DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2008/31

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Contents

Summary

This report presents an evaluation of the future runoff conditions from the hydrological basin Pakitsup Akuliarusersua near Ilulissat, West Greenland. This basin is complicated because it is mainly supplied by meltwater from the ice-sheet margin, requiring glaciological modelling of future ice sheet behaviour. The evaluation is based on all the available observational data for the region, the most recent climate model scenario and state-of-the art ice sheet models for ice dynamics and meltwater hydrology. The main results are

- The configuration of the ice-sheet hydrological basin is likely to remain constant
- As a minimum, the basin discharge is likely to remain constant until 2035, followed by a steady increase towards 2080
- The ice-sheet margin is likely to keep thinning at the current rate of approx. 1 m/yr

The glaciological evaluation presented here forms a continuation of previous glaciological activities by the Geological Survey of Denmark and Greenland related to hydropower in the Paakitsoq region, as summarized in a previous report by Ahlstrøm (2007).

Introduction

The annual discharge has been estimated for the whole catchment extending to the year 2080, with the contribution from the largest sub-basin specified on its own. This is illustrated in Figure 9. The discharge estimate relies on a particular choice for the future global greenhouse gas emissions, namely the IPCC SRES B2 scenario[a]. This particular emission scenario was chosen because it is fairly conservative in its predictions. That implies that the discharge estimate provided here is most likely also conservative, as most of the water comes from ice sheet melt, a process which is particularly sensitive to predicted rise in air temperature and changes in precipitation. The conclusion is that even with a fairly conservative climate evolution scenario, the discharge is predicted to remain relatively constant on average until 2035, at which point a steady increase in the discharge sets in. This prediction includes the response of the ice sheet margin to climate change in terms of dynamics and mass balance and is robust for the range of realistic basal water pressures, that might otherwise cause changes in the delineation of the ice-sheet hydrological basin.

A range of observational data was required for the glaciological modelling, including hydrological and climatological data series collected by the Greenland Survey (Asiaq), used for the purposes of calibrating model output. Airborne elevation and ice-thickness measurements derived from radar and lidar measurements collected and processed by the National Space Institute at the Technical University of Denmark were used to define the surface topography and thckness of the ice sheet. A detailed surface topography for the ice free part of the basin, based on stereophotogrammetry was supplied by the Department of Geological Mapping of the Geological Survey of Denmark and Greenland (GEUS). The dynamic and melt models were driven by output from a combined global/regional climate based on an IPCC climate scenario run by the Danish Meteorological Institute (DMI). Other data including existing ice sheet observations from GEUS and from US automatic weather stations were used to verify and calibrate modelling work.

Surface topography and ice thickness

A combination of existing and new data including ice-penetrating radar to determine subglacial topography and laser altimeter measurements to characterise the current surface elevation. The new data was collected in 2005 during 5 hours of flying with flight tracks roughly 1 km apart (funded by the Commission for Scientific Research in Greenland, KVUG). Measurements were made with a 60 MHz coherent radar system and a scanning laser altimeter (lidar). Positioning was accomplished with several onboard differential GPS's and aircraft orientation with an inertial navigation system (INS).

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[a] IPCC SRES: Intergovernmental Panel for Climate Change - Special Report on Emission Scenarios

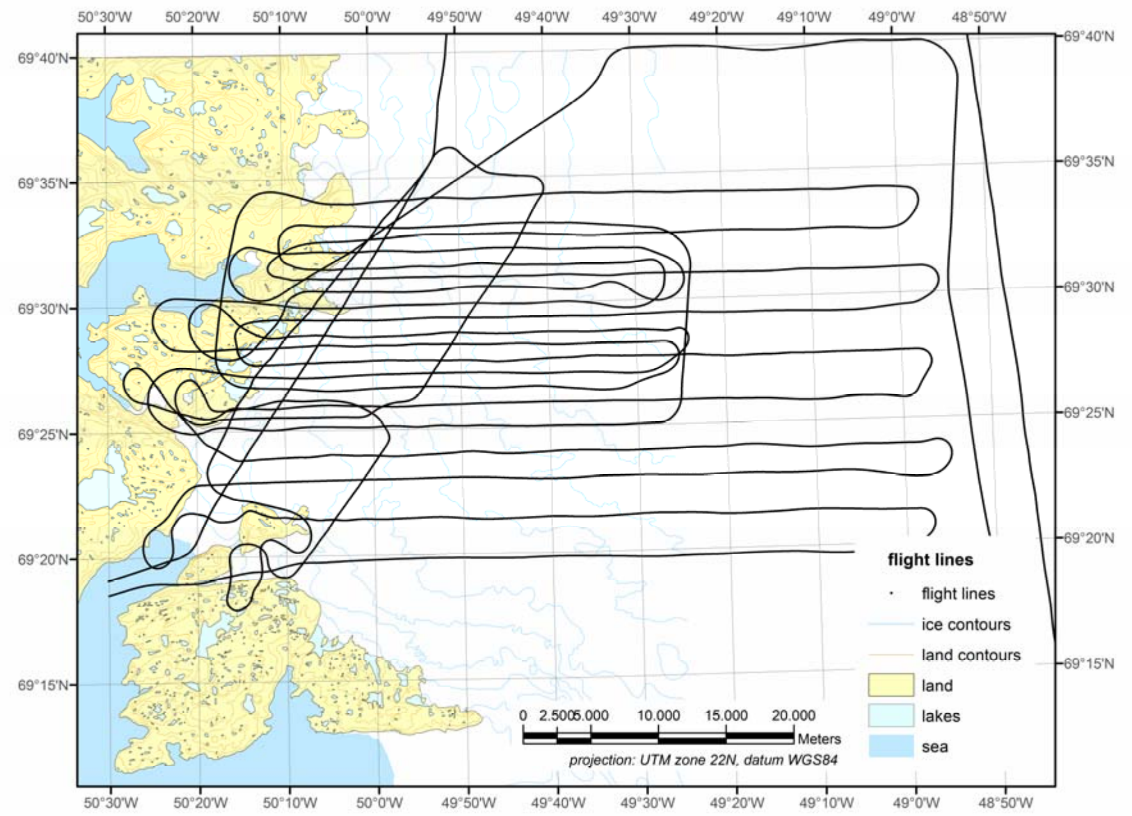

Figure 1. *Flight lines from the ice sheet survey in 2005. The survey was designed to facilitate a future investigation of the hydropower feasibility at Paakitsoq and is thus more dense in the most critical part of the ice sheet margin, with a track spacing down to approx. 1 km.*

The radar data collected in 2005 was processed by the National Space Institute at DTU, following a new processing chain to optimise the radargrams and reformatted to conform to the standard RAMAC format. The radargrams provided by DTU were enhanced in contrast and gain corrected using the software 'ReflexW', hereby making the surface and bed reflection stand out clearly. These reflections were then visually identified and digitized, and from these digitized lines the bed and surface elevation could be calculated. The interpretation required the visual identification and digitizing of surface and bed radar reflection for some 85,000 different points. There was little or no evidence of internal layers which might have been useful for understanding the dynamics of the ice margin. Laser measurements of the distance from the plane to the surface (lidar) were made on the same flight.

Since the surface reflections were not visible over large parts of the radargrams, and the precision of the lidar is an order of magnitude higher in quality than the radar, the lidar data were superior to the radar for calculating the surface elevation. The radar elevations are known with a precision of ± 80 m, lidar elevations are given a precision of ± 0.3 m. Using the geographical positioning information the two datasets could be matched up precisely, and by use of the combination of lidar and radar data, together with maps of the area, the data could be divided into bare rock elevation (outside of the ice sheet), bedrock elevation (below the ice sheet) and ice-sheet surface elevation. These data sets were then used for the construction of the digital elevation models (DEM's).

Previous work with similar data sets have shown that the geostatistical interpolation method known as block kriging method is superior for creating regular grids from the airborne radar and lidar data. Kriging is used to estimate elevation at an unobserved location from observations at nearby locations. In making each calculation, the algorithm applies more weight to the values of locations closer to the unknown point and less weight to observations from farther away. It is a particularly powerful technique for topographic interpolation, as the algorithms can also be used to take into account the directional variability of topography. That is, in some directions topography may have greater variability than in other directions around an unknown point. Initial data produced by the radar interpretation was used to develop a suitable kriging formulation designed to take into account topographic profiles and data distribution in the software package ‘Surfer’ from Golden Software. The algorithm developed for the bedrock and sub-glacial topography approximated the topography as a rational quadratic function and also included a correction to account for the uncertainty in the location of each point due to the measurement limits of the radar data. For the ice surface topographic data set a linear model was found to work best, probably since the ice flow acts to linearise and smooth out elevation.

GEUS data from an airborne stereophotogrammetric survey carried out in 1985 was utilized to produce high-resolution vector maps of the topography and prominent landscape features with special focus on topography in ice free areas. The vector map data was reprocessed for physical modelling purposes including extraction of the relevant points, polylines and polygons from the vector data, and it was transformed into a standard DEM, suitable as input for numerical models. The local detailed DEM was merged with the other datasets to produce both a surface DEM and a basal DEM of the whole region up to the centre of the ice sheet (see Figures 2 and 3). In order to avoid substantial discontinuites resulting from merging DEM’s of different scales, the kriging algorithms developed for the Paakitsoq area were also applied to the large scale DEM’s.

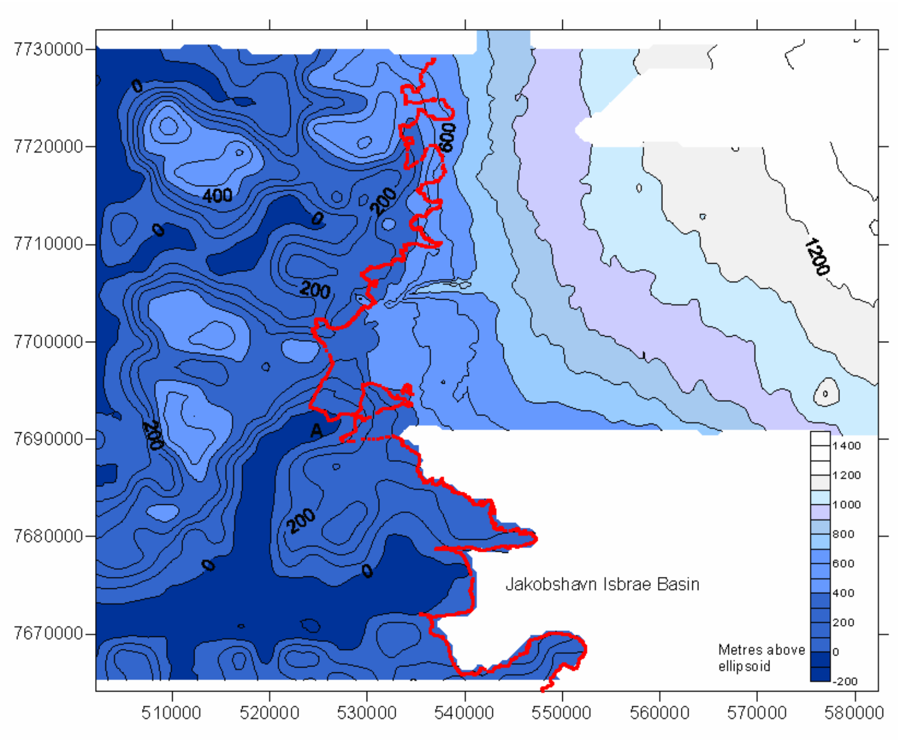

Figure 2. *The new surface topography map showing both ice free and currently ice covered terrain. The red line indicates the glacier terminus, taken from the GEUS DEM of the area and based on aerial photos from 1985. The white space represents areas with missing or poor data. The map is in UTM22 coordinates (Northing [m] and Easting [m]), datum WGS-84.*

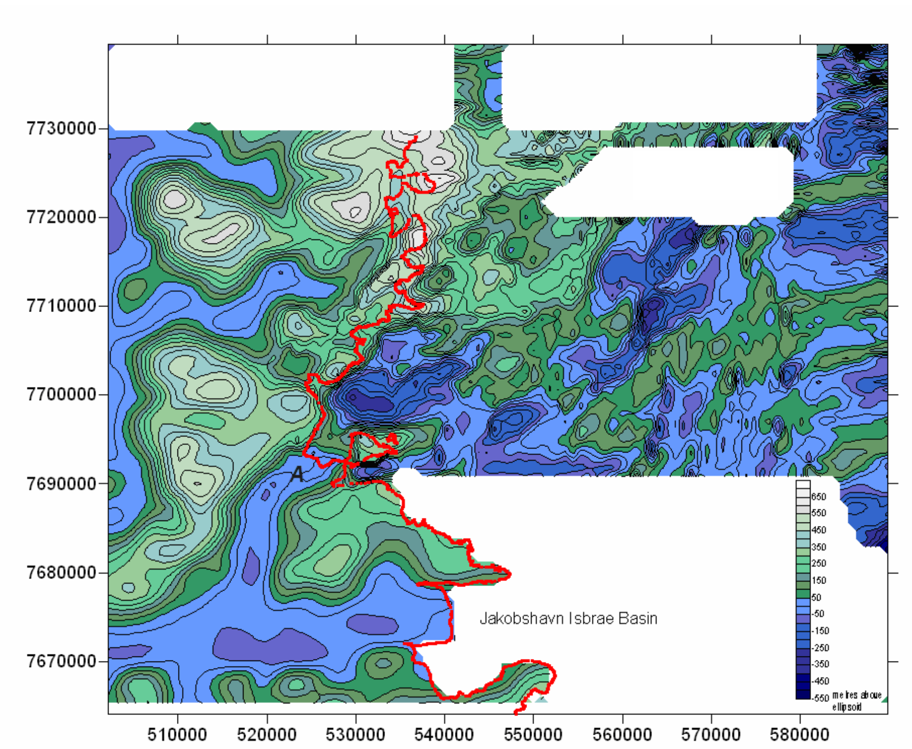

Figure 3. *Basal topographic map showing both ice free and currently ice covered terrain. The map is in UTM22 coordinates (Northing [m] and Easting [m]), WGS-84.*

Climate and melt

The climate scenario used for this discharge prediction is the IPCC SRES B2 scenario. It was published in the Special Report on Emission Scenarios by the Intergovernmental Panel for Climate Change (Nakicenovic & Swart, 2000) along with 3 other main scenarios (A1, A2 and B1) and was intended for use in the IPCC third assessment report, published in 2001. The B2 scenario was chosen as it is relatively conservative, with the term 'medium' assigned to the all the following parameters: 'Population growth', 'GDP growth', 'Energy use', 'Land-use changes', 'Resource availability', 'Pace of technological change'. It is described in the SRES as follows: 'The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.' The SRES scenarios have been critizised as being too optimistic, in particular about the development of environmental technologies. However, the SRES scenarios remain useful by providing a common ground for making predictions of climate-induced change.

The IPCC SRES B2 scenario was used as input to a climate model at the Danish Meteorological Institute (DMI) consisting of a regional climate model, HIRLAM, nested in a global circulation model, ECHAM4. The aim of the nesting was to deliver high-resolution (25 km by 25 km grid) regional climate predictions, in this case for Greenland. The combined model has been given the name HIRHAM4 and is among the most advanced of its kind. A transient run of HIRHAM4 covering from 1950 and up to 2080 produced the 2 m air temperatures and precipitation fields necessary to force our mass balance model, a so-called temperature-index model (or degree-day model) which exploits the high statistical correlation between ice/snow melt and the amount of time the air temperature is above the melting point. The climatic output data was used for two purposes, in the first instance to drive the dynamic changes of the ice sheet, and in the second to predict rates of melt and run-off. This required substantial processing of the output. For the purposes of the dynamic modelling, the temperature and precipitation data were combined to give the total mass balance over the area, that is the balance between the accumulation of snow and melting of snow and ice.

Downscaling the climate model output

The HIRHAM4 climate model output was used to predict ice-sheet surface melt and snow accumulation. However the initial 25 km grid squares required interpolating to be useful on the catchment scale of this study. The HIRHAM4 output was therefore downscaled to our finer grid resolution (250 m by 250 m catchment scale grid) and calibrated to the air temperature and snow accumulation measured on the actual ice sheet margin. The HIRHAM4 model was not designed to model individual years, but rather catch the overall climate dynamics. It was therefore not feasible to compare model output and observations for specific years. Instead, we compared mean values over the entire period of the observations.

Observations of air temperature and snow accumulation are available from five automatic weather stations on the ice sheet margin in the region, forming a part of the US Greenland Climate Network (GC-Net). These data have been collected from 1995 to present and were reduced to monthly means to facilitate a comparison.

As the ice sheet surface itself can never exceed beyond the melting point, it exerts a cooling effect on the surface boundary-layer of the atmosphere during large parts of the summer. This means that temperature lapse rates can be very different depending on the season, and also that standard values from non-ice-sheet locations can not be used. Thus, the observed air temperature series were used to establish the monthly temperature lapse rate on the ice sheet. As the next step, the elevation difference between the coarse DEM of the HIRHAM4 model and the detailed high-resolution DEM available for the Paakitsoq region was determined. Using this known elevation difference, the HIRHAM4 output was lapse rate corrected to the high-resolution catchment scale, effectively downscaling the air temperature predictions on a monthly basis. As the HIRHAM4 model is not well suited to capture the atmospheric boundary-layer peculiarities of an ice sheet surface, an additional correction was performed. The correction consisted of comparison of the mean monthly modelled and downscaled temperature fields with mean monthly observed temperatures over the entire observation period. This made it possible to establish a monthly correction scheme as a piece-wise linear function of elevation on the ice sheet. Subsequently, this temperature correction scheme was applied to the entire HIRHAM4 model output series spanning 1950 to 2080.

Similarly, precipitation from the HIRHAM4 model was compared to snow accumulation measured at the US automatic weather stations (AWS). Actual precipitation gauges are notoriously poor at collecting snow precipitation, especially in windy conditions. A more robust measurement of snow height from the AWS was used, employing an assumed fixed mean snow density of 380 kg/m^2. The snow density value was taken from a 10-year study at the Amitsuloq ice cap (Ahlstrøm and others, 2007). The comparison showed that the modelled precipitation was only half of the observed precipitation in the Paakitsoq region. Consequently, the entire model output series were corrected to twice the amount of precipitation. Both the near-surface temperature and the precipitation corrections were substantial and calls for caution in relying too much on the absolute values of the resulting climate parameters. Emphasis should be on the trend of the HIRHAM4 output, rather than on the absolute values.

The downscaled fields of near-surface air temperature and snow accumulation were used to drive a mass balance model, based on the temperature-index method. This type of model exploits the high statistical correction between ice/snow melt and the amount of time the air temperature is above the melting point. The actual conversion factors, or degree-day factors (DDF's) are determined for snow and ice separately. The DDF for ice is known to vary with elevation on the western margin of the Greenland ice sheet, due to differences in the surface albedo. This change with elevation was incorporated with values from the literature. The DDF for snow was also chosen within published values, but higher than the few values previously determined for the Greenland ice sheet in order to approach the observed discharge. Thus, the choice of the DDF for snow incorporated a degree of model calibration with the observed basin discharge series.

Ice-dynamics and basin delineation

Ice dynamics refers to processes relating to the flow of ice. Much of the dynamics of glaciers and ice sheets result from the balance between accumulation through snowfall, usually at the centre of the ice sheet, and the loss of mass due to melting or iceberg calving, at lower levels closer to the margins. Driven by gravity, ice flows slowly outwards from areas of accumulation to areas of ablation (mass loss). If the amount of snowfall or melt changes then the rate of ice flow will also change, along with the surface elevation and geometry of the ice sheet, with a consequent change to the surface and to drainage patterns. Even if there is no climatic change, not taking into account the dynamic effects bringing ice to lower elevations to replace losses due to melting will result in unrealistic predictions of changes to the ice margin. Therefore, when modelling ice sheet changes over longer time periods, and especially given predicted climatic changes, the dynamics of ice flow must be taken into account.

The ice-dynamic model used for this purpose was developed by Reeh (1988) using the standard Fortran programming language. It was modified and updated for the purpose of this project and run in five year increments. The calculates the location and direction of the flow line from any point at the margin to the centre of the ice sheet, based on surface and basal topography. The flow lines used in this study are shown in Figure 4. At regular 500m intervals along the flow line the model calculates the full stresses in 3 dimensions and the velocity of the ice sheet based on a sound physical understanding of the material properties of ice. Based on these, the model can then predict the surface elevation of the flow line, based on the given mass balance for the 5 year period.

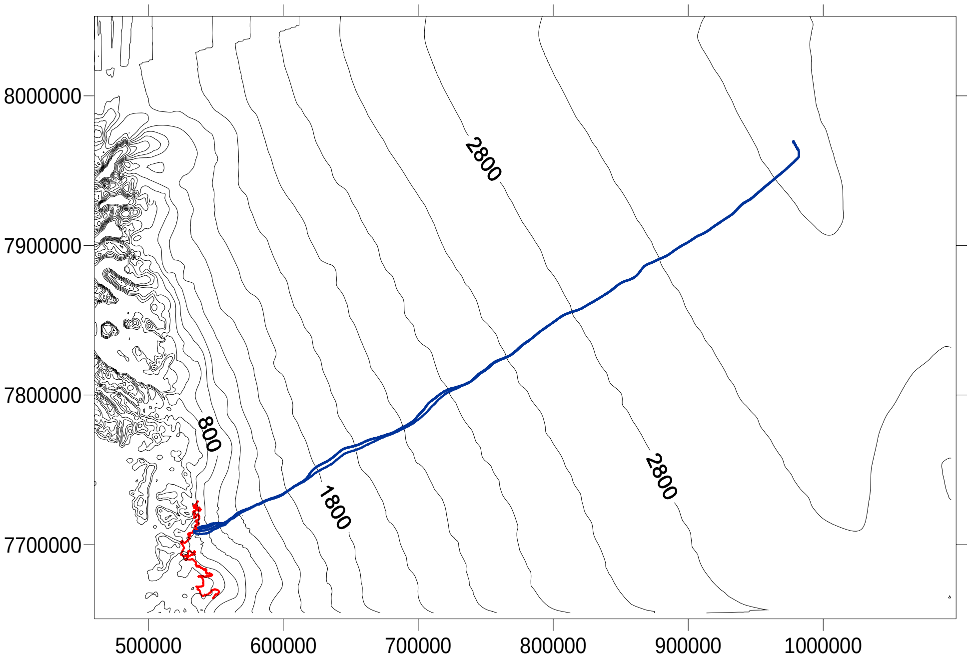

Figure 4. *The four selected flow lines (in blue) used in this study, extending from the ice divide to the ice sheet margin (shown in red). Elevation contours are in metres and the map coordinates are Easting (m) and Northing (m) UTM zone 22. The map datum is WGS84.*

Since the material properties of ice are dependent on temperature and pressure, data on surface and basal topography and ice thickness are crucial. Other corrections are incorporated in the model to account for the basal and surface temperature of the ice and the vertcial transition between older and colder Weichselian age ice (ca. 20,000 years ago) and younger warmer Holocene age ice (ca. 12,000 years old), which have different flow properties. The model does not include the effects of sliding on the bed. This is known to occur in some places areas close to the margin, however for the majority of the area in this study, it is not a relevant process. Recent measurements within the ice sheet basin indicate that the sliding component contributes only a very small amount to the overall velocity. In order to determine if significant changes occur at the margin during the period of interest, four different flow lines were plotted and calculated within each model run (Figure 4). The four flow lines all converge higher up and the surface elevation changes between the four were not found to be significantly different from each other. The elevation changes were generalised from the predicted surface elevation change along the flow line profile and applied across the surface using an extrapolation technique based on a polynomial function. The model was run for five year increments, with detailed output being presented every ten years. The ouput surface of each increment was used to initialise the input surface for the following model run. Figure 5 below shows the development of the surface profile at 20 year intervals.

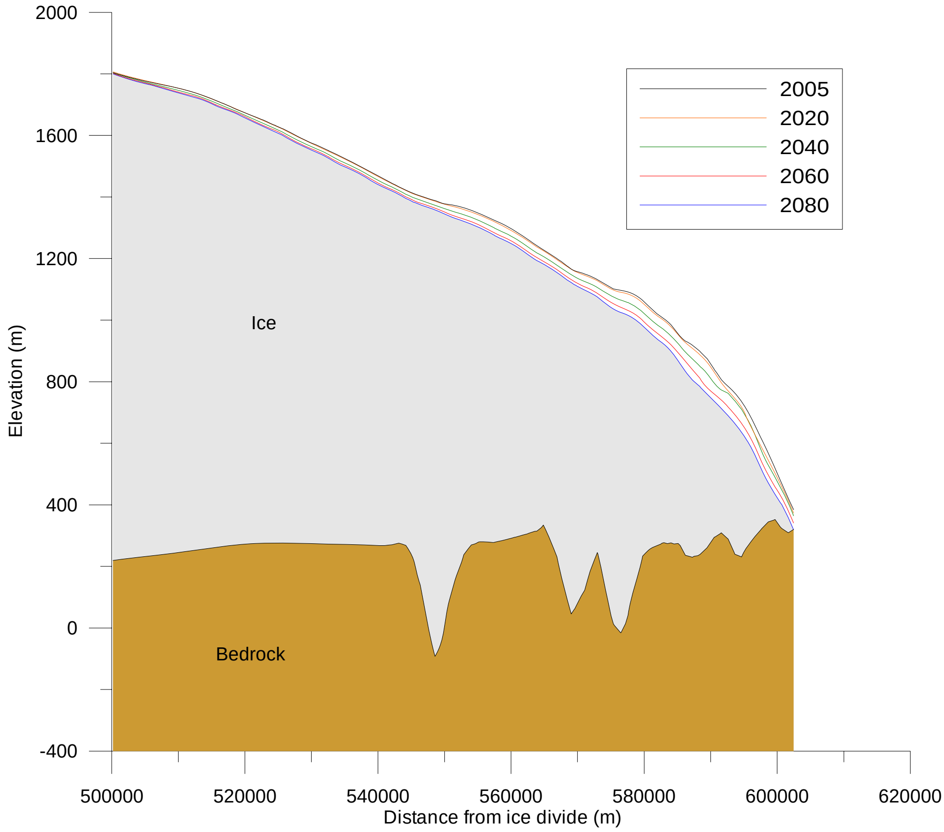

Figure 5. *Modelled surface elevation profiles along the central flow line of the basin from 2005 to 2080.*

The output surfaces from the dynamic model produced at 10 year intervals were used as input to a basin delineation model. This model predicts, based on surface topography, the shape and direction of the flow of water at the surface and beneath the ice. Subglacial drainage is important as it forms the bulk of the run-off water entering into the lakes. Subglacial drainage routing is determined in the model by the basal water pressure at the bed, the overburden pressure of ice and the basal topography. The ratio of the basal water pressure to the pressure exerted by the overlying ice is expressed in the model by the so-called k-factor. Measurements in boreholes drilled through the ice near the ice-sheet margin within the basin late in the melt season, points at basal water pressures ranging between 79% and 105% of the ice overburden pressure, corresponding to a value of the k-factor between 0.79 and 1.05.

Conclusion

A combined global/regional climate model (HIRHAM4) scenario covering 1950–2080 was downscaled to catchment scale and corrected using observational data. Subsequently, the corrected HIRHAM4 output was used as input to a temperature-index mass-balance model in turn forcing an ice-dynamic model in order to predict the future ice sheet geometry. Together with a detailed map of subglacial topography produced from ice-penetrating radar data, these ice sheet geometries were used to predict the size of the ice-sheet part of the hydrological basin Pakitsup Akuliarusersua for a range of 11 different levels of basal water pressure every 10 years from present day to 2080.

Thus, the present analysis takes into account global and regional climate change, ice-dynamical response and changes in the internal drainage system of the ice sheet. However, care should be taken in the use of the predictions presented for a number of reasons:

- Our analysis shows that the HIRHAM4 output needs substantial adjustment to reproduce observations on catchment scale
- Ice-dynamic models do not yet capture all the important processes of the ice sheet, in particular its dynamic response to an increase in the surface meltwater input to its internal drainage system
- Our knowledge of the internal drainage of the Greenland ice sheet is insufficient to model the likely evolution and distribution of the basal water pressure, which may cause changes in the basin delineation and thus the discharge

The ice-sheet margin is predicted to continue its present thinning trend, causing a thinning of approx. 80 metres over the next 70 years as shown in Figure 5. This corresponds roughly to the current rate of ice-sheet thinning in the region amounting to approx. 1 metre per year on average over the last 40 years. The predicted retreat rates seem realistic from a glaciological point of view and causes only minor changes in the basin delineation for high (realistic) basal water pressures. Figure 6 shows the modelled evolution of the basin corresponding to a basal water pressure of 90% of the ice overburden pressure (k=0.90) from 2000 to 2080. Measurements in boreholes drilled through the ice near the ice-sheet margin within the basin late in the melt season, points at basal water pressures ranging between 79% and 105% of the ice overburden pressure.

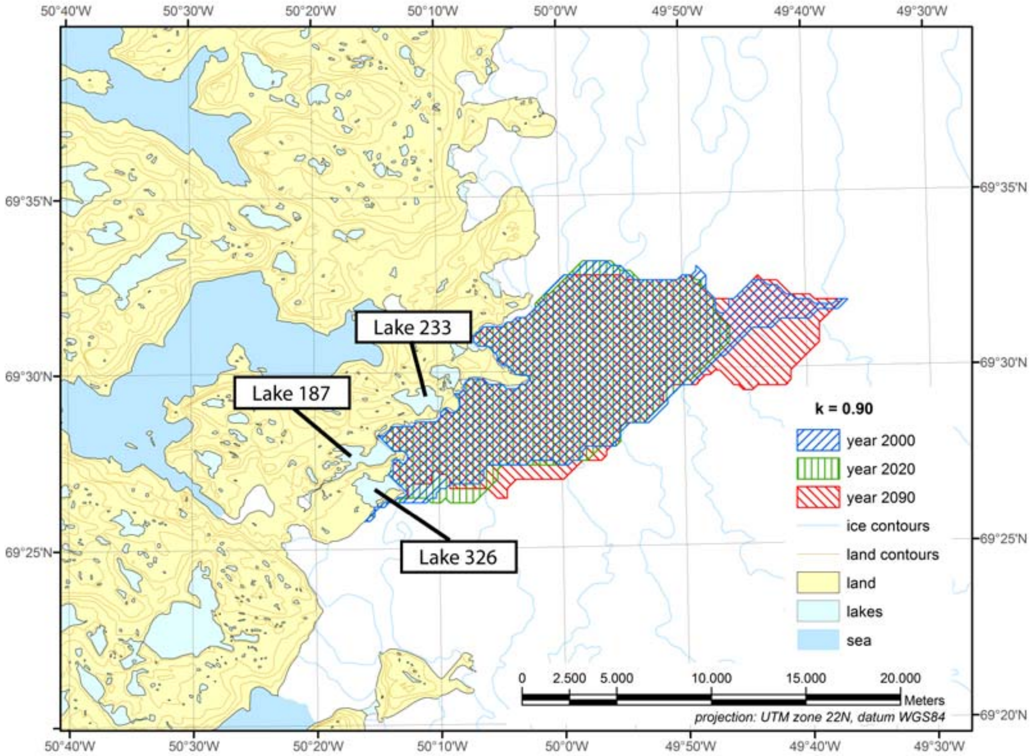

Figure 6. *The modelled evolution of the drainage basin configuration for a constant basal water pressure of 90% of the ice overburden pressure (k=0.90). The selected years show the maximum variation of the basin delineation.*

The basal water pressure varies diurnally, annually and may possibly shift over longer time scales if melt rates increase. The time of year (late melt season) and the proximity of the ice margin implies that this range should be taken as a minimum value. Choosing 90% (or k=0.90) as a reference value therefore makes sense. Further away from the ice margin, where the ice is thicker, the basal water pressure is likely to be higher rather than lower than 90% of the ice overburden pressure. This is important when examing basin delineation changes. Even if the present analysis suggests a possible switch to a smaller basin for k=0.70-0.80 after 2080 as indicated in Figure 8, the switch occurs at some distance from the ice margin, implying that k is probably >90% in this region even in the late melt season when the basal drainage system is fully developed and meltwater supply starts vaning, causing a drop in the basal water pressure. However, in order to assess the extreme cases of lower basal water pressures, values of k ranging from k=0.50 to k=1.00 in increments of 0.05 were examined for the entire model period 1950 to 2080. Figure 7 shows the maximum variability of the basin configuration with basal water pressure for the year 2000 (present-day ice sheet geometry).

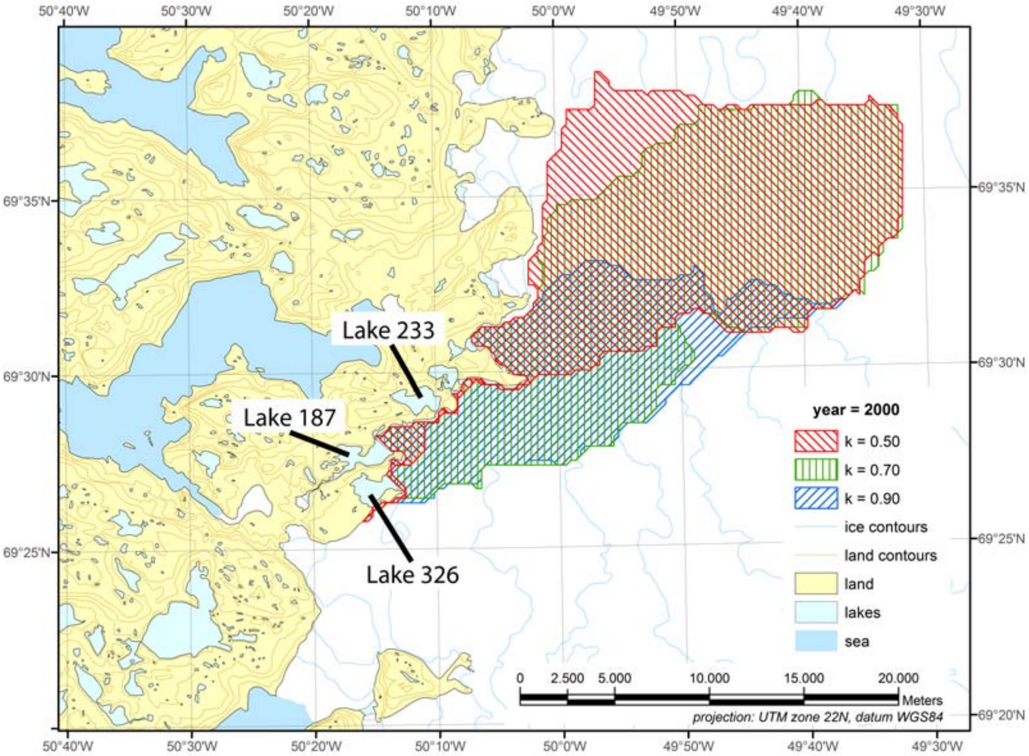

Figure 7. *Basin delineations for different values of basal water pressure, ranging from 50% to 90% of the ice overburden pressure. Measurements indicate a present minimum value between 79% and 105%. The values of k were chosen to show the different extremes in basin configuration.*

The HIRHAM4 model does not capture the local climate of the catchment well enough to rely on the absolute values of predicted discharge. This is illustrated by the inability of the predicted discharge to reproduce the observed mean, even after calibration of the melt model (see Figures 8 and 9). After melt model calibration (carried out using k=0.90) we obtain only 87% (366 hm^3) of the observed mean (419 hm^3) over 1984–2006, after removing known lake outburst floods in 1989 and 1993 and noting that there was inadequate or no data from 1988, 1991, 1992 and 1994. We believe that the absolute values of the predicted discharge shown in Figure 9 are somewhat underestimated and should be regarded as a minimum discharge estimate. Our discharge prediction for 2014–2039 has a mean value of 307 hm^3 which is very low compared to the mean of 470 hm^3 over 2000–2006. The main conclusion to draw from the inclusion of the HIRHAM4 scenario in the discharge prediction is that the average discharge remains relatively constant until 2035, at which point a steady increase in the discharge sets in continuing to 2080. This increase is driven by climate warming rather than changes in basin delineation.

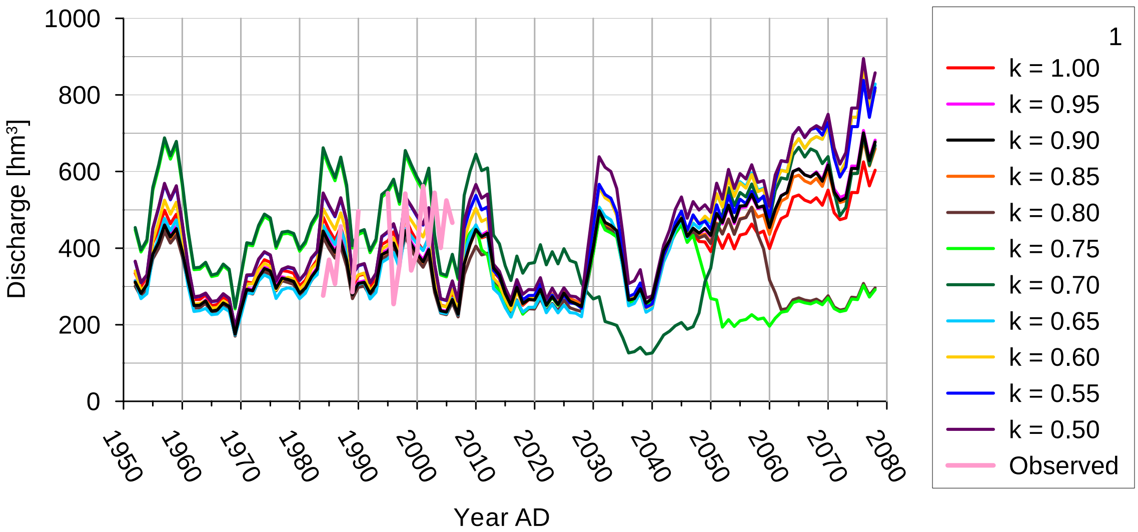

Figure 8. *Predicted discharge, shown as 5-year running averages, for various levels of basal water pressure, ranging from k=0.50 (low water pressure) to k=1.00 (ice nearly floating). The retreat of the ice sheet margin is causing drops in discharge for k=0.70 to k=0.80, due to rearrangement of the ice-sheet hydrological basin. The value of k is expected to have a minimum value between 0.79 and 1.05 from previous borehole measurements in the area.*

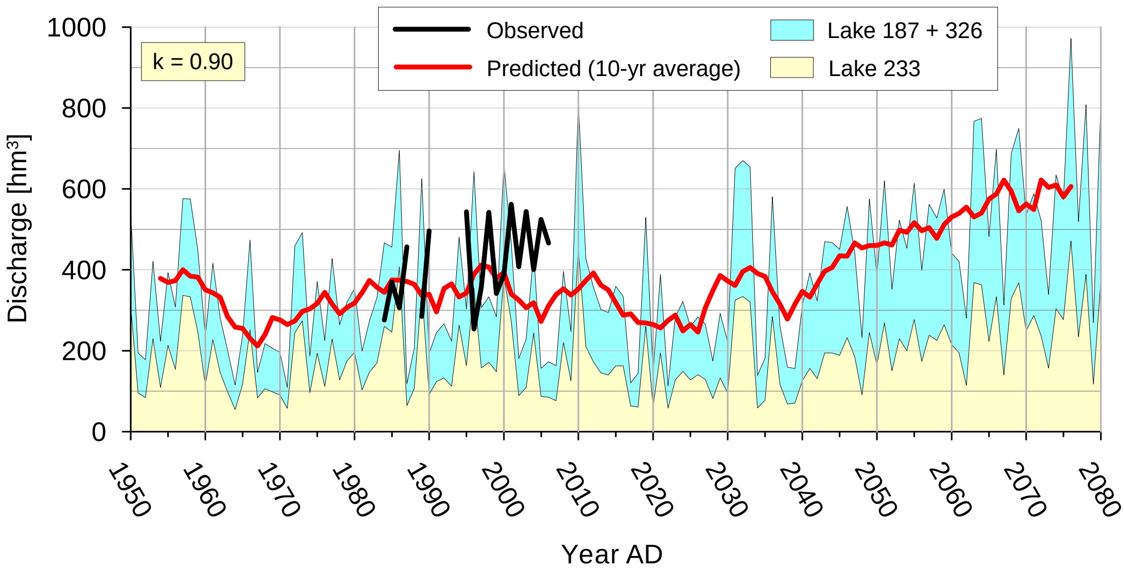

Figure 9. *Predicted and observed discharge from the Pakitsup Akuliarusersua basin, with division between Lakes 187 + 326 and Lake 233. The prediction shown is based on a high basal water pressure, close to what has previously been measured in boreholes in this part of the ice margin (k=0.90). This prediction of the discharge is considered the most likely.*

The main conclusions can be summarized as follows

- The configuration of the ice-sheet hydrological basin is likely to remain constant
- As a minimum, the basin discharge is likely to remain constant until 2035, followed by a steady increase towards 2080
- The ice-sheet margin is likely to keep thinning at the current rate of approx. 1 m/yr

The first conclusion implies that the hydrological basin supplying the water to the lakes adjoining the ice sheet margin is not likely to change. This reduces the main risk of relying on ice sheet catchments for hydropower production. The second conclusion implies that climate change will, as a minimum, have a small positive influence on the discharge increasing after 2035. The third conclusion reduces the risk of a readvance of the ice sheet margin that could potentially change the way the lakes connect in the off-ice-sheet part of the basin.

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