

Glacier model

WaSiM offers two methods for modelling glaciers. Here are some common and differences:

- The traditional static glacier model was implemented in 1999
 - this is mainly a model describing glacier melt and discharge accumulation and routing within the glacier in a conceptual way.
 - No changes in glacier extend, no explicit mass balance (i.e. total ice mass calculation) and no metamorphosis of snow to firn and ice is modelled. Thus, the extend of a glacier can and must be statically defined.
 - Each glacier cell is defined by a code in a glacier grid (with separate codes for ice and firn).
 - For each separate glacier, a separate sub-basin must be defined in the sub-basin grid – accordingly, the routing model must be extended by routing descriptions for those glacier sub basins. A glacier subbasin mustn't contain any unglacierized cell
- The dynamic glacier model was implemented in 2010
 - it uses exactly the same melt methods as the static glacier model (t-index with or without radiation correction)
 - however, the glacier extend is dynamic: depending on the annual balance (at a given day, e.g. September, 30th) the extend of the glaciers will shrink or grow based on a relatively simple relation, the A-V-relation, see also Stahl et al. (2008)
 - An explicit balance grid is calculated, allowing the shrinking and growing calculations as well as other estimations associated with glacier mass changes.
 - Since the glaciers can vary in their extend, the fixed relation of one sub basins per glacier is not applicable here. Instead, each sub-basin may contain any number of glaciers (which are identified as in the static model by their code).
 - Each single ice body or glacier can be defined in the glacier code grid with a unique code, so the A-V-relation is applied to each separate glacier, allowing for different behaviors of different glaciers depending on their altitude, precipitation and temperature.
 - In addition to the melt model, the dynamic glacier model allows for modelling the metamorphosis of snow to firn (which is done once per model year), so the glaciers mass can change not only by melt but also by precipitation – this is quite important for the algorithm to work, since an explicit balance combined with modelled glacier melt would mean that the ice mass will be smaller year after year if there weren't sources of new ice as well.

The dynamic glacier model can be seen as an advancement to the static glacier model. By allowing the glacier size to be changed, it provides a possibility to calibrate the glacier model not only at discharges but also at observed historic glacier extends. Also, the future projection of glacier extends is one of the central practical applications of such an approach.

Static glaciers

The static glacier option assumes that the glacier hypsometry and extent remains constant although in reality the glacier may retreat or advance. The melt model describes the melt of firn, ice and snow on glaciers as well as the routing of the glacier discharge within the glacier. The module is fully integrated in the snow model and it can be used with both model versions (Topmodel and RICHARDS-approach).

To enable the glacier module, an additional standard grid, the so called glacier grid, has to be read

in. It codes the cells which are covered by glaciers with the codes 1 for ice and 2 for firn, respectively. Further it is required that glaciers are defined in the subbasin grid as separate subcatchments. Thereby, it is not necessary that each small glacier must be a separate subbasin, it is perfectly possible to put some small glaciers together into one subbasin (glacier subbasins do not have to be closed areas). However, it is required that the glacier subbasins as defined in the subbasin grid does not contain any other landuse than firn or ice and that both, firn and ice, are present only in glacier subbasins, thus the glacier subbasins are exclusive for the glacier melt model. This must hold because of the internal model branching since all of the following submodels are skipped for glacierized cells when using the static glacier model (note: this is not always the case when using the dynamic approach):

- interception
- soil model (RICHARDS-approach or TOPMODEL-approach)
- irrigation control
- real evaporation
- groundwater flow
- solute and tracer transport in all of the above mentioned modules

Only the discharge routing re-unites the data streams again, because discharges of glacier subbasins are routed like any other discharges. A section “[ice_firn]” was inserted in the control file containing all melt and runoff concentration parameters and file names for the glacier model. In addition to the statistics output file and the grid for the snow melt, there will be also grids and statistics files for melt of ice and firn. A fourth statistic file contains the total glacier melt. This last statistics file contains the already internally routed and superposed discharges, whereas the snow, firn and ice melt statistics files contain the areal averaged melt rates for each time steps without reservoir effects. All of these statistics files contain data columns for each subbasins, even if there are no glaciers, in which last case the data are only zero for firn and ice melt.

melt of firn and ice:

There are two methods for calculating glacier melt: a classical temperature index method and an extended temperature index method after Hock (1998, 1999) including information on the global radiation during each time step on each grid cell in order to modify the melt. The melt after the classical temperature index approach is calculated by:

$$M = \begin{cases} \frac{1}{n} DDF_{snow/ice/firn} \cdot (T - T_0) & T > T_0 \\ 0 & T \leq T_0 \end{cases} \quad (2.21.1)$$

- with M melt [mm/time step]
 n number of time steps per day [day^{-1}]
 DDF 3 degree-day-factors for snow, firn and ice, respectively [$\text{mm} \cdot \text{C}^{-1} \cdot \text{day}^{-1}$]
 T air temperature in a standard elevation of 2 m [$^{\circ}\text{C}$]
 T_0 threshold temperature for melt [$^{\circ}\text{C}$]

The melt is calculated for snow, firn, and ice separately using specific parameters. If a glacier cell, which is recognized by the codes 1 or 2 in the ice_firn-grid, is covered with snow, the melt calculation is done using the parameters DDF_{snow} and no firn or ice melt is calculated. If the cell is not covered by snow, then the melt calculation is done using the parameters according to the cell code: DDF_{ice} for ice cells (code 1) or DDF_{firn} for firn cells (code 2). Usually the relation $DDF_{ice} > DDF_{firn} > DDF_{snow}$ holds. All three parameters are constant in space and time for the entire model domain. The parameter values are ranging between 2 ... 10 $\text{mm} \cdot \text{C}^{-1} \cdot \text{day}^{-1}$.

Using the extended melt approach after HOCK (1998), the melt of snow, firn, and ice is calculated

by:

$$M = \begin{cases} \left(\frac{1}{n} MF + \alpha_{\text{snow/ice/firm}} \cdot I_0 \cdot \frac{G_s}{I_s} \right) \cdot (T - T_0) & T > T_0 \\ 0 & T \leq T_0 \end{cases} \quad (2.21.2)$$

with M	melt [mm/time step]
n	number of time steps per day [day^{-1}]
MF	melt factor with identical values for snow, firm and ice (around $2 \text{ mm} \cdot \text{°C}^{-1} \cdot \text{day}^{-1}$)
α	empirical coefficients for snow and firm (identical, app. 0.002) and for ice (around 0.001) [$\text{mm} \cdot \text{Wh}^{-1} \cdot \text{m}^2 \cdot \text{°C}^{-1} \cdot \text{day}^{-1}$]
I_0	potential direct incoming shortwave radiation (visible incoming sun radiation) for each grid cell (depends on shading, aspect and slope angle, time and season, but not on cloudiness) [$\text{Wh} \cdot \text{m}^{-2}$]
I_s	like I_0 , but for the well defined location of a meteorological station [$\text{Wh} \cdot \text{m}^{-2}$]
G_s	observed radiation at the same station [$\text{Wh} \cdot \text{m}^{-2}$]
T	air temperature in a standard elevation of 2 m [°C]
T_0	threshold temperature for melt

The coefficient is multiplied by global radiation, hence increasing melt when shortwave radiation input is high and vice versa. For each grid cell the interpolated global radiation is used. The actual global radiation correction is done in the evaporation module. However, for this melt model approach, it is necessary to enable the radiation correction and to use PENMEN-MONTEITH or WENDLING evaporation in order to get corrected radiation. Also it is recommended not to use net radiation instead of global radiation. If no radiation correction and shading is done, no variations in the melt pattern will be recognizable since only the interpolated radiation is used for scaling the melt. The model stops its execution if no radiation is found during the initialization.

The parameters α_{ice} , α_{firm} , and α_{snow} are becoming smaller in this order and range between $10^{-4} \dots 5 \cdot 10^{-3} \text{ mm} \cdot \text{Wh}^{-1} \cdot \text{m}^2 \cdot \text{°C}^{-1} \cdot \text{day}^{-1}$. The radiation is given in $\text{Wh} \cdot \text{m}^{-2}$ scaling the small α -values to the order of reasonable degree day factors. Since the product of α and interpolated global radiation is added to the melt factor MF , MF is smaller than the degree day factors for a classical temperature index approach (Equation (2.21.1)) and its value is around $2 \text{ mm} \cdot \text{°C}^{-1} \cdot \text{day}^{-1}$.

If a glaciated cell is coded as firm but covered with snow, the melt was calculated using the parameters for snow. However, since this snow melt flows directly into the firm layer and since the reservoir effects of firm are so much larger than the reservoir effects of snow, the melt of snow on firm cells is handled like melt of firm.

The radiation coefficient vary over time. The control file must provide the minimum and the maximum value for the radiation correction factors ($\alpha_{\text{ice,min}}$, $\alpha_{\text{ice,max}}$ and $\alpha_{\text{snow,min}}$, $\alpha_{\text{snow,max}}$), which are then internally used to compute the effective radiation correction factors for any given Julian day:

$$\alpha = a + b \cdot \sin(c \cdot (d + JD)) \quad (2.21.3)$$

with a	the respective correction factor for snow, ice or firm
a	mean value $(\alpha_{\text{min}} + \alpha_{\text{max}})/2$ of the respective α -parameters
b	amplitude $(\alpha_{\text{max}} - \alpha_{\text{min}})/2$ of the respective α -parameters
c	conversion of the Julian Day number into radiant measure: $c = 2\pi/365 = 0.017214$
d	shift of the $\sin()$ function to give the result of 0 at March, 21 st and September 21 st and 1 at June, 21 st and -1 at December 21 st

routing of the different melt components through the glacier:

For glacierized subbasins there are three runoff components calculated after equations (2.21.1) and (2.21.2), respectively. These components are now superposed and routed to the subbasin outlet using a set of parallel single linear reservoirs.

The total runoff from a glacier subbasin is given by:

$$Q(t) = \sum_{i=1}^3 \left(Q_i(t-1) \cdot e^{-\frac{1}{k_i}} + R_i(t) \cdot (1 - e^{-\frac{1}{k_i}}) \right) \quad (2.21.4)$$

with $Q(t)$ total runoff during time step t [mm/time step]
 i reservoir index (1 reservoir for snow melt, 1 for firn melt and 1 for ice melt)
 $Q_i(t-1)$ outflow of reservoir i during the last time step $t-1$ [mm/time step]
 $R_i(t)$ input into reservoir i in the actual time step t , this equals the sum of melt and additional rain [mm/time step]
 k_i storage coefficient (recession constant) for reservoir I

Equation (2.21.4) describes the superposition of three parallel reservoirs 1... i ($i=3$), each of which has specific storage coefficients k_i and inflow rates R_i , representing the areal means of the three melt components. The storage coefficients for ice, snow and firn range in this order with values for k_{firn} of around 100 to 1000, for k_{snow} of 10 to 100, and for k_{ice} of 1 to 20 hours.

For the calibration of the model it is important to initialize the three parallel reservoirs with matching initial values. If the calibration starts at a state when the total glacier is frozen, e.g. in January, then only the firn reservoir must be initialized with a small initial outflow, the other two reservoirs may be initialized with zero.

The total runoff from the glacier subbasins is handled in the discharge routing module like the runoff of any other subbasin. Thus, WaSiM can be applied also to very large basins ranging from glacierized high mountains down to low land regions with important groundwater reservoirs, lakes and irrigation impacts.

The control file must contain a section named [ice_firn], if an ice_firn-grid is given as a standard grid:

```
[standard_grids]
<n>      # number of standard grids
# path   # identification # fillcode 0=no, 1=yes (fill with values of nearest neighbor)
$inpath//${ice_firn_grid}      ice_firn      0 # grid with firn or ice cells
...
[ice_firn]
2 # method for glacier melt: 1=static with t-index, 2= static with t-index and radiation
# correction, 11 = dynamic glaciers with t-index, 12= dynamic glaciers with t-index and
# radiation correction
5      # t-index factor for ice
4      # t-index factor for firn
3      # t-index factor for snow
2      # melt factor
-0.00010 # radiation coefficient for ice_min (for method 2/12)
+0.00070 # radiation coefficient for ice_max (for method 2/12)
+0.00006 # radiation coefficient for snow_min (for method 2/12)
+0.00030 # radiation coefficient for snow_max (for method 2/12)
12     # single linear reservoir (SLR)-constant for ice
120   # single linear reservoir (SLR)-constant for firn
24    # single linear reservoir (SLR)-constant for snow
1     # initial reservoir content for ice discharge (SLR approach)
1     # initial reservoir content for firn discharge (SLR approach)
1     # initial reservoir content for snow discharge (SLR approach)
$outpath//${firn_melt} # melt from firn
$Writegrid      # 0, if no grid-output is needed, else one of the codes described above
$outpath//qfir//${grid}///${code}//${year} $hour_mean # melt from firn as statistic file
```

```

$outpath//qice_melt # melt from ice
$Writegrid # 0, if no grid-output is needed, else one of the codes described above
$outpath//qice//qgrid//.$code//year $hour_mean # melt from ice (statistic)
$outpath//qglc//qgrid//.$code//year $hour_mean # melt from ice and firn (statistics)
...

```

dynamic glaciers

The dynamic glacier model does not only model the glacier mass balance but also advance or retreat of the glacier by removing or adding glacierized grid cells or fractions thereof. The model does not account for changes in surface elevation of glacier grid cells, only the extent of the glacier.

As for the static approach, first the glacier mass balance has to be calculated. This is done by balancing mass gain (snow accumulation) and mass losses (snow, firn, ice melt) over one mass-balance year (usually October 1st to September 30th). The month and day for calculating the balance (and the glacier advance and retreat) are parameters to the dynamic glacier model as well. It is recommended to choose the parameters to date when most old snow is molten and the new snow season didn't start already, so e.g. September 30th may be a good choice under northern hemisphere conditions.

Equation (2.21.5) will be used when initializing WaSiM with a grid containing glacierized cells under cold start conditions. This is one of two new input grids. The glacierized cells may have any value between 0 and 1, so a cell may also be fractionally glacierized. Beside modelling the firn layers, this is the other important improvement compared to the method presented in Stahl et al. (2008). With this range of glacier coverage between 0...1 it is possible to use the dynamic glacier model with smaller resolutions (e.g. 100m to 500m). Also, an annual balance is possible (and not only one balance per decade).

Modelling glacier retreat and advance

Glacier area changes are modeled using volume-area scaling

$$V = b \cdot A^f \quad (2.21.5)$$

with V volume of the glacier in $\text{m} \cdot \text{km}^2$
 A area of the glacier in km^2
 b empiric factor
 f scaling factor assumed to be 1.36

This relationship (2.21.5) was first presented by Chen and Ohmura (1990) and physically validated by Bahr et al. (1997). The parameters b and f must be provided in the parameter file. A value of $b=28.5 \text{ m}$ is suggested (would be the mean ice thickness of a 1 km^2 glacier) but other values may be chosen if data are available..

By using equation (2.21.5), the newly calculated WE value of the mass balance - converted into a volume by multiplying the resulting mass with the ice density of approx. 918 Kg/m^3 - can be used to calculate the new area for each glacier by equation (2.21.7):

$$A = \left(\frac{V}{b} \right)^{\frac{1}{1.36}} = \left(\frac{V}{b} \right)^{0.735} \quad (2.21.7)$$

The “tricky” thing is to add or remove fractions of grid cells to or from the glacierized area. Glacierized areas usually grow/shrink at the tongue faster than in the accumulation area, retreat should not occur in areas with a positive balance, so the area covered by firn should also not be affected by the retreat at the edge of the glacier as long as there are cells which are completely free of firn. Also, the mean temperature should be regarded when changing the glacierized areas. To take

all this into account, the area change is first converted into the number of grid cells to be added or subtracted from the glacier. The next step is to divide the glacier into elevation belts and to reduce or increase the number of gridcells (or the ice covered fraction) according to the elevation. This process is done iteratively. The glacier is partitioned into elevation bands of equal elevation differences (how many belts there will depends on a control file parameter – upper limit is the equilibrium line if there are cells without firn, else the entire glacier is used for growing/shrinking).

Only the lowermost elevation band will be processed in the first iteration step. The next elevation band will be part of the iteration starting with the second step, the third band will be handled for the first time in the third iterations step and so on, such that the uppermost elevation band will be affected by growing or shrinking in the last iteration step only whereas the lowermost elevation band is affected in every iteration step. In addition, for the lowermost elevation belt an additional number of iterations (`extraWeightFactorBand0`) can be set in order to pronounce the advance/retreat at the glaciers tongue.

Example: A glacier has an elevation range from 1500 to 2500m a.s.l. The equilibrium line lies at 2100 m a.s.l. The control defines: Number of iterations: 10; `extraWeightFactorBand0=4`. The model runs with a resolution of 500 m.

The elevation range between 1500 and 2100 m is divided into 10 elevation bands of 60m each. When the new area is calculated, there should be 10 cells be subtracted from the rim of the glacier. The count of cells at the glaciers edge are (as an example):

band 1: 8 cells, affected in each of the 10 iteration plus 4 extra iterations: $8 \times (10+4) = 320$
band 2: 13 cells, affected in iterations 2 to 10 = $13 \times 9 = 117$
band 2: 15 cells, affected in iteration 3 to 10 = $15 \times 8 = 120$
band 2: 14 cells, affected in iteration 4 to 10 = $7 \times 14 = 98$
band 2: 14 cells, affected in iteration 5 to 10 = $6 \times 14 = 84$
band 2: 12 cells, affected in iteration 6 to 10 = $5 \times 12 = 60$
band 2: 18 cells, affected in iteration 7 to 10 = $4 \times 18 = 72$
band 2: 7 cells, affected in iteration 8 to 10 = $3 \times 7 = 21$
band 2: 10 cells, affected in iteration 9 to 10 = $2 \times 10 = 20$
band 2: 9 cells, affected in iteration 10 only = 9

in total: 120 cells are affected, whereas the 10 iterations will split the 10 cells into 921 fractions. So each affected cells glacierized fraction has to be decreased by $10/921 \times \text{number of iteration}$. A single change amount is $10/921 = 0.01086$. From each edge-cell in band 1 the amount of $40 \times 0.01086 = 0.43$ is subtracted, so 3.47 cells are removed from the glacier in band 1 already. From band 2, there have to be removed the area of 117×0.01086 cells = 1.27 cells, spread over all 13 edge-cells and distributed over iterations 2 to 10 and so on.

This schema could have been run without iteration at all. But: since the exact geometry is not known to the algorithm, the shrinking and growing could lead to a changing number of cells during the process of retreat or advance. Therefore the algorithm runs iteratively, changing only a small amount of area in each iteration. If the number of edge cells changes, then the total of removed fractions will be smaller than computed first. So the amount to be removed from each cell (or to be added to each cell) can be changed dynamically from iteration step to iteration step.

The entire procedure is quite fast, since it is done only once a year and for a rather limited number of glaciers (even if there were hundreds of glaciers). So there is no sensible negative performance impact of the dynamic glacier model on the total model performance (in terms of computing speed).

Firn model

The dynamic model also includes a dynamic firn model, i.e. changes in firn depth are calculated at the end of each mass-balance year using a simple approach of *metamorphosis of snow to firn to ice*:

Snow which does not melt within one balancing period will automatically become firn at the beginning of the next balancing period. When this firn layer is covered by snow in the following winter and only partially melts in the following summer, then another firn layer forms. . During the following year, another layer of snow covers the now two (numeric) layers of firn. This process will eventually lead to the firn turning into ice. Usually, this metamorphosis will take several years The number of years needs to be defined in the model (default is seven, i.e. after seven years old snow becomes finally ice). These grids are stacked together to a so-called firn stack, which can (and must) be initialized in cold start conditions by providing some parameters:

- Number of years it takes the snow to convert into ice (recommended default: 7)
- Elevation of the equilibrium line in m a.s.l. This is the elevation where the amount of precipitation (as snow) equals the amount of snow melt, so the mass balance is zero there. All elevations above have a positive net balance (more snow fall than melt), all elevations below have a negative balance (more melt than snow fall). Typical elevations for the equilibrium line in the Swiss Alps are between 2300 and 2800 m a.s.l.
- To be able to initialize the amount of firn for each stack layer, the last parameter defines the rate of change in the water equivalent (WE) of firn with each meter of elevation rise. This is typically something between 1 and 2 mm/m, so the WE value of firn rises by 100 to 200 mm per 100 m elevation rise.

After each mass-balance year the firn stack will be adjusted in thickness according to the mass balance, i.e. the total firn depth (in water equivalent) may change. Changes may occur in the top layer(s) and at the bottom of the firn pack. In case of a positive mass balance (i.e. not all winter snow has melted), a new firn layer is added equal in thickness (in w.e.) to the mass balance. In case of a negative mass balance, firn layers are removed or decreased in thickness according to the excess melt once the snow is melted. Depending on the mass balance several of the uppermost firn layers may completely melt as well. In extreme situations it may even occur that all firn layers will completely melt. If a firn layer melts away the layer is technically not removed but given a thickness of 0 m w.e.

In addition, the lowermost layer is removed from the firn pack assuming it to become ice. Consequently, the number of firn layers remains the same and after each year firn layers move one layer down, leaving the uppermost layer to be replaced by the WE amount of the snow which did not melt during the current mass-balance year.

Control file changes for the dynamic glacier model

There are a few additional parameters as well as name definitions for additional statistic outputs and grids:

```
[variable_grids]
2      # Number of variable grids to read
$outpath//glca.grd GlacierizedCells 0  -9999  # glacierized fraction
7 # $Writegrid
1 # $readgrids
$outpath//$glid  GlacierCodes      0  -9999  # unique codes for each glacier
7 # Writegrid
1 # $readgrids
...

[ice_firn]
... #here the entries of the static glacier model must follow
# -----
# now some new parameters for the new dynamic glacier model (methods 11 and 12)
$outpath//qsgl.stat $once_per_interval  # melt from snow from glacier only
$readgrids # 1=read grids and stacks from disk, 0=generate new grids and stacks
```

```

#(using the parameters in the following line for WE_Firn stack)
7 2700 1.8 # number of layers for the firn stack, followed by two
# initialization parameters: average Equilibrium line elevation in m
# (e.g. 2500) and change rate of WE per m in mm (e.g. 2) -> every 100m
# the WE of firn in each layer will grow by 200mm
09 30 # month and day (hour is set automatically to 24) for which the Volume-
# Area-Relation will be applied newly (and temporary (i.e. internal) Balances
# are reset to 0)
28.5 1.36 10 4 # VAScaling and VAexponent for Volume-Area-Relation of glaciers
# and number of iterations (elevation belts) and
# extraWeightFactorBand0 (elevation band 0 will be processed in each
# iteration this given number of times more than once. Default = 0)
$outpath//$firn_WE_stack # water equivalent for firn (given as stack, number of
# layers taken from the parameter given before); layer 0 will contain the total
# WE for all firn layers
$Writestack # write code for the Firn stack
$outpath//glfirn.stat $once_per_interval # water equivalent for firn as
# statistics file (sum over all firn layers)
$outpath//glmb.grd # output grid with mass balance of the glacier
$Writegrid # writecode for the glacier mass balance
$outpath//glmbo.grd # output grid with mass balance of the glacier (old year)
$Writegrid # write code for the glacier mass balance (old)
$outpath//glmb.stat $sum_per_24Invs # mass balance for the glaciers as
# statistics file (mass balance for each time step with respect to the
# entire subbasin the glaciers are located in)
$outpath//glmb2.stat $sum_per_24Invs # mass balance for the glaciers as
# statistics file (mass balance for each time step with respect to the glaciers
# only!)

```

example for dynamic glacier model results

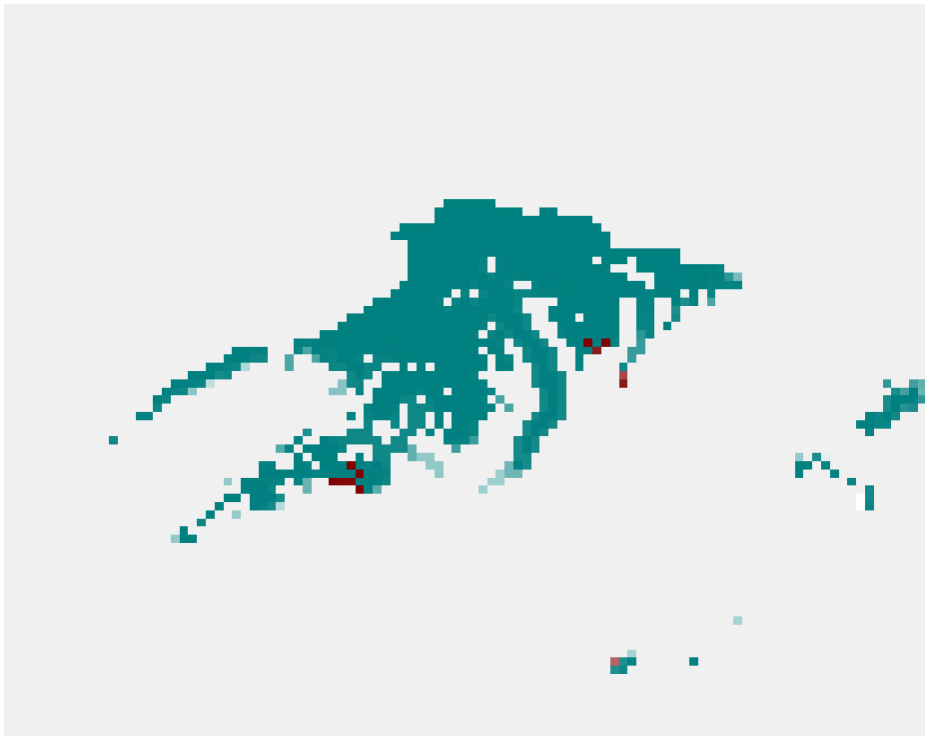


Figure 1: Glaciers in the Swiss Alps (center: Aletschgletscher) for 1996

Figures 1 and 2 show the model results for the Swiss Alps around the Aletsch-Gletscher (the one with the long tongue in the center) between 1996 and 2010. Brown cells indicate areas where the glaciers have retreated according to the parameters used in the model setup and the meteorologic input used.

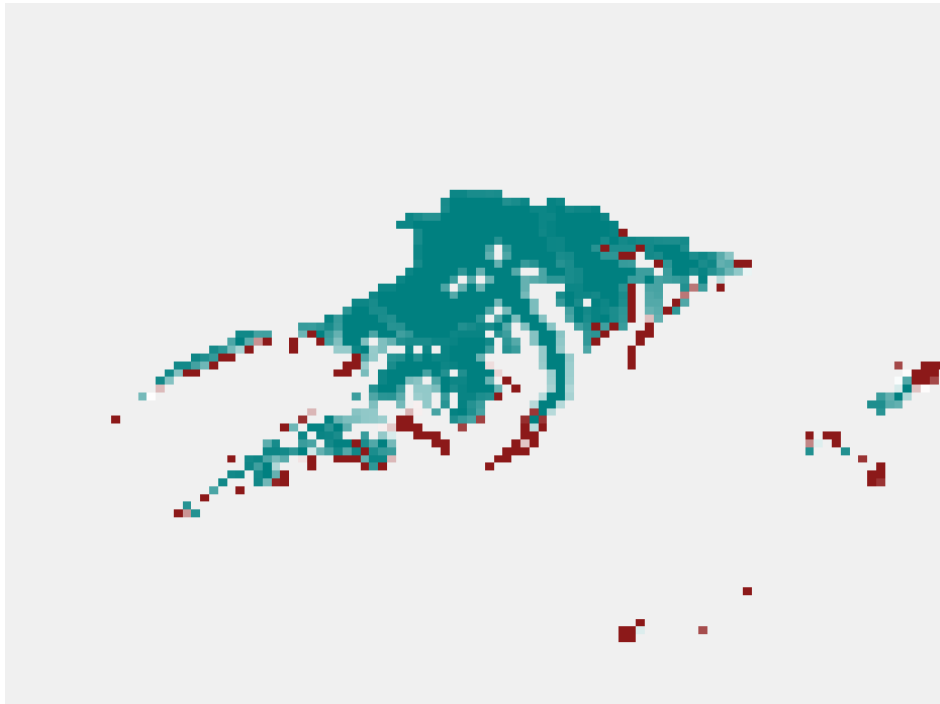


Figure 2: Glaciers in the Swiss Alps for 2010