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Climate change and energy production. Project A3: Glacier Models. Minutes from a work group meeting in Copenhagen 11-13. November 1991

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CLIMATE CHANGES AND ENERGY PRODUCTION
Project A3: Glacier Models

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1. INTRODUCTION

The purpose of the meeting was to organize an Inter-Nordic research project on glacier modeling in order to estimate the effect of climate changes due to greenhouse warming on glaciers in the Nordic countries. The project is a part of the cooperative research program "Klimaendringer og energiproduksjon" (Climate Changes and Energy Production) which is organized by the Nordic cooperative committees CHIN ("Cheferna för Hydrologiska Institutioner i Norden", The Heads of Hydrological Institutes in the Nordic Countries) and KOHYNO ("Koordineringskommittén för Hydrologi i Norden", The Coordinating Committee for Hydrology in the Nordic Countries).

Present at the meeting were Niels Reeh and Roger Braithwaite from GGU, Denmark, Tron Laumann from NVE, Norway and Tómas Jóhannesson from Orkustofnun, Iceland. Tron and Tómas are project leaders for the glacier modeling project. The meeting took place at the GGU headquarters in Copenhagen.

Tron and Tómas used one of the three days for a discussion of the overall organization and the time plan of the project. The rest of the meeting was devoted to a discussion of glacier mass balance models.

The conclusions of the discussions that took place during the meeting are described below. In addition, degree-day mass balance models, which are in use in the Denmark, Iceland and Norway, are described based on information that the participants compiled after the meeting.

2. GOAL

The goal of the glacier modeling project is to estimate the response of glaciers and ice caps in Iceland, Norway and Greenland to climate changes due to an increased greenhouse effect in the Earth's atmosphere.

The ice cap Hofsjökull in Central Iceland, the glaciers Nigardsbreen and Hellstugubreen in Norway and possibly a suitable outlet glacier from the Greenland ice sheet will be studied for this purpose. Changes in the volume of the glaciers and corresponding time-dependent changes in runoff from the glaciers will be computed based on climate scenarios which describe possible climate changes due to greenhouse warming during the next decades. Special emphasis will be placed on the consequences of the runoff changes for the design and operation of hydro-electric power plants.

3. ORGANIZATION

The institutions GGU, NVE and Orkustofnun all conduct research in the field of mass balance and ice flow models. Roger Braithwaite and Niels Reeh at GGU have developed degree-day mass balance models which have been used in Greenland and in Norway. Tron Laumann at NVE has developed a dynamic glacier model which has been used for a number of years and he is currently involved in glacier mass balance modeling using the Norwegian version of the HBV runoff model. Tómas Jóhannesson at Orkustofnun has developed a dynamic glacier model which has been used to model the effect of climatic warming on the Hofsjökull ice cap in Iceland. The glacier modeling project described here will focus a part of the ongoing glacier modeling efforts of GGU, NVE and Orkustofnun towards a common goal. Each institution will finance its contribution on its own, but Nordic funds will be used to finance travel expenses and other costs of coordinating the work in the different countries. Reports describing the results of the project will be written jointly by the participants when appropriate.

4. PROJECT PLAN

The project will be focused on three related subjects:

1. The effect of climate changes on glacier mass balance.
2. The effect of changes in glacier mass balance on steady state glacier volume.
3. The transient adjustment of glaciers to time-dependent changes in mass balance and associated changes in runoff from the glaciers.

In the first stage of the project, existing mass balance models in use in the Nordic countries will be documented and compared and a suitable model for the continuation of the project will be chosen. During this stage a family of climate scenarios, spanning the likely range of climate changes during the next decades, will be chosen. These scenarios will be based on recommendations which will be worked out under project C1: "Klimascenarier for Norden" (Climate scenarios for the Nordic countries), which is another project within the main program "Climate Changes and Energy Production". This stage will be concluded with a common report on glacier mass balance models which will be published around the middle of 1992. The work on glacier mass balance models will be carried out by Tron Laumann, Roger Braithwaite and Tómas Jóhannesson (using glacier mass balance data from Norway, Iceland and Greenland).

After a suitable mass balance model has been decided upon, dynamic glacier models will be coupled with the mass balance models in order to compute the response of the glaciers to the proposed climatic changes. The glacier models in use and under development in Norway and Iceland will be used for the computations. In the second stage of the project, the glacier models will be used to compute steady state glacier geometries corresponding to different climatic conditions in order to estimate the total amount of water that may be released from the glacier reservoirs as a consequence of greenhouse warming. This amount will only depend on the magnitude of the climatic changes, and not on how fast they take place.

In the third stage of the project, glacier models will be used to compute time-dependent runoff changes corresponding to time-dependent climate scenarios. This will make it possible to estimate the magnitude of glacier runoff changes associated with given climatic changes and the length of the time period when reduction in glacier volume affects glacier runoff.

Preparation and necessary development of the dynamic glacier models (implementation of a number of new features in the Icelandic model and coupling of the dynamic glacier models and the mass balance model) will be carried out in the middle and latter parts of 1992 by Tómas Jóhannesson and Tron Laumann. The Icelandic and the Norwegian models will be compared and their differences analyzed.

The steady state computations will be partly carried out during the testing and comparison of the dynamic glacier models in the latter part of 1992 and in the beginning of 1993 by Tómas Jóhannesson and Tron Laumann. Following the steady state computations, the time-dependent computations will be carried out in 1993 by Tómas Jóhannesson, Tron Laumann and Oddur Sigurðsson (Orkustofnun). They will include both an analysis of historical mass balance, glacier geometry and runoff data from Norway and Iceland and prediction model runs based on climate scenarios.

The glacier modeling project will be concluded in 1994 by report writing. Some of the results will be jointly submitted by the participants in the project to international scientific journals for publication.

5. MASS BALANCE MODELS

5.1 Choice of a mass balance model for the project

The mass balance model will be used to compute the mass balance of the glaciers based on meteorological parameters (temperature, precipitation, *etc.*) from nearby weather stations or derived from climate scenarios. It must take changes in the time-dependent elevation of the ice surface into account. Time steps less than a year have little meaning in the dynamic glacier models which will be used in this project. Therefore, the interaction between the mass balance model and the dynamic models should be based on a time increment of one or more whole years. Mass balance computations within each year will be based on a fixed glacier geometry and the net balance of the year will be passed on to the dynamic glacier model. The runoff computations of the mass balance model will use a shorter time resolution in order to define the runoff distribution within the year.

A number of degree-day mass balance models are in use in the Nordic countries. The Swedish HBV model is used in Sweden and Norway. The Norwegian version includes a number of new features in its snow melt routines. In Iceland, a variant of the Danish NAM2 model has been developed for similar use. Roger Braithwaite has developed the model MB1 for use in Greenland and Niels Reeh has developed a simple model which has been used for analysis of mass balance data from Greenland and Norway. These models are briefly described in separate sections below.

5.2 Description of degree-day models

The meeting made a list of questions that need to be answered for each degree-day mass balance model in order to describe the computations performed by the model in some detail. This list serves two purposes. First, it simplifies a systematic comparison of the different models and, second, it can be used as a starting point for the specification of the mass balance model to be used in the project. The answers to the questions have been collected from the authors of the models after the meeting in Copenhagen and they are summarized below. The answers are from Nils Roar Sælthun (the Norwegian version of the HBV model), Lárus Hólm and Kristinn Einarsson (the Icelandic version of the NAM2 model), Roger Braithwaite (the MB1 model) and Niels Reeh. The questions are:

1. How is lapse rate specified (variation within the year, variation with weather)?
2. Does precipitation change with elevation and if so how?
3. How is the ratio of snow and rain determined?
4. If a time series of measured precipitation is used, is it adjusted in some way (possibly in different ways depending on whether the precipitation is snow or rain)?
5. How is the degree-day factor computed (different albedo for snow and ice)?
6. What is the threshold temperature for the computation of degree-days.
7. How are degree-days computed (from daily or monthly values, using statistics or not)?
8. How does the model handle refreezing of meltwater and heating of the snow pack in the spring.
9. Does snow turn into ice in the model, is the snow thickness set to zero by brute force in the fall or is snow allowed to accumulate to arbitrary thickness as time goes?

5.2.1 HBV

The information below is from a telefax from Nils Roar Sælthun dated 20. January 1992.

The computations of the HBV model are based on daily mean values of the temperature and daily sums of the precipitation.

1. Lapse rate is specified separately for days with precipitation and for days without precipitation. Lapse rate can also be set to be season dependent, specified by calendar month. Default values are then set to the lapse rates given in "Temperaturen i Norge" (Norwegian Meteorological Institute, 1956).

2. Precipitation is computed from precipitation at a base station. It is changed by a constant factor, given as percent per hundred meters.
   Alternative: "Lapse rate" is calculated from two precipitation stations at different altitudes, but constrained by limiting "lapse rates".

3. Sharp transition between snow and rain at a specified temperature, default is 1 *°C*, in each altitude zone.

4. Precipitation data from precipitation stations are adjusted by a constant factor. The factor is higher for snow than for rain.
   Alternative: Correction by wind dependent empirical functions, developed at the Norwegian Meteorological Institute.

5. Degree-day factor (temperature index) is calculated by three sub-components:
   - season, albedo and precipitation depentent ("short wave radiation")
   - constant ("convection")
   - precipitation dependent ("latent head/condensation")

   Different albedo values are used for snow and ice.
   Documentation: Nils Roar Sælthun: "Forbedringer av de hydrologiske rutinene i HBV-Modellen", VHD-notat 9/90.

6. Constant threshold in altitude zones (default 1 *°C*).

7. Degree-days are directly computed from daily temperature values. No seasonal or annual variation.

8. (?) A constant proportion of the meltwater refreezes in the snow pack. No snow pack heat content simulation.

9. Reduction of snow pack to a specified maximum value at a fixed date (same date for all levels).

5.2.2 MB1

The information below is summarized from a letter from Roger Braithwaite dated 18. November 1991.

The computations of the MB1 model are based on monthly mean values of the temperature and monthly sums of the precipitation.

1. Lapse rate is constant within the year.

2. Not explicitly included.

3. A probability of freezing temperatures is computed for each month using a threshold temperature of 0 *°C*. The amount of snow is computed by multiplying the total precipitation with this probability.

4. Measured rain and snow can be adjusted to compensate for precipitation lost by precipitation gauges (a factor of 1.15 has been used for rain and 1.85 for snow).

5. Separate fixed degree-day factors are used for snow and ice. They are determined from a comparison of measured ablation with measured temperature.

6. A threshold of 0 *°C* is used.

7. Monthly degree-days are computed based on a probability approach (*i.e.* from the mean temperature of the month and assumptions about the distribution of daily temperatures about the mean).

8. It is assumed that meltwater refreezes until the snow density reaches a specified threshold density. There is

no runoff from the snow pack until this threshold density is reached.

9. Snow below a certain depth (now 20 *m*) is assumed to turn into ice (*i.e.* the snow pack is never allowed to become thicker than 20 *m*.)

Note that adjustment of precipitation (*e.g.* in order to compensate for an underestimate of precipitation by snow gauges), which is not explicitly included in the model, can be a part of the preparation of precipitation data before the model is run.

5.2.3 NAM2

The information below is summarized from a paper by Lárus Hólm and Kristinn Einarsson which was presented at a meeting in the work group of the project A2: "Snøsmelte-modeller" (Snow Melt Models) on 24.-25. October 1991 in Helsinki, Finland (the project on snow melt models is jet another project under the main program "Climate Changes and Energy Production").

The computations of the NAM2 model are based on daily mean values of the temperature and daily sums of the precipitation.

1. Separate lapse rates can be specified for each subarea and for each months. The lapse rate can also be different depending on whether precipitation has been observed at a meteorological station or not.
2. Precipitation can increase with elevation according to the precipitation gradient method or it can be computed for each subarea as a weighted average of the precipitation at a number of meteorological stations.
3. Precipitation falls as snow if the temperature of a subarea is above a specified (usually slightly positive) threshold value.
4. Measured precipitation can be corrected in order to take into account the underestimate of precipitation by precipitation gauges. The correction can be different in different months and it can also depend on the type of precipitation (rain/snow).
5. The degree-day factor is a function of the albedo of the surface and the seasonally varying amount of incoming short wave radiation reaching the outer atmosphere (two different albedo values are used, one for snow and another for ice).
6. A user specified threshold (usually slightly positive) is used.
7. Degree-days are directly computed from daily temperature values.
8. The cooling of the snow pack during the winter is determined by solving the heat flow equation. In the spring, meltwater refreezes until the temperature of the snow pack reaches 0 °*C*. There is no runoff from the snow pack until the snow pack reaches 0 °*C*.
9. Snow below a certain depth (which varies from 30 *m* at the top of the glacier to 0 *m* at the firn line) is assumed to turn into ice (*i.e.* the snow pack is never allowed to become thicker than the local firn thickness).

5.2.4 Niels Reeh's model

The information below is summarized from a letter from Niels Reeh dated 12. December 1991.

The computations of Niels Reeh's model are based on the yearly mean temperature and the amplitude of the variation of the temperature from summer to winter.

1. Lapse rate is constant within the year. There is no variation with weather.
2. The precipitation can either be specified as a function of elevation, or specified at a given elevation in which case a constant precipitation gradient with elevation is used.
3. The fraction of snow of the yearly precipitation is determined as the relative length of the season where the temperature is below the freezing point (or

below a specified threshold temperature).

4. Different adjustment factors can be introduced for measured rain and snow.
5. Different degree-day factors are used for snow and ice melt.
6. A threshold of 0 °*C* is used.
7. Yearly degree-days are computed based on an assumed sinusoidal variation of the temperature within the year (specified by the mean temperature of the year and a maximum temperature during the summer) and a probability approach similar to the method used in the MB1 model.
8. A specified fraction of the snow accumulation melts and refreezes before runoff occurs. The superimposed ice is melted before melting of "glacier ice" begins.
9. No adjustment of the snow pack in the fall.

5.3 Energy balance versus degree-day mass balance models

The suitability of glacier mass balance models based on energy balance considerations was discussed at the meeting. The participants at the meeting agreed that glacier mass balance models based on degree-days would be more suitable for the project than energy balance models. The primary reason for this view is that some of the data needed by the energy balance models (data on radiation, cloud cover, etc) is often not available in practice and that its specification would be impractical in this project.

Another reason, which is probably also related to difficulties in the specification of input data for energy balance models, is that energy balance models do not seem to perform better than degree-day models in practical hydrological applications. The previously mentioned work group on snow melt models recommends the use of snow melt models of the degree-day type and states that energy balance models have not so far lead to an overall improvement in the description of accumulation and melting of snow in hydrological models. Their recommendation is thus in accordance with the above conclusion regarding a glacier mass balance model for the project discussed here.

A final reason for the choice of a degree-day mass balance model is the practical experience with such models (HBV, MB1, NAM2) which has been built up in Denmark/Greenland, Iceland and Norway. By using a degree-day model the project can benefit from this experience which would not be the case if an energy balance model had been chosen.

5.4 Specification of a mass balance model for the project

The specification of the requirements for the mass balance model still has to be worked out in detail. This work will be based on the above list of questions with the aim of defining as simple model as possible.

This work was started at the meeting with a discussion of the method for the computing degree-day factors and the adjustment of the snow pack in the fall.

Roger Braithwaite expressed doubt that the method used in the HBV model for the computation of degree-day factors (the degree-day factor depends on whether there is precipitation or not) leads to significantly better results. This issue will be further examined by Tron Laumann.

It was agreed that the method used by the MB1 model and the Icelandic version of the NAM2 model for the adjustment of the snow pack in the fall (snow turns to ice below a certain depth) is the most sensible to use.