**Practical 5: Glacier Mass Balance Modelling**

## **OVERVIEW**

In this session you will be modelling the mass balance of Storglaciären (a glacier with which you should be familiar after completing the preparation quiz).

The model uses air temperature and top-of-atmosphere *insolation* (incoming solar radiation) to compute mass loss via surface melting with a simplified *energy balance* approach. The fraction of insolation used to heat the glacier surface is a function of the *albedo* (reflectivity: the fraction of incident radiation reflected). Air temperature controls the temperature-dependent (turbulent and longwave) heat fluxes. Mass accumulates in the model from snowfall, which also influences the albedo. As a reminder, a full explanation of the model is provided in [Giesen and Oerlemans (2012](https://tc.copernicus.org/articles/6/1463/2012/)). We will refer to this as the “GO” model hereafter.

An additional feature implemented here is that the glacier can change size, growing and retreating in response to positive and negative mass balances, respectively. To achieve this, the model implements a simple ‘volume-area scaling’ method (e.g., [Radić et al., 2007](https://www.cambridge.org/core/journals/annals-of-glaciology/article/volumearea-scaling-vs-flowline-modelling-in-glacier-volume-projections/122E007DEEEADD9DD272B794B6A093FA)).

We will conduct two exercises with the GO model in this practical:

1. **Calibrate the mass balance model**
2. Through a manual tuning approach, adjusting the parameters by hand to try and improve the match to observations;
3. Using a Latin hypercube sampling technique to generate an *ensemble* of simulations, retaining only those that pass a history matching assessment with historical observations. (These are referred to as 'Not Ruled Out Yet', NROY).
4. **Apply the mass balance model to project the future extent of Storglaciären**

Using the tuned (i) and not ruled out yet (ii) parameter values identified in #1, we will force the model with climate model output under the RCP4.5 scenario. For the purposes of this practical, we use data from the NorESM-MM model. Note that we covered *how* to access climate model data in Practical 1.

**LAUNCH THE MODEL**

Launch the model by clicking [here](https://mybinder.org/v2/gh/climatom/MEC/main?urlpath=rstudio). This will open an RStudio interface on MyBinder – a service that enables us to run R code on a remote server (removing the need for you to install anything locally). Please be patient whilst this loads as it can take several minutes; if you get an error, please re-try.

For those interested, you can also download all the source code and data from the relevant [GitHub repository](https://github.com/climatom/MEC), enabling you to repeat everything on your own machine (but note that this is ***not*** needed for today).

## **GLACIER MODEL CALIBRATION**

1. **OBSERVATIONS AND IMPLAUSIBILITY**

We will calibrate the model using mass balance observations from 1990-2010. The climate forcings driving the model during this period are daily temperature (°C) and precipitation (mm d-1) from the [E-OBS dataset](https://www.ecad.eu/download/ensembles/download.php).

The calibration data are a time series of annual values. Instead of summarising the observations as before (e.g. using the mean or trend), here we will calculate the implausibility value for every year, then summarise these by using the **maximum implausibility**.

As a reminder, the implausibility of a given simulation *i* when evaluated with one observation is defined as:

Here, *y* is the mass balance in a given year. The maximum implausibility will be calculated over all years.

The error is the *combined* observed and modelled uncertainty, which (from Lecture 2) is defined as:

is estimated by [Zemp et al. (2013)](https://tc.copernicus.org/articles/7/1227/2013/tc-7-1227-2013.pdf) as 0.34 m w.e. (metres water equivalent - see preparation); we make the assumption here that model uncertainty is the same, and hence is 0.48 m w.e.

Note that *I* is dimensionless. The implausibility is the “number of errors” the model is away from the observation. A value of 3 means that the modelled value is 0.48=1.44 m w.e. away from the observation in that year). The *smaller* the value of *I,* then, the better the model performance.

The graph below shows the annual mass balance observations (thick line), along with the ±3 envelope around those observations (light lines): i.e. the observed value ± 1.44 m w.e..

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If we use maximum implausibility < 3 as the threshold for our calibration, this ensures that all simulations lie within the envelope of the two dashed lines.

1. **TUNING BY HAND**

Once RStudio has loaded, click on the “Code” directory in the window at the bottom right of your screen. Then click “GO.R” to open the R script containing the (manual) calibration version of the model. Once the script appears in the window in the top left of your screen, you are ready to edit the parameters and begin modelling.

Scroll down the model code until you find the block titled “PARAMETERS TO TUNE”. Note the following mapping between parameter names used in the script and in the GO model:

* *trans* =
* *ice\_albedo* =
* *t\_sens* = *c*
* *t\_constant* =
* *t\_tip = Ttip*

**Q. Before going any further, check Giesen and Oerlemans (2012) and fill out the table below with the parameter values they calibrated for the AWS sites (hint: find Table 2!)**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Set** | **(ND)** | **(ND)** | ***c* (W m-2 K-1)** | (**Wm-2)** | ***Ttip* (°C)** |
| **Small c** |  |  |  |  |  |
| **Large c** |  |  |  |  |  |

Check the parameters are set to the **Small c** values in the script.

Run the model now by clicking on the *Source* button (top right). When the model has finished, it will print the *maximum* *implausibility* to the screen.

**Q. What is the maximum implausibility, max(*I*), when running the model with the *small c* parameter combination?**

The R script also prints to screen the mean observed and modelled specific mass balance. In tuning the model (below) you want to get the modelled value as close as possible to the observed mean!

**Q. Write “increase” or “decrease” next to the parameter values below to suggest how you could change the respective parameters to move the simulated mass balance closer to the observed mass balance (hint: look at the relevant equations in Giesen and Oerlemans, 2012).**

|  |  |
| --- | --- |
| **Parameter (notation in Giesen and Oerlemans (2012))** | **Adjustment** |
| ***trans* ()** |  |
| ***albedo\_ice* ()** |  |
| ***t\_sens* (*c*)** |  |
| ***t\_constant* ()** |  |
| ***t\_tip* (*Ttip*)** |  |

Now manually ‘tune’ your model (by changing the parameter values) to get the maximum implausibility max(*I)* value as low as possible. When you are satisfied with your tuning (or perhaps once your patience has run out - don't spend longer than 10 mins), make a note of the final parameter values in the table below.

|  |  |
| --- | --- |
| **Parameter (notation in Giesen and Oerlemans (2012))** | **Tuned value** |
| ***albedo\_ice* ()** |  |
| ***t\_sens* (*c*)** |  |
| ***t\_constant* ()** |  |
| ***trans* ()** |  |
| ***t\_tip* (*Ttip*)** |  |

Note that when you edit these files online, they will not be saved when you return to or refresh the page.

1. **PERTURBED PARAMETER ENSEMBLE**

As addressed in Lecture 2, tuning to a single best parameter set – whilst intuitive – ignores uncertainty when we then use that model to make some sort of prediction. We can improve upon things by making predictions using *all* parameter sets that pass a history matching calibration.

We will do this now by:

1. using *Latin hypercube sampling* (LHS) in R to efficiently sample from the parameter space,
2. running the model for all these combinations, and
3. retaining those parameter sets which give a maximum implausibility *max(I)* < 3, i.e. an absolute difference between simulated and observed annual mass balance that is *no larger* than 3 (see the lecture for justification of this threshold).

In the history matching literature, ensemble members that pass the calibration with observations in (c) are called 'Not Ruled Out Yet' (NROY).

To launch this ‘ensemble’ version of the model, click on the GO\_CAL\_LHS.R file in the window at the bottom right of the RStudio screen (i.e., from where you selected the GO.R model earlier).

Once you see the model code in the main viewer (middle/left of the screen), scroll down until you find the text:

# # # # # # # # # # # # # #

# PERTURBED PARAMETER ENSEMBLE

# # # # # # # # # # # # # #

Underneath this you will find the code:

*ranges <-*

*list(lower = c(0.2,5,-50,0.1,-2),*

*upper = c(0.6,50,-2,0.6,3))*

The numbers in parentheses indicate the lower and upper bounds of our parameters between which will be used to constrain the LHS. As indicated in the code comments, the parameters are listed in the following order:

# 1. ice\_albedo (reflectivity of ice; fraction [0-1])

# 2. tsens (sensitivity of temp-dep heat fluxes to temp; W/m^2/C)

# 3. t\_constant (constant heat flux when temperature below t\_tip; W/m^2)

# 4. trans (atmospheric transmissivity to insolation; fraction [0-1])

# 5. t\_tip (temperature beyond which the temperature-dependent heat fluxes scale with air temperature; C)

That is, for the values pasted above, the first number for ‘lower’ is 0.2, and the first for ‘upper’ is 0.6, meaning these are the lower and upper bounds, respectively, for the albedo of ice.

**Edit the values in the lower and upper vectors (i.e., those in the c(0.2…) and c(0.6…) vectors) so that they encompass the ranges of values calibrated at the AWS sites by Giesen and Oerlemans (2012)** (Hint: again, check their Table 2).

When you are satisfied that you have completed this, run the model (by clicking *Source*, top left). The script will then create a 250-member ensemble, using different parameters combinations on each run. Be patient whilst this takes ~10-15 minutes to complete.

At the end of the ensemble run, a file called LHS\_params.csv will be saved: this contains parameter sets which *passed* our history matching calibration(i.e. a maximum *I* no more than 3).

Download the file to your computer by navigating to the *Data* directory in the Files Viewer (bottom right window of RStudio). Next, make sure the *LHS\_params.csv* box is ticked, and then select more 🡪 Export 🡪 Download. You can then open/inspect this output file on your computer. The five columns are the five parameters; each row is a simulation that passed the calibration (NROY).

**Q. How many simulations are not ruled out yet (i.e. how many rows are there in the file)? What percentage is this of the original ensemble?**

## **GLACIER MODEL PROJECTIONS**

Here we will use real projections of future climate in the 21st century from the NorESM-MM model, under the RCP4.5 scenario, as our forcing for the glacier model. We will project the *area* of the glacier.

In other words, our scientific question is: "What is the projected 21st century response of the Storglaciären glacier area to climate change under the RCP4.5 emissions scenario?"

1. **THE HAND-TUNED PARAMETER SET**

You can now launch the projections version of the model. Do this by clicking “GO\_FUTURE\_CSV.R” in the bottom right window.

Scroll down to the block of code that says PARAMETERS TO SET. Edit these values to match the best performing subset you found during the manual tuning of the model earlier.

Run the model when you are happy that the parameters have been set correctly (using the *Source* button, as usual).

The model will use these parameter values – plus the climate model projections – to simulate glacier area out to 2100. The annual area is written to a file called *Results.csv.* Download this file to your local file system as before.

This is the structure of Results.csv:

|  |  |  |
| --- | --- | --- |
| **Column** | **Units** | **Notes** |
| **year** | Years since 0 AD | - |
| **area** | m2 | Divide by 1,000,000 for km2 |
| **MB** | m w.e. a-1 | Specific mass balance |
| **temp** | °C | Mean air temperature over the mass balance year |
| **precip** | mm d-1 | Mean precipitation over the mass balance year |

Open the file with Microsoft Excel and make a line plot of *year* on the x-axis and *area* on the y-axis.

Calculate the area at 2100 as a percentage of the area at the start of the simulation in 1990.

**Q. What is your projected area at 2100 (as a % of 1990 area) using the hand-tuned model?**

1. **THE PERTURBED PARAMETER ENSEMBLE**

We will now create an *ensemble* of projections, with each member generated with a different parameter set taken from the LHS\_params.csv file. There is nothing to do to this script, other than run it. So long as the LHS\_params.csv already exists (which should be the case if you have completed all the steps so far), you should not encounter any errors.

Open the ensemble version of the model now (*GO\_FUTURE\_ENS\_CSV.R*) and then run it (by clicking Source).

At the end of the script, a csv file is written to the Data directory called *EnsResults.csv*. It provides the glacier area (in m2) for each year out to 2100. Download this now (following the same process as before) and inspect the contents in Excel.

Each column is one projection of mass balance for the years 1990-2100 (i.e. one for each row in LHS\_params.csv).

Now integrate this output into your plot of future glacier area, creating an *envelope* of plausible projections. The final result should look something like the below, but the details will depend on the ranges you chose in the LHS design. The dashed lines mark the minimum and maximum glacier area for each year, and the solid line is the result from the best manual tuning. (Hint: paste the columns into the Results.csv spreadsheet and go from there).

**Q. What is the range of your calibrated projections at 2100, i.e. the minimum and maximum % of 1990 area in your NROY ensemble?**

**Q. Rewrite these values to give your answer to the scientific question:**

**The projected 21st century response of the Storglaciären glacier area to climate change under the RCP4.5 emissions scenario is a loss of \_\_\_\_ - \_\_\_\_\_ % relative to 1990.**

**ADVANCED: FURTHER EXTENSIONS**

## **SENSITIVITY ANALYSIS**

NOTE: in what follows, it is assumed that you are comfortable manipulating data in Excel. Please ask if you need further guidance (on the KEATS forum, or arrange to come to our office hours, or go to the Geography Study Cafe).

We can assess the sensitivity of the NROY projections to the different parameter values. To do this we will first *normalise* the projections, computing the change in area *per degree of warming* (i.e., dA/dT). This normalisation means you can more easily compare your results with other studies.

You can calculate the normalised projections in Excel by:

1. calculating the mean area and mean temperature for the first (1990-2009) and last (2081-2100) 20 years of the simulation; and then
2. subtracting the first 20-year mean from the second 20-year mean. The difference in air temperatures defines ‘dT’, whilst the difference in areas is ‘dA’.
3. Now divide dA by dT to compute dA/dT for *each* ensemble projection (noting that dT is the same for each ensemble member)

Once the above steps have been completed, you should have as many values for dA/dT as you have parameter sets.

Now construct five scatter plots (one for each parameter) with parameter value on the x-axis, and dA/dT on the y-axis. [Hint: the first scatter plot would have the *n* values for ice albedo across the x-axis, and the *n* values for dA/dT on the y-axis (where *n* is the number of ensemble runs that passed our minimum performance threshold)]

**Q. Inspect these scatter plots. Which of the five parameters do you think dA/dT is most sensitive to?**

**Q. How do you think the results of this sensitivity analysis would differ if we ran and plotted the full perturbed parmeter ensemble, not just the subset that passed our history matching calibration?**

## **PLOTTING AND CHANGING DATA**

If you want to plot or change the model forcing and calibration data yourself, e.g. for coursework, then in the Data folder look for:

* **mass balance observations:** MBs column in AnnMB.csv
* **climate forcing data** (temperature and precipitation): t and p columns in met.csv (historical) and projections.csv (future)

## **CLIMATE PROJECTIONS**

These climate projections were "bias-corrected" using the E-OBS dataset that we used to force the model for the historical period. This means monthly corrections have been applied so that the observed and modelled temperature and precipitation match during the 1981-2010 period. It is assumed that the same corrections are valid for the future, projected climate. Although the details of this are beyond the scope of today’s section, note that the correction is additive for air temperature, and multiplicative for precipitation.