The effect of continentality on glacier response and mass balance

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ABSTRACT. The continentality index is a good measure of the nature of the climate in a region, as it reflects not only the temperature but also the large-scale circulation. It correlates well with glacier mass-balance parameters. The climate along the west–east transect slightly north of the Arctic Circle across the Scandinavian Caledonides is governed by the prevailing westerlies; however, during winter the eastern part of the Caledonides is influenced by weather systems from the southeast. The differences in continentality meant by temperature and precipitation have a major impact on the response times of glaciers. The climatic change in this area has been dominated by increased summer mean temperatures (1910–20) and increased maritime influence since the 1980s. The slower-reacting glaciers on the Swedish side of the mountains are still adapting to the temperature increase at the beginning of the 20th century, and the influence gradually becomes less important towards the west. Thus, differences in the behaviour of glacier fronts along the west–east transect mirror differences in continentality.

INTRODUCTION

Glaciers are known as good climatic indicators. Changes in glacier length are used as delayed and filtered proxy information about climate variables such as temperature and precipitation. High resolution is obtained using annual mass-balance data, a high-quality but time-consuming and expensive way of monitoring glaciers. A mass-balance record is the key to climatic fluctuations, while front position changes are much more difficult to interpret, especially in cold and continental areas where glacier response times are long. A proxy measurement of the net mass balance is the size of the accumulation area at the end of a melt season, often referred to as accumulation area ratio (AAR). Assuming a balanced state and a constant net balance gradient, AAR is expected to correlate well with the net balance and thus the climate (Fig. 1).

In this study we compare some AAR observations with a continentality index along a transect from the west coast of Norway to inland Sweden. The aim is to show the importance of clarifying whether glacier changes are due to local climate effects or large-scale trends when studying glaciers as climate indicators.

We used climate data from the two national weather stations in Bodo (Norway) and Jokkmokk (Sweden), and from our own stations at Sulitelma and Pärtejäkkä, both in Sweden (Fig 2; Table I). Data on glaciers were taken from Engabreen on the Norwegian coast, Salajekna at the water divide and Pärtejäkkna on the eastern side of the mountains.

Fig. 1. The correlation between accumulation area ratio (AAR) and the net balance of Storglaciären highlights the validity of using AAR as proxy measurements for mass balance.

Fig. 2. Location map showing sites mentioned in the text.
DESCRIPTION OF THE GLACIERS STUDIED

Engabreen

Engabreen’s areal extension is 32 km², and it is part of western Svartisen covering 221 km² (Fig. 2). Its vertical extension ranges between 40 and 1594 m a.s.l. It is a temperate, valley-type, outlet glacier. The extension of the glacier has been documented since the mid-18th century, and the first photograph was taken in 1881. At this time Engabreen covered the lake Engavannet, and the front was only a few hundred metres until recently when the glacier posed. After this, the terminus fluctuated back and forth over a few hundred metres until recently when the glacier began advancing significantly (personal communication from N. Haakensen, 1996) (Table 2).

Mass-balance measurements were initiated in 1966. After a few years with a balanced state the glacier has since had a positive mass balance. The glacier has grown 15 m thicker on average since 1972 (Haeberli and others, 1994).

Salajekna

Salajekna is situated in the Sulitelma massif at the border between Sweden and Norway (Fig. 2). It is a valley-type glacier in a glacier complex covering ~30 km². Salajekna proper has an areal extension of 24 km², a volume of approximately 2.4 km³ and a vertical range between 880 and 1580 m a.s.l. (Östrem, 1983). The glacier is oriented towards the south.

The first scientific observation of a Swedish glacier was made in 1807 on Salajekna by Wahlenberg (1809). He described the glacier in a figurative way; he heard continuous audible cracking and water running underneath the glacier. Fortunately, he also made a painting of the glacier from a nearby frontier cairn on the border between Norway and Sweden.

In 1897 the glacier was photographed from the same frontier cairn used by Wahlenberg. The panoramic view shows that Salajekna was heavily crevassed by then and had a greater extension than in 1807 (Westman, 1899). Later lichenometric studies by P. Karlén (personal communication, 1996) show that the glacier had an extension very close to its Holocene maximum at the turn of the 19th century. Westman made front observations during a 10 year period over the extensive phase of the glacier (Westman, 1910). He also drew a map of the glacier (Westman, 1899).

In 1965 the glacier was included in the official Swedish glacier monitoring programme, and the snout has been regularly surveyed since then by means of frontal changes (Schytt, 1968; Holmlund, 1993). The glacier has retreated about 1.5 km with annual recession rates of 15–20 m since 1910, though the recession speed is now declining (Table 2). The most accurate map is based on aerial photographs taken in 1980 and printed at a scale of 1:20 000 (Östrem, 1983). Less than 5% of the ice mass is below freezing point, and Salajekna is thus referred to as a temperate glacier.

Pärtejekna

Pärtejekna is situated in the Pärte massif in southern Sarek National Park (Fig. 2). It is a valley glacier oriented east, with a divided accumulation area. Its areal extension is 11.1 km², its volume approximately 0.85 km³ and its vertical extension ranges from 1090 to 1760 m a.s.l. (Holmlund, 1995). The glacier was first described by Hamberg (1901, 1910) who made ablation measurements and documented the glacier photographically between 1897 and 1901. He called the glacier Lulevaggeglaciaren, a name which is no longer in use. In 1965 Pärtejekna was included in the Swedish glacier-monitoring programme (Schytt, 1968; Holmlund, 1993). The glacier began its recession later (around 1930) than most other Swedish glaciers and is presently retreating at a speed of about 10 m year⁻¹. At present there is no sign of a decline in the recession rate (Table 2). There

<table>
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<th>Year</th>
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<th>Winter precipitation</th>
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<tbody>
<tr>
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<td>1992</td>
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<td>1995</td>
<td>10.6</td>
<td>732</td>
</tr>
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</table>

Table 1. Meteorological characteristics of four stations along a west–east transect located slightly north of the Arctic Circle in Scandinavia (Fig. 2). Data from Bodø and Jokkmokk provided by the Norwegian and Swedish weather services, respectively.
is no printed large-scale map of the glacier, though a xeroxed working map at a scale of 1:20 000 is available at the Department of Physical Geography, Stockholm University. About 50% of the glacier mass is below freezing temperatures, and in most senses it is referred to as a sub-polar glacier (Holmlund, 1993; paper in preparation by P. Holmlund).

DESCRIPTION OF CLIMATE STATIONS

The climate stations used in this investigation are located on a west–east transect through the Scandinavian Caledonides from Bodø at the Norwegian coast in the west to Jokkmokk in the east (Fig. 2). The profile is located at a latitude of ~67°N. The stations Bodø and Jokkmokk are official weather stations in the Norwegian and Swedish weather services, respectively. Bodø is located at sea level, and Jokkmokk at an altitude of 263 m a.s.l. (Table 1).

The two other stations used in this study are run by the Tarfala Research Station. They are automatic weather stations located in front of Salajekna at an altitude of 900 m a.s.l., and on the top plateau of Partetjåkkå at an altitude of 1830 m a.s.l. (Fig. 2). The stations are equipped with a Campbell Scientific CR10 data logger and powered by solar panels. At Salajekna, temperature and relative humidity are measured by means of a Rotronic MP300 probe 2 m above ground. The station was installed in August 1994 (Table 1).

The observation site on Pårtejåkkå is located near the former observatory of A. Hamberg, who carried out meteorological observations at the beginning of the 20th century (Hamberg, 1901; Hamberg and Jönsson, 1933). There are sporadic observations from 1901 to 1914 and continuous records from July 1914 until September 1918. Since August 1993, temperature has been measured in Hamberg’s former radiation screen (Table 1), as well as 2 m above ground with the help of platinum resistance probes (Pt100), mounted in a Young radiation shield. The temperature data used in the present investigation are from the Pt100 in the Young shield. In August 1994 a Young wind monitor was installed 3 m above ground to measure wind speed and direction.

CLIMATIC DEVELOPMENT DURING THE LAST 200 YEARS

A strong climatic gradient can be distinguished along a latitudinal transect from the Atlantic Ocean to central Sweden. The climate in western Norway is maritime; at the water divide it is locally maritime; and east of the mountains it is locally continental (Angström, 1974). This climatic gradient also influences net balance gradients on glaciers and the glaciation level. Typical values on net balance gradients are 1.5 m per 100 m in western Norway and 0.5 m per 100 m in the eastern part of the mountains. The glaciation level (Brückner, 1887) increases in the opposite direction at a gradient of approximately 0.7 m km⁻¹ (Enquist, 1916). The rate of maritime in the mountain area has varied with time. It was especially pronounced during the late 19th century (Wallén, 1986), as well as during the last 10 years (Holmlund, 1993; Grudd and Schneider, 1996; Holmlund and others, 1996). Changes in the rates of maritime and continentality have almost certainly varied earlier during the Holocene.

There are a number of front moraines representing for-
justing to the early 20th-century temperature rise, though glaciers. Over the last decades Engabreen has gained mass and the effect of topography, with orographic precipitation as a consequence of the dominant wind direction from the west, giving a maritime climate along the western coast of Norway and a local continental climate in the Swedish mountains, as they carry a significant part of these glaciers' annual mass gain. This complication may cause a local maritime influence along the easternmost part of the mountain range. However, this is not seen in the rudimentary analysis carried out in this paper.

RESULTS

The continentality index increases from west to east (Fig. 3; Table 1). The CI gradient was calculated as 2.8°C per 100 km. The temperatures at Jokkmokk fluctuate strongly in contrast to the uniform maritime climate at Bodo.

As a test we correlated AAR and net balance of Stor­gjleirna and Partejekna, and summer mean temperature, and winter precipitation at Bodo and Jokkmokk. Data provided by the weather service in northern Norway and by the Swedish Institute for Meteorology and Hydrology (SMHI). The correlation between AAR values of Engabreen, Salajekna and Partejekna, and summer mean temperature, and winter precipitation at Bodo and Jokkmokk. Data provided by the weather service in northern Norway and by the Swedish Institute for Meteorology and Hydrology (SMHI).

Fig. 4. The correlation between AAR values of Engabreen, Salajekna and Partejekna, and summer mean temperature, and winter precipitation at Bodo and Jokkmokk. Data provided by the weather service in northern Norway and by the Swedish Institute for Meteorology and Hydrology (SMHI).

DISCUSSION

The degree of continentality increases towards the east as a consequence of the dominant wind direction from the west and the effect of topography, with orographic precipitation along the Norwegian coast and föhn effects on the east side of the water divide. The CI (Fig. 3; Table 1) shows a difference of 12°C between Bodo and Jokkmokk, situated 250 km apart at a similar latitude. The differences are also mirrored in the frontal-change records of the nearby glaciers. Over the last decades Engabreen has gained mass again and the glacier is now advancing. Salajekna is still adjusting to the early 20th-century temperature rise, though its mass balance has most probably been positive for the last 10 years (Table 2).

The situation at Partejekna is more complicated than at the other two glaciers. It is a sub-polar type of glacier which is responding slowly to climatic changes (Table 2).

Though it is based on few data points, we may conclude that the mass balance of the glaciers studied is controlled by the westerlies. The general circulation also controls the climate in Jokkmokk. The AAR of Engabreen is slightly better-correlated with the winter precipitation at Bodo than with the summer temperature at Jokkmokk, whilst the AAR from Partejekna is correlated with the summer temperature in Jokkmokk. This result was expected. The reason for the poor correlation between the summer temperature in Bodo and the AARs is the influence of a maritime climate which produces more equitable temperatures.

During a normal winter there are several intrusions of low-pressure systems from directions other than the west, e.g. the southeast. These systems are not long lasting and do not influence the CI value at Jokkmokk. They probably have a negligible effect on the accumulation of maritime glaciers. However, these weather systems influence the low inland precipitation rates and thus the correlation with the AARs on glaciers. These weather situations may also play an important role on glaciers along the eastern rim of the Swedish mountains, as they carry a significant part of these glaciers’ annual mass gain. This complication may cause a local maritime influence along the easternmost part of the mountain range. However, this is not seen in the rudimentary analysis carried out in this paper.

CONCLUSION

The CI is a good measure of the nature of climate in a region, as it reflects not only the temperature but also, indirectly, the large-scale circulation. It is also useful for highlighting anomalies in glacier responses.

Based on this study it is clear that the climate in northern Scandinavia is almost entirely governed by low-pressure systems from the west, giving a maritime climate along the west coast of Norway and a local continental climate in central Sweden, as has been described by Enquist (1916) and others. There is a strong correlation between mass-balance parameters along the transect investigated, and the winter precipitation at Bodo, and the summer temperature at Jokkmokk. The eastern rim of the mountains also receives orographic precipitation from southeasterly winds during winter.

The use of climatic parameters is a necessity for interpreting glacier fluctuations correctly. Using the method outlined in this paper, anomalous behaviour such as glacier-front reactions diverging from a general pattern can be identified and classified as caused by local climate effects. This method may also encourage future detailed studies of the complex relationship between climate and glacier response.

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