The impact of climate change on glaciers and glacial runoff in the Nordic countries

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ABSTRACT

Possible changes in glacier mass balance are among the most important consequences of future climate change in Iceland, Greenland and some glaciated watersheds in Scandinavia. These changes have both local and global implications, such as changes in the discharge of glacial rivers, changes in the vertical stratification in the upper layers of the Arctic Ocean and a rise in global sea level. Changes in glacier mass balance and glacier geometry for several ice caps and glaciers have been modeled with mass balance and dynamic models to estimate the future response of the glaciers to climate change as specified by the CE climate change scenario. Many glaciers and ice caps are projected to essentially disappear over the next 100–200 years. Runoff from presently glaciated areas may increase by 25–50% in the period 30–100 years from now for typical glaciated watersheds in the Nordic countries. The expected runoff increase may have practical implications in connection with the use of water in various sectors of society. Changes in water divides and changes in river courses may also have important consequences.

1. INTRODUCTION

Glaciers cover about 11% of the area of Iceland and they receive about 20% of the precipitation that falls on the country. They store the equivalent of 15–20 years of annual average precipitation over the whole country as ice. Substantial changes in the volume of glacier ice may, therefore, lead to large changes in the hydrology of glacial rivers, with important implications for the hydropower industry and other water users. Glacial runoff affects most of the larger watersheds in Greenland, which have been investigated with regard to hydropower potential, and it constitutes a relatively large component in the water budget of several hydropower plants in Norway. Glacial runoff is particularly important for the hydropower industry because hydropower plants utilise runoff from highland areas, where glaciers tend to be located. As an example, the Svartisen ice cap and smaller ice caps and
Glaciers significantly modify streamflow in quantity, variability and timing by temporarily storing water as snow and ice and in liquid form on different time-scales. Annual basin runoff is enhanced or decreased in years of high or low melting, respectively. Glacial discharge shows pronounced melt-induced diurnal and seasonal cyclicality, the latter beneficial in many cases since glacial meltwater is typically released during periods of otherwise low flow conditions in many areas of the world. The effect of climate warming on glacial runoff includes an initial increase in total glacial runoff and peak flows, and a considerable amplification in the diurnal runoff oscillation, followed by significantly reduced runoff totals and diurnal amplitudes as the glaciers retreat.

In addition to the direct effect on runoff caused by glacier mass balance changes due to changes in climate, feedback effects caused by glacier dynamics may lead to migration of ice divides and subglacial watersheds and change subglacial water courses. This can in some cases cause locally very large relative changes in the discharge of rivers that issue from glacier margins, with implications for bridges, roads and other infrastructure.

Glaciers and ice caps in the Nordic countries have retreated and advanced during historical times in response to climate changes, which are believed to have been much smaller than the greenhouse induced climate changes that are expected during the next 100–200 years. These changes have in many cases left clear marks on the landscape in the neighbourhood of the glaciers as shown in Figure 1.

Melting of all glaciers and ice caps on Earth, excluding the large ice sheets of Greenland and Antarctica, has been estimated to raise sea level by about 0.5 m, although there is still considerable uncertainty in the sea level rise equivalent of the ice stored in these glaciers. The rate of retreat of glaciers, and their contribution to sea level rise has been monitored and modeled, and found to have increased in the latter part of the 20th century. Increased meltwater flux from glaciers into the world oceans may also have other far-reaching effects including changes in salinity and vertical stratification of the upper layers of the Arctic Ocean and nearby oceanic areas with possible consequences for thermohaline circulation in the Atlantic Ocean. Studies of the response of glaciers in the Nordic countries to climate changes

Figure 1. The forefields of Brikdalsbreen in western Norway (left, photo: Kurt Erik Nesje, 2005) and Blágnípujökull in the Hofsjökull ice cap in central Iceland (right, photo: Oddur Sigurðsson, 2001) show clear signs of past changes in the position of glaciers in the same watershed cover about 50% of the drainage area that is utilised by the Svartisen hydropower plant in northern Norway.
are an important contribution to global climate change studies, as glaciers in these countries are more accessible and better studied than in most other regions of the world.

Several ice caps and glaciers were studied within the CE project (see Figure 2)

**Iceland**
- The Vatnajökull, Hofsjökull and Langjökull ice caps

**Norway**
- The Svartisen ice caps in northern Norway, including the outlet glacier Engabreen from Vestre Svartisen, and Storbreen, a valley glacier in central, southern Norway

**Sweden**
- Storglaciären and Mårmaglaciären

**Denmark/Greenland**
- Tasersiaq basin, a partly glaciated basin at the margin at the Greenland Ice Sheet where hydropower potential is being studied

The main topics of study were

1. Mass balance modeling, including studies of precipitation and snowfall on the glaciers.
2. Dynamic glacier modeling where ice flow models were coupled to mass balance models.
3. Adaptation of climate scenarios for glacier modeling.
4. Runoff modeling with an emphasis on changes in total runoff, runoff seasonality and diurnal runoff variation.

The models were in all cases calibrated with available observations of the mass balance and geometry of the glaciers. They are able to reproduce the main characteristics of the mass balance turnover and ice flow and may be expected to yield realistic estimates of the response of the glaciers to assumed climate changes. The main source of uncertainty in the results is the
future climate development, which for temperature spans the range from very little warming in the North Atlantic area to a warming similar as in other oceanic areas on Earth. The precipitation are also very uncertain, both with regard to absolute changes, and seasonal and spatial distribution.

2. CLIMATE SCENARIO

Several different types of climate change scenarios, based on the general CE scenarios, were used for the glacier modeling. Figure 3 shows scenarios for temperature and precipitation at three locations near the modeled glaciers. The climate records are shifted and scaled within the glacier mass balance models in order to better represent the climate on the glaciers, which are located at other altitudes than the climate stations and in regions where orographic precipitation effects are most often quite different from precipitation conditions at the stations. Therefore, the absolute values of temperature or precipitation shown in the figures should not be interpreted as reflecting the climate on the glaciers, but the variations in the time-series do, however, indicate the changes in the climate on the glaciers.

3. MASS BALANCE AND DYNAMIC MODELING

Glacier mass balance was modeled with degree-day models of different complexity (Jóhannesson et al., 2006; Thorsteinsson, et al., 2006; Schuler et al., 2005; Andreassen et al., 2006; Radic and Hock, 2006) and, in case of Storbreen, with an energy balance model (Andreassen et al., 2006). In the degree-day models, snow accumulation and ablation are computed from daily temperature and precipitation observations (or estimates) at nearby meteorological stations (or model grid points). Temperature on the glacier is found using a constant vertical lapse rate and precipitation is computed using horizontal and vertical
precipitation gradients. The energy balance model is calibrated with observations of radiation, temperature, relative humidity and wind speed from an automatic weather station on the glacier and from nearby meteorological stations, and is run using data from meteorological stations outside the glacier.

The static sensitivity of the mass balance of the modeled glaciers to temperature changes (defined as the change in the mass balance that results from a warming of 1°C) was found to vary from approximately $-0.5 \text{m w.e. a}^{-1} \text{C}^{-1}$ for Storglaciären, through $-0.6$ to $-0.7 \text{m w.e. a}^{-1} \text{C}^{-1}$ for Storbreen and Hofsjökull, and $-0.9 \text{m w.e. a}^{-1} \text{C}^{-1}$ for Engabreen, to $-1.1$ to $-1.3 \text{m w.e. a}^{-1} \text{C}^{-1}$ for Langjökull and S-Vatnajökull. The glaciers with the longest ablation season and largest mass balance turnover have the largest static sensitivity as has been found in previous studies (see for example Oerlemans and Fortuin, 1992; de Woul and Hock, 2005). The sensitivity to a 10% increase in precipitation was typically much smaller, so that if future precipitation changes are as small as projected by the CE scenarios, it is estimated that the effect of future temperature changes will dominate that of precipitation changes, except for coastal glaciers in western and northern Norway where larger precipitation changes may be possible.

The dynamic response of the Icelandic glaciers to the modeled mass balance changes was simulated with the 2D ice flow model developed by Aðalgeirsdóttir (2003) coupled to the MBT degree-day mass balance model (Aðalgeirsdóttir et al., 2006), and in case of Storglaciären with a simple model for the evolution the ice volume with time based on a volume-area scaling (Radic and Hock, 2006). In addition, the initial reduction in ice volume for Storbreen and Engabreen was modeled based on the static sensitivity of the mass balance (Andreassen et al., 2006).

Figure 4 (left) shows the simulated ice wastage for the modeled glaciers. The simulations with the 2D ice flow model are run to 2200, but the Storglaciären simulation is only run to 2100 because of limitations in the volume-area scaling model. The Engabreen and Storbreen
simulations are terminated in 2144 and 2049, respectively, when the reduction in ice volume reached 30%, because of limitations in the static sensitivity models. The time evolution of ice volume has a similar character for all the modeled glaciers, except Engabreen. The modeled ice volume is reduced by more than half within the next 100 years, and the glaciers essentially disappear in 100–200 years after the start of the simulations, given that the rate of warming with time remains the same. Engabreen retreats more slowly because of the substantial increase in precipitation, which is projected by the CE-scenario for the area where this glacier is located.

The projected change in the mass balance of the glaciers leads to a substantial increase in glacier runoff as seen in Figure 4 (right), which shows the modeled increase in runoff from the area covered with ice at the start of the simulations. About 2030, annual average runoff is projected to have increased by approximately 0.5–0.7 m\text{w.e.}a^{-1} for Storglaciären, Storbreen and Engabreen, and 1.5–2.5 m\text{w.e.}a^{-1} for Langjökull and Hofsjökull and S-Vatnajökull. The runoff increase reaches a comparatively flat maximum between 2050 and 2150 when the increasing contribution from the negative mass balance is nearly balanced by the counteracting effect due to the diminishing area of the glacier. This maximum in the relative runoff increase is for all the glaciers in the range 50–100% with respect to the present runoff from the area presently covered with ice. For the Icelandic ice caps, the specification of climate change during the initial decades of the simulation based on the observed climate of recent years (Fig. 3) and the seasonality of the climate change with the largest warming in spring and fall (Fig. 4), leads to a rapid increase in runoff with time, much more rapid than according to the previous CWE scenario, which was used by Jóhannesson \textit{et al.} (2004) and Aðalgeirsdóttir \textit{et al.} (2006) in modeling of Hofsjökull and S-Vatnajökull. The model results for Engabreen show that, although the precipitation increase for the other glaciers of much smaller importance than the temperature change, the assumed precipitation change can significantly alter the simulation results in case substantial precipitation changes take place. The fact that this only happens for one of the glaciers, highlights the uncertainty of the climate change scenario.

4. CONCLUSIONS

These results clearly show large changes in runoff from glaciated areas, which are projected to have reached significant levels compared with current runoff already by 2030. The associated changes that may be expected in diurnal and seasonal characteristics of glacial runoff (de Woul \textit{et al.}, 2006; Hock, 2006) will come on top of the changes in the annual average, which are shown in Figure 7. These changes may be expected to have practical implications for the design and operation of many hydroelectric power plants, and other uses of water from glaciated highland areas in the Nordic countries.

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REFERENCES


