A Statistical Approach to Estimating the Contribution of Glaciers to Future Sea-level Rise.

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Aim

To construct and sample a response surface that reflects the global distribution of glaciers in the climate-topography phase space, in order to estimate the contribution of valley glacier melt to global sea-level rise with a meaningful estimation of error.

I. Introduction

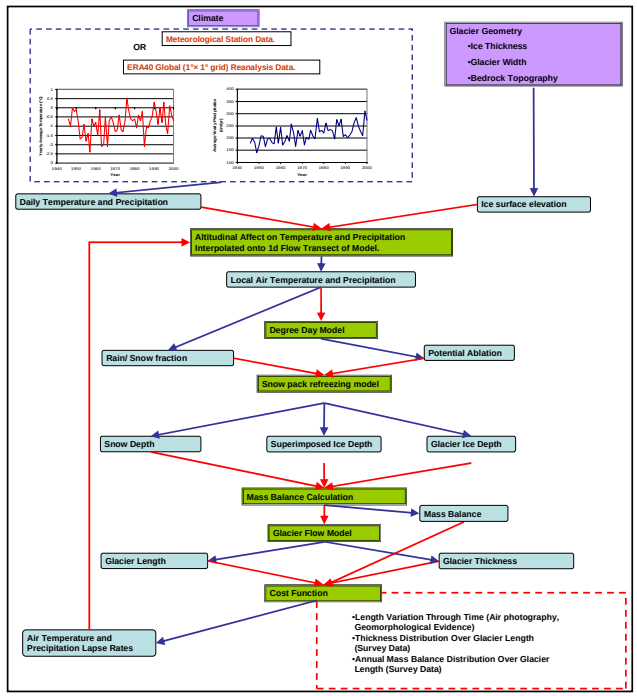
- Valley glaciers and small ice caps are expected to provide the bulk of the cryosphere's contribution to sea-level rise over the next century (~ 0.23 m, IPCC, 2001). A lack of quantitative data for the vast majority of glaciers worldwide (only 100 glaciers out of a total population of 160,000 have mass balance records for longer than 5 years) makes this estimation difficult.
- We have developed the following four stage procedure to calculate sea-level rise with an associated error:
  1. Construct a generic valley-glacier system model that predicts variations in width, depth, accumulation and ablation along the glacier.
  2. Calibrate the model against the small number of glaciers for which we have sufficient data.
  3. Using the calibrated model and synthetic input, construct a response surface of sea-level contribution as a function of glacier climatology and topography with an assessment of associated uncertainty.
  4. Sample the response function in accordance with estimates of the global distribution of glaciers in the climate-topography phase space to estimate overall sea-level rise.
- To construct a response surface that captures glacier variability to topographic and climatic changes, one must understand the spatial variation and sensitivity of parameters within the model.
- This poster demonstrates the modelling technique used in the project and investigates the regionalisation of model parameters

II. Model

- One-dimensional flow line model capable of dealing with tributary systems.
- The model can either be forced with ERA 40 or metrological station data.
- Ice flow in the model is described by the usual Glen Law.
- Three schemes are available to calculate the mass balance
  - a Positive Degree Day scheme
  - a simple energy balance model
  - a full energy balance model.
- Ice thickness and width are allowed to evolve over the length of the glacier.
- Snow pack evolution. The model accounts for the formation of superimposed ice within the snow pack. As the snow pack melts a fraction is allowed to refreeze as superimposed ice. Finally, once the snow pack and superimposed ice is removed, the glacier ice is ablated.
- Optimisation of parameters in this model run uses the Nelder-Mead Method. Other optimisation routines are used with the model such as Genetic Algorithms and PEST.

The overall structure of the model is detailed in the flow diagram (Figure1).

Figure 1 *Flow diagram of the model structure. Currently the model is configured to use Meteorological Data from the meteorological station from the nearest station to the glacier of interest*



III. Optimisation of parameters

- The generic nature of the model requires a number of parameters within the model to be tuned. Parameters that require optimisation are those associated with;
  - downscaling from ERA 40 data to local climate conditions,
  - setting of initial conditions (such as glacier thickness),
  - mass balance regime used (e.g. albedo for energy balance methods, and pdd factors for positive degree day models).
- In this study the parameters that are optimised are the air and precipitation lapse rates, the positive degree day factors (pddfs) and the fraction of precipitation that can refreeze (Wmax).
- The cost function determines how well the model is capturing glacier response to the climatic forcing through evaluating modelled thicknesses against survey data.
- Additional data can be built into the cost function, such as gridded mass balance values. Weights can be used to indicate confidence in the various data sets. Attention must be paid to the different scales of the optimising data to prevent bias in the cost function.

VI. Summary and Future Work

- A numerical model capable of responding dynamically to imposed climate change has been tested for two glaciers; Midre Lovénbreen and Storglaciaren.
- Parameter calibration was performed using the Nelder-Mead method on both glaciers. A significant regionalisation of parameter values was found.
- Future work includes
  - Selecting glaciers from a variety of climatic and topographic regimes to test the model further.
  - testing the model with the Energy Balance Model to investigate the impact of slope and aspect
  - integration with ERA-40 reanalysis data with associated error estimates
  - further investigation of the length scales at which parameters within the model vary (i.e., their geostatistics)

V. Results

- The model is able to find the global minimum for 4 parameters for Midre Lovénbreen (Figure 5) . The optimised values are given in Table 1. With these optimised values it is able to produce a good representation of glacier thickness over its length (Figure 7a).
- The model struggles to find a global minimum when optimising for 4 parameters for Storglaciaren (Figure 6). The values it optimises to are a local minima (Table 1). It is still capable of capturing the changes in ice thickness over the glacier length (Figure 7b).
- The phase space diagrams also show the model's sensitivity to the different parameters. Both glaciers are not sensitive to Wmax (fraction of precipitation that refreezes), and both are sensitive to the air and precipitation lapse rates.
- The phase diagrams (Figures 5 and 6) indicate that there is variability in the minimum for the different combinations of parameters between the two glaciers. Storglaciaren's global minimum in the temperature/ precipitation lapse rate requires a much colder air temperature lapse rate.
- As the four parameters operate in a compensatory manner, determining where the global minima is a complex iterative process.

Table 1. *The optimised values for both Storglaciaren and Midre Lovénbreen*

Glacier	Temperature lapse Rate	Precipitation lapse rate	Wmax	Positive degree day factor (snow)
Storglaciaren	-0.004173	0.000009683	0.4567	0.004043
Midre Lovénbreen	-0.003789	0.000001070	0.7287	0.002876

Figure 5. *Phase space diagrams for all combinations of the 4 free parameters in the model for Midre Lovénbreen.*

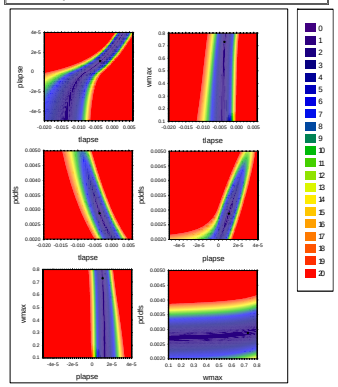
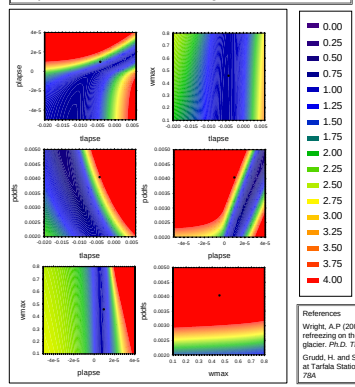


Figure 6. *Phase space diagrams for all combinations of the 4 free parameters in the model for Storglaciaren.*



References

Wright, A.P (2005). The Impact of meltwater refreezing on the mass balance of a high Arctic glacier. *Ph.D. Thesis, Bristol*

Grudd, H. and Schneider, T (1996). Air Temperature at Tarfala Station 1946-1995. *Geografiska annaler 78A*

IV. Glaciers

The two glaciers, Midre Lovénbreen and Storglaciaren, used in this study were chosen as they have similar climatic regimes, with comparable average annual precipitation and annual mean temperatures (Figure 2). The glaciers also have comparable geometry (length ~ 4 km, maximum width ~ 1 km, average thickness ~ 110 m) and have a corresponding retreat history, with only small changes in length over the last 30 years. Both valley glaciers terminate on land (Figure 3).

These glaciers have good climate records and survey data on which to initialise the model. This limits the number of free parameters in the model and allows an investigation of the remaining free parameters. Additional survey data is used to calculate the thickness along the flowline and this is used in the cost function.

The glaciers differ in their classifications, Midre Lovénbreen is an Arctic glacier while Storglaciaren is a Subarctic glacier. They also occupy very differ altitudinal ranges: Midre Lovénbreen ranges from 50 m a.s.l at the terminus to 550 m a.s.l, while Storglaciaren ranges from 1130 m a.s.l at its terminus to 1760 m a.s.l..

The similarities of these two glaciers provides an opportunity to investigate the impact of altitudinal range on parameters within the model.

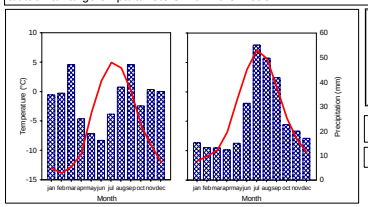


Figure 2. *Mean monthly temperature and precipitation for Midre Lovénbreen (left) and Storglaciaren (right) for the period of study.*

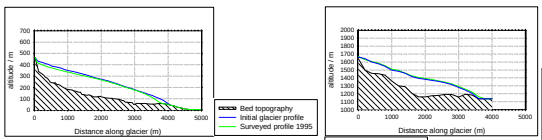


Figure 3. *The glacier profile along the central flow line for Midre Lovénbreen (left) and Storglaciaren (right), for the initial conditions and at one of the survey thicknesses used for optimisation.*

Figure 4 a and b. *Location maps for the glaciers used in this study. Midre Lovénbreen has a more northerly aspect than Storglaciaren.*

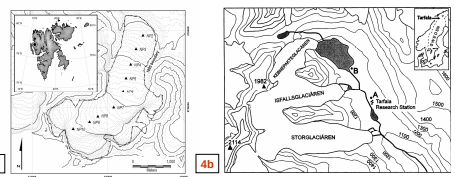


Figure 7a. *Modelled ice thickness along the glacier flow line optimised for all 4 parameters (green) compared to the surveyed data at 1995 for Midre Lovénbreen (blue).*

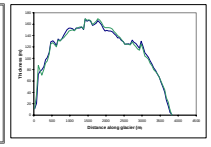


Figure 7b. *Modelled ice thickness along the glacier flow line with no optimisation (pink) and optimised for all 4 parameters (green) compared to the surveyed data at 1990 for Storglaciaren (blue).*