceland, with glacier expansions dated by tephrochronology to 5000, 3100 and 1400 years BP, at around AD 950, 1350 and 1705, and between 1795 and 1890. Modelling experiments reveal that the glacier expansions are due to a maximum temperature change of -1.6 °C relative to 1960–1990 mean conditions. A glacier minimum at AD 1783 is due to a temperature change of + 1–2 °C relative to the 1960–1990 mean between AD 1700 and 1750. Glacier expansions have followed periods when sea ice incidence was high in surrounding ocean waters. During the last 300 years, a decadal-scale climatic oscillation was present involving changes in sea ice extent. The Little Ice Age in Iceland was climatically variable, and included a warming event similar in magnitude to 20th century warming.

KEY WORDS: Holocene, climatic change, glacier fluctuations, sea ice, numerical modelling.

Introduction

The aims of this study are: 1. To show that a glacier model can successfully reconstruct 20th century climatic changes using evidence of recent changes in glacier extent; 2. To apply the model to a climatic reconstruction of the 17th, 18th and 19th century using high resolution historical evidence of glacier fluctuations; 3. To reconstruct long term Holocene climatic trends by modelling glacier fluctuations derived from geomorphic evidence; and, 4. To compare the climatic reconstruction at Sólheimajökull with wider climate proxy evidence, in order to understand the dynamics of Holocene climate changes around Iceland.

Iceland lies in the centre of the North Atlantic Ocean, in the path of the storm tracks and just south of the seasonal boundary between temperate and polar ocean waters. Its climate is sensitive to changes in atmospheric and oceanic circulation. The North Atlantic Oscillation (NAO) index records changes between two dominant modes of the climate system on annual and decadal timescales (Cook et al., 1998). During the positive mode of circulation, the Icelandic Low is intense and stormy temperate air masses cross Iceland. During the negative mode, high pressure occurs over Iceland, storm tracks are located further south, and the Icelandic climate is influenced by polar air masses. Observational records since the 1960s indicate changes in ocean water masses occur in phase with decadal switches between modes of the NAO (Mysak and Venegas, 1998). During negative phases, positive sea ice anomalies appear in the Iceland/Greenland Sea and the climate of Iceland is cooler. During positive phases, North Atlantic Drift waters dominate the ocean around Iceland and the climate is temperate.

Documentary records of historical climate indicate that Iceland has experienced climatic variability for many centuries. Stable, mild conditions are known, as well as periods when the climate was especially cold (Ogilvie, 1984, 1992). Documentary evidence also reveals that sea ice had a higher incidence along the Icelandic coastline during cold periods (Ogilvie, 1992). Despite this rich palaeoclimatic record, there is still much to learn about climatic variability in Iceland. Temperature fluctuations from prior to the establishment of the instrumental climate record in AD 1823 are not well constrained, because a quantitative climate reconstruction is impossible with existing documentary evidence. This makes it difficult to assess whether or not 20th century climatic changes in Iceland are unusual in the context of natural climate variability. Little climatic information exists for the period before c. AD 1000. Tephrochronology has made it possible to broadly discern periods of warm and cool climate associated with large changes in glacier extent (Dugmore, 1989; Gudmundsson, 1997; Stötter et al., 1999). Changes in glacier extent can be used to quantitatively reconstruct climatic changes using glaciological methods (Nye, 1965) but this has not been attempted in Iceland until now.

A glacier modelling approach to climatic reconstruction has several advantages. The model allows the timing of climatic changes to be reconstructed by accounting for the glacier response time. Secondly, the model allows the magnitude of climatic changes to be reconstructed because it incorporates dynamic feedbacks between the glacier and the bedrock geometry. Finally, model performance can be assessed using the recent period when both the history of glacier fluctuations is known, and the instrumental climate record is complete.

Methodology and study site

Sólheimajökull

Sólheimajökull is a 15 km long valley glacier outlet of the Myrdalsjökull ice cap located on the south coast of Iceland. The glacier is temperate and covers an altitudinal range from 1500 m to 100 m, draining through a valley 1–2 km wide in its lower reaches. The record of glacier length fluctuations measured by the Icelandic Glaciological Society since 1932 is a known indicator of climatic changes (Sigurdsson and Jonsson, 1995). Historic fluctuations from as early as AD 1705 are documented in a series of sketches and descriptions (Dugmore, 1987). Holocene fluctuations were mapped and dated using tephrochronology by Dugmore (1987, 1989).

Modelling

The ice-flow model is a simplified version of Hubbard (1997). It is a one-dimensional model based on the shallow ice approximation, and time-dependent calculations are made on a centered finite difference array at a fixed interval of 100 m along a central glacier flow line. Similar models are used to predict the response of glaciers to climatic warming (Oerlemans et al., 1999). Ice flow is driven by shear stresses and the calculation of ice thickness is based on mass conservation principles, i.e. divergence of the mass flux must be balanced by a change in the cross-sectional area of the glacier at each point because ice is assumed to be incompressible (Paterson, 1994). The three-dimensional geometry of the valley is parameterised as a parabola of variable width with ice depth data from a GPS and radio echo-sounding survey of the glacier (Mackintosh et al., 2000). Model flow parameters (Paterson, 1994), are determined in an initial run by comparing modelled output with glacier maps following Oerlemans (1997).

The glacier flow model is forced by imposing vertical shifts in the equilibrium-line altitude (ELA) on a reference mass-balance profile. The reference mass-balance profile is calculated from an energy-balance model based on Oerlemans (1992) that uses data from a nearby climate station to generate a mass-balance profile over the glacier. It represents mean modelled mass-balance conditions over Sólheimajökull for a 30 year period from 1960–1990. It predicts c. 4 m of snow accumulation at 1500 m and –10 m of ice melt at 100 m (Mackintosh, 2000) which is typical for southern Iceland (Björnsson, 1979).

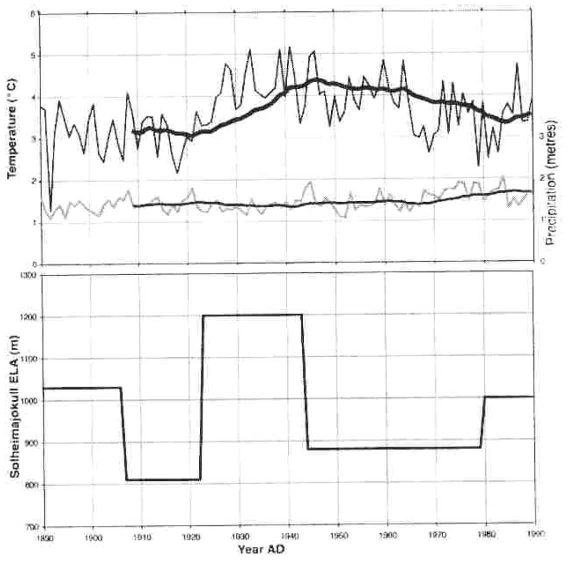

Fig. 1. Reconstructed ELA and instrumental climate data AD 1890–1990. The top chart shows instrumental climate data from Stykkisholmer in western Iceland (Temperature, black line) and Vestmannaeyjar in southern Iceland (Precipitation, grey line). The data is presented as yearly values and a 20 year running mean (bold line). The lower chart shows the reconstructed ELA trend over the same period for Sólheimajökull. The ELA reconstruction captures the main features of the instrumental temperature trend; the temperature rise from 1920–1940, the temperature decline from 1940–1985 and the temperature rise from 1985–1990.

The inverse method

Allison and Krus (1977) and Smith and Budd (1981) have previously used numerical models to reconstruct climatic trends from glacier length variations. If measurements of glacier length are closely spaced in time (as for the late 17th, 18th and 19th centuries at Sólheimajökull), an inverse method can be used (Nye, 1965; Oerlemans, 1997). The aim is to minimise the difference between simulated and recorded glacier fluctuations by forcing the flow model with the parameters ΔELA_i, and t_i

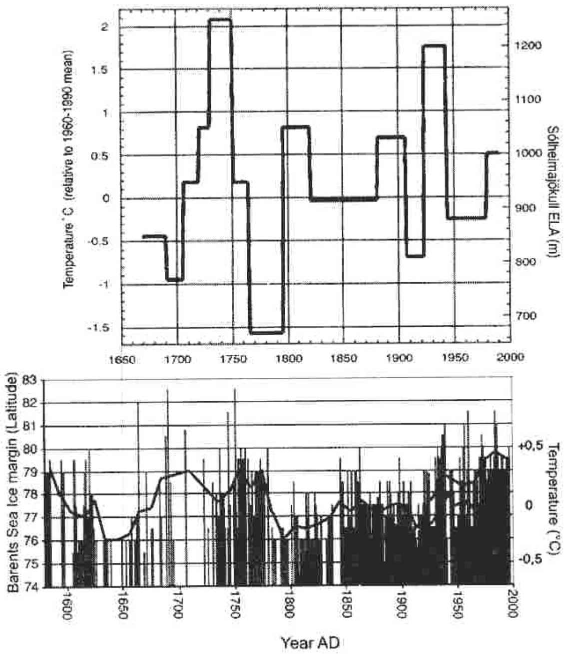

Fig. 2. A comparison between reconstructed temperature and ELA at Sólheimajökull, and fluctuations of the sea-ice margin of the Barents Sea over the period from AD 1650 to 2000. The ELA reconstruction is presented as temperature changes assuming that no change in precipitation occurred during this period. The Barents Sea data represents the August ice edge position in the western Barents Sea between Svalbard and Franz Josef Land as reconstructed from records of whalers, sealers and fisherman (Vinje, 1999). Each bar represents an annual ice edge position, and the white line is a smoothing with a 10 year mean. The atmospheric temperature deviation from the Northern Hemisphere mean temperature as recorded in climate stations from 1961–1990 is also shown. The Barents Sea ice edge fluctuations are correlated with the Sólheimajökull ELA reconstruction. The warming from 1700–1750 is visible in both charts and corresponds to a higher latitude sea ice edge position in the Barents Sea, comparable to that of the present day. The cooling in the 1780s and 1790s evident in the Sólheimajökull record is characterised by a large southward migration of the sea ice edge position in the Barents Sea. The cooling spike evident from 1905–1920 in Iceland is evident in another southward movement of the Barents Sea ice edge. The warming of the Arctic from 1920–1940 is clear in both records.

(where t_i is the time that the balance perturbation has the value ΔELA_i). The two parameters are varied progressively in time starting from an initial state, which is estimated from the response time and a steady state solution of glacier length. 14 pairs of values [ΔELA_i, t_i] are sufficient in this case to obtain a close match between the simulated and observed glacier positions between AD 1670 and 1990.

For the earlier part of the Holocene, a simpler method is used where the ELA is determined by assuming that the glacier reaches equilibrium with the climate at each former ice limit. This is a reasonable assumption because the ice limits are marked by moraines, implying that the glacier was stationary for some time (Mackintosh, 2000). It is not possible to use the more sophisticated method for this period because the time gaps between known glacier positions are > 100 years, which is longer than the glacier response time (c. 70 years, Mackintosh, 2000). This is a less reliable method of climatic reconstruction because climatic changes of large magnitude and short duration will be underestimated.

Results

AD 1670-1990

In Fig. 1 the ELA reconstruction for the 20th century is plotted against the instrumental temperature and precipitation records. It is evident that large temperature changes occurred during the 20th century, while precipitation remained more constant. Interannual variations in temperature appear to have little relationship to the ELA, but if the mean instrumental temperature is calculated for each time block in the ELA reconstruction (t_i), then a strong correlation is found ($r^2 = 0.87$ for period from 1907–1980). On the other hand, if instrumental precipitation is averaged over the same time blocks, it does not correlate with the ELA reconstruction ($r^2 = 0.13$). This confirms that the inverse reconstruction is picking up decadal temperature trends, and that precipitation has a smaller influence during this time period.

To further understand the relationship between temperature change and the ELA reconstruction, a scale factor is used to calculate temperature changes from the ELA reconstruction. This is on the basis of energy-balance modelling experiments which show that a 1 °C temperature change causes an ELA shift of 160 m at Sólheimajökull (Mackintosh, 2000). The resulting temperature reconstruction captures the main features of 20th century climatic changes in Iceland (Einarsson, 1991); the cool period from 1905–1920, the large warming from 1920–1940, the subsequent cooling from 1940–1985 and the warming since 1985. The magnitude is also captured: The model reconstructs a 2.4 °C increase in temperature between 1920 and 1940 while the instrumental record indicates a temperature increase of 2.6 °C during this time.

The ELA reconstruction indicates that the climate of the 19th century was similar to mean 1960–1990 conditions. This is in agreement with the instrumental temperature record, which indicates that the 19th century was cold, but not as cold as the late 18th century (T. Jonsson, pers. com. 1998). There is a mismatch between the ELA reconstruction and the documentary record during the first two decades of the century; The ELA reconstruction indicates warm or wet conditions while the documentary record indicates cold conditions, although not as severe as the 1780s and 1790s (Ogilvie, 1992). The match is better in the middle and later part of the 19th century, when the ELA reconstruction and the instrumental temperature record indicate a cold spike in the 1850s and a warming trend after 1880.

The ELA reconstruction and the documentary record indicate that the late 17th century and 18th century experienced great climatic variability (Fig. 2). At Sólheimajökull, a cold or wet phase is identified between AD 1670 and 1700. The documentary record indicates cold conditions in the 1670s, 1680s, and especially the 1690s. Sea ice was present along the Icelandic coastline during most years and in 1694 penetrated as far south as the Westman Islands, adjacent to Sólheimajökull (Ogilvie, 1992). The years from 1700 to 1750 saw a return to warmer or dryer conditions according to the ELA reconstruction. The historic record indicates that the decades from 1700 to 1730 were the mildest of the century (Ogilvie, 1992). There is a mismatch between 1730 and 1750 when the documentary record indicates a return to colder conditions (Ogilvie, 1992). The most impressive match between the ELA reconstruction and the documentary record is evident at the end of the 18th century. The ELA reconstruction shows a deteriorating climate, reaching a cold peak in the 1780s and 1790s corresponding to a temperature of 1.6 °C below than the 1960–1990 mean (Fig. 2). Documentary evidence records this as the coldest period in historic time (Ogilvie, 1992). During the 1780s, sea ice was present every year off the Icelandic coastline and in 1782 it remained until August along the south coast near Sólheimajökull (Ogilvie, 1992).

Earlier Holocene climatic changes

The Sólheimajökull ELA reconstruction indicates that the Holocene experienced several periods where temperatures were at least 1 °C colder or 70% wetter than the 1960–1990 mean. These are minimum estimates of the temperature depression because the glacier was assumed to reach equilibrium with the climate during the simulation of these ice limits. Very little can be said about the intervening periods except that warming or decrease in precipitation must have occurred in order to explain the overall pattern of glacial retreat since the mid Holocene.

Discussion

The Little Ice Age in Iceland

The ELA reconstruction, documentary evidence and the instrumental temperature record indicate significant interdecadal climatic variability between AD 1670 and 1900 in Iceland. This precludes an earlier view of an uniformly cold 'Little Ice Age' between 1600 and 1900 in Iceland (Grove, 1988). This study indicates that the Little Ice Age was of shorter duration, extending from 1750 to 1920 in agreement with evidence from marine sediment cores in coastal Greenland and ice cores in central Greenland (Fig. 3).

The relationship between wider Arctic sea ice conditions (Vinje, 1999) and the ELA reconstruction at Sólheimajökull is presented in Fig. 2. Periods of low ELA/cold temperatures in Iceland are correlated with a more southerly extent of the Barents Sea ice margin. In contrast, periods of high ELA/high temperatures in Iceland are correlated a more northerly extent of the Barents Sea ice margin. The sea ice reconstruction also shows decadal variability, which is in phase with the ELA reconstruction over the last 300 years. The climatic extremes evident in the reconstruction resemble the two dominant modes of the North Atlantic Oscillation evident in sea ice and atmospheric records from the last few decades (Mysak and Venegas, 1998). This suggests that climatic changes in Iceland dating from before the establishment of instrumental records resulted from similar climate dynamics to that recorded in the last few decades. Natural climatic variability has dominated recent climatic changes and 20th century changes are not unusual within their historical context.

Earlier Holocene climatic changes

Holocene fluctuations of Sólheimajökull were synchronous with other Icelandic glacier and with glaciers more widely in both hemispheres (Denton and Karlen, 1973) (Fig. 4). This suggests that Sólheimajökull responded to wider temperature changes. In Iceland, the climatic oscillation can be inferred by the model to have an amplitude of 1–2 °C and a period of c. 1500 years. O'Brian et al., (1995) indicate that these long term climatic changes are associated with changes in the strength of the polar vortex. During cold phases the mean position of the zonally averaged surface westerlies migrates southwards. Warmer intervals are associated with the northward movement of the cyclone tracks. This scenario resembles the atmospheric signal of the NAO, suggesting that the climatic dynamics of millennial and decadal climatic changes in Iceland are similar.

Conclusions

1. A numerical model has successfully reconstructed climatic changes in Iceland from the record of past glacier fluctuations at Sólheimajökull.
2. The climate of the 17th, 18th and 19th centuries was dominated by decadal-scale climatic variability, associated with changes in sea ice extent. This natural climatic variability has a large signal in Iceland. Warming in the 18th century was similar to that of the 20th century.

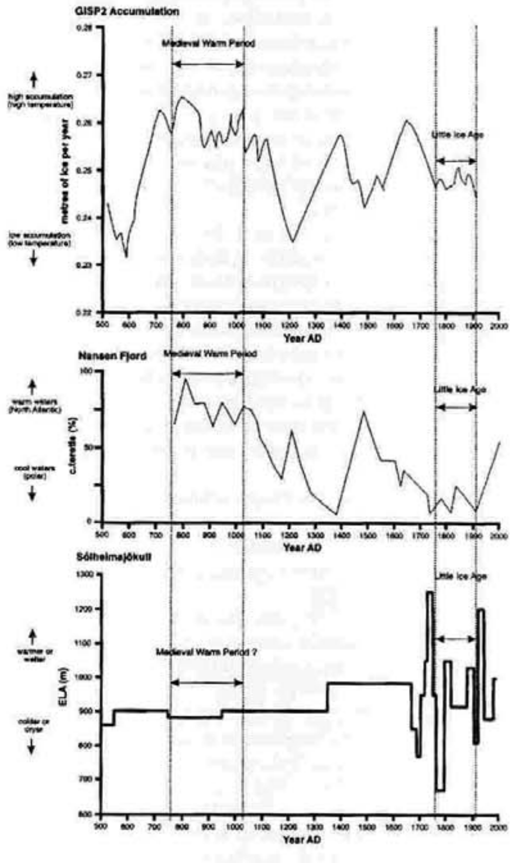

Fig. 3. A comparison between the Sólheimajökull ELA record, the GISP2 accumulation record from central Greenland (Meese et al., 1994) and the Nansen Fjord Cassidulina terretis (formaminifera) record from a marine core in east Greenland (Jennings and Weiner, 1996). All three records show evidence of a Little Ice Age event between approximately AD 1750 and 1920.

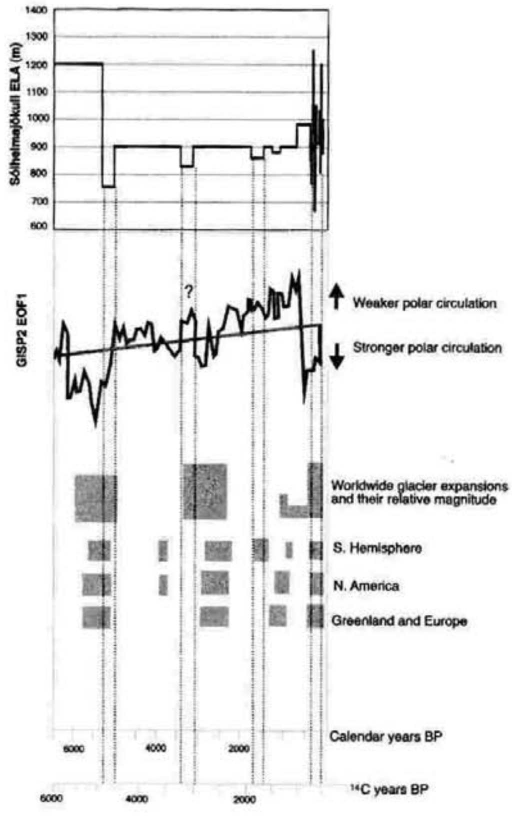

Fig. 4. A comparison between the Sólheimajökull ELA record, the GISP2 EOF1 record and a synthesis of worldwide glacier fluctuations (O'Brian et al., 1995). There is general agreement between all three records in terms of the timing and magnitude of Holocene cool phases. This indicates that fluctuations in the ELA of Sólheimajökull reflect wider climatic changes. Specifically, periods of low ELA at Sólheimajökull occur during periods of stronger polar circulation in central Greenland, when the westerly belt migrates southward.

3. Earlier Holocene climatic changes from 5000 years BP have also involved changes in atmospheric circulation and sea ice extent, and temperature changes of 1–2 °C relative to 1960–1990 conditions.

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