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Assignment 1

Exercise 1: Geodetic glacier mass balance

Q: How large was the specific mass change rate experienced by the glacier during the period? Express your result in units of "m water equivalent per year" (m w. e. a-1), and make sure to explain what assumptions you did for computing this number.

Steps to get to the result:

Volume change of each grid cell:

Initially, we begin by identifying the grid cells that contained a glacier in the year 1980, which is indicated by a value of 1 in the associated mask file. Within these identified grid cells, we calculate the difference in elevation between the years 1980 and 2009 by comparing the Digital Elevation Models (DEMs) from these respective years. We created a new matrix with these new values meaning for each cell (that had a glacier in 1980) we took the elevation and distributed the elevation in 2009.

The formula we use to determine the volume change within these grid cells is as follows:

$$\Delta V_{gridcells} = Elevation(1980)_{icecovered} - Elevation(2009)_{icecovered}$$

At those grid cells where there was no glacier in 1980, the grid cell got the value nan (not a number)

<u>Assumption</u>: We make an underlying assumption that, in cases where a glacier was absent in 2009, the observed elevation difference only resulted from the melting of snow and ice. This assumption implies that there were no changes to the underlying rock terrain, such as erosion or rockfall, and that the height change was uniform throughout the entire grid cell.
Additionally, we assume that the grid cell either had a full snow cover or no snow at all. We acknowledge that, in reality, the snow cover within a grid cell could exhibit varying proportions, ranging from a full snow cover to a complete absence thereof.

Absolute volume change:

We calculated the total change in volume ($\Delta V_{absolut}$) by adding up the height changes of all grid cells. To account for the grid cell size, which is 50x50 meters, we multiplied this total volume change with 50*50. We added a multiplicator of -1 in front, because we have an ice loss (as an alternative, we could also have distributed 2009-1980 at the equation before).

$$\Delta V_{absolut} = -1 * 50 * 50 * \sum \Delta h_{gridcells}$$

Surface of the glacier

We determined the average surface area (A_{mean}) for the two years by taking the mean number of grid cells that were covered with snow or ice in 1980 and 2009. Since each grid cell measures 50x50 meters, we multiplied the mean value by 50x50 to obtain the absolute area of the glacier.

$$A_{mean} = 50 * 50 * \frac{\sum Gridcells(1980)_{iceovered} + \sum Gridcells(2009)_{iceovered}}{2}$$

Mass change per year

We calculated the rate of mass change per year ($\frac{\Delta Mass}{year}$) by dividing the absolute volume change by the product of the mean area (A_{mean}) and the number of years ($\Delta years$ = 29 years) to get a value in m³ per m² per year.

$$\frac{\Delta Mass}{year} = \frac{\Delta V_{absolut}}{A_{mean} * \Delta years}$$

Water equivalents

We converted this mass change into meters of water equivalent per year ($\frac{waterequiv}{year}$) by taking into account the density of ice (ρ_{ice}= 850 kg/m³) and the water density (ρ_{water} = 1000 kg/m³).

$$\frac{waterequiv}{year} = \frac{\Delta Mass}{year} * \frac{\rho_{ice}}{\rho_{water}}$$

Result: -0.6307 m w. e. a^{-1}

Assumption: we assume that the mass change per year is linear, meaning that the change occurred at a consistent rate throughout the 29-year period whereas there can be vast differences from year to year. Also, if year 1980 of 2009 exhibited an extreme event of ablation or accumulation, this could affect our result.

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Exercise 2: Meteorological Data

Q: Which data did you chose and why?

We used the following Swiss Meteo page to find the meteorological stations with such long-term time series: https://www.meteoswiss.admin.ch/services-and-publications/applications/ext/climate-tables-homogenized.html

On the following map we could see the meteorological stations of Meteo Swiss: https://www.meteoschweiz.admin.ch/service-und-publikationen/applikationen/messwerte-und-messnetze.html#param=messnetz-automatisch&lang=de

Out of those we tried to find the one that is the most representative for the Fiescher glacier by looking at their location and altitude. The stations that are the closest to Fiescher glacier are:

Jungfraujoch

Distance to Fieschergletscher: about 12 km

Altitude: 3571 m above sea level (asl)

Data available since 1933

Problem: No precipitation data available!

Grimsel Hospiz

Distance to Fieschergletscher: about 17 km

Altitude: 1980 m asl

Data available since 1932

Conclusion

Fiescher glacier has a mean altitude of 3122 m asl, so regarding the altitude both stations would be applicable. Jungfraujoch is the closest station but doesn't provide precipitation data. **Therefore, Grimsel Hospiz is the best option.**

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Exercise 3: Melt model calibration

Question 3.1

Q: What was your procedure to calibrate the DDF?

Make sure to provide a step by step explanation and to mention any assumption.

With the DEMs from 1980 and 2009, coupled with the glacier masks in 1980 and 2009, we have evaluated a certain amount of melting happening seen above in question 1. This gives us a calculation of the balance change from 1980 to 2009. The DDF has been calibrated with this result, with the following procedure:

For each grid and for each time step, the balance can be very simply modelled with the following variables:

$$B = C - A$$

The accumulation (C) has been estimated as the amount of precipitation when temperatures drops below 0 degrees celsius. It follows the block-rain model in which c_{prec}=dP/dz=0 and D_{snow}=1. This gives us:

$$C = Precipitation \text{ for T<0° [Celsius]}$$

The ablation (A) is then calculated. It does not include an albedo dependence, a radiation term or a location dependency. Instead, it is using the very simple Temperature Index model TI, as “longwave atmospheric radiation and sensible heat fluxes provide 75% of the melt energy. Both are well correlated to air temperature“ (Ohmura, 2001). Using this assumption, it has been modelled that:

$$A = T * DDF \text{ for T>2° [Celsius]}$$

As a grid data approach was preferred over a mean altitude approach, at each time step we had to integrate all the different temperature conditions for each different grid elevation and consequently compute a balance at each different grid in order to get a more precise balance result for the glacier:

$$B_t = \frac{\sum_{grid}(C - A)}{number\ of\ grids}$$

From there, we could get the total balance over the years with the following equation, where we inserted the equations mentioned above for the variables:

$$B_{tot} = \sum_t B_t = \sum_t \frac{\sum_{grid}(C - A)}{number\ of\ grids}$$

$$= \sum_t \frac{\sum_{grid}(P_{t,grid} - T_{t,grid} * DDF)}{number\ of\ grids} = \frac{\sum_t \sum_{grid} P_{t,grid} - DDF * \sum_t \sum_{grid} T_{t,grid}}{number\ of\ grids}$$

Since the total balance change (B_{tot}) has been calibrated to the loss of mass between 1980 and 2009, we could extrapolate the DDF with the following equation:

$$DDF = {\left(B_{tot} - \frac{\sum_t \sum_{grid} P_{t,grid}}{number\ of\ grids}\right)} \Big/ {\sum_t \sum_{grid} T_{t,grid}}$$ with T > 2° and P only when T<0°.

From this equation, the DDF has been found with a value of 8.89 mm d^{-1} K^{-1}.

Question 3.2

Q: What value (and unit) do you obtain for the calibrated DDF, and how does it compare to values reported in the literature?

Value and unit we obtained for the calibrated DDF:

- around 13.08 mm d^{-1} K^{-1} when we only considered the mean glacier elevation
- around 8.89 mm d^{-1} K^{-1} with the distributed modelling approach

Values from the Literature:

Braithwaite et al. (2006)got estimations of low DDF (3.49 ± 0.05 mm d^{-1} K^{-1}), medium DDF (3.96 ± 0.06 mm d^{-1} K^{-1}) and high DDF (4.40 ± 0.08mm d^{-1} K^{-1}). They got this data by setting the observed winter balance of 180 glaciers worldwide in relation to the modelled annual temperature.

Focusing more on swiss glaciers, Sugiyama et al. (2011) mention DDFs between 5.2 mm d^{-1} K^{-1} to 11.2 mm d^{-1} K^{-1} for the Rhone glacier. In this case our secondly calibrated DDF would be in the same range.

Possible reasons for the inaccuracy in our first DDF

Possible reasons for the inaccuracy in our first DDF estimation could be, that we calibrated the DDF using a mean altitude of the glacier. In reality, there would be way more melt at the glacier tongue because of the lower altitude and therefore higher temperatures. This leads in our model to a higher number of days with temperatures below 0, which doesn't reflect the reality. Therefore, the distributed modelling approach is the more suitable way to calibrate the DDF.

Question 3.3

Q: Reflect upon the various assumptions that were necessary for the calibration. Which assumptions are likely to introduce a bias? In what direction do the individual biases go, and which assumption are likely to introduce the largest biases?

We simplified the glacier mass balance model and didn't take into account all variables that could potentially play a role. Depending on if they are part of the accumulation or ablation processes, this leads to an under- or overestimation of the DDF.

Overestimation of the DDF (due to underestimation of the accumulation)

We didn't take snowfall, hoar, freezing rain, windborne snow, avalanching and internal accumulation into account and only focused on snowfall. This is by far the largest accumulation contributor, but ignoring the other factors still leads to an underestimation of the glacier mass and an overestimation of the DDF.

Apart from that, Cui et al. (2013) mentions that the DDF for ice is generally greater than the one for snow. The DDF in our model only refers to ice, while in reality the composition of the glacier might not be that uniform. This also contributes to an overestimation of the DDF in our model.

Underestimation of the DDF (due to underestimation of the ablation)

Regarding the ablation, we only based our calculation on the DDF and change of air temperature. Nonetheless, the effects of radiation, increased debris cover (particularly in the lower part of the glacier), avalanches and melting from below have a significant impact on ablation, but they were neglected .

Moreover, glaciers are flowing downwards which leads to a decreasing elevation of the glacier and therefore higher temperatures and accelerated melting. This might lead to an underestimation and quite large bias of the DDF in our model.

Neglected factors whose effects are uncertain

We conducted our meteorological data from the station Grimsel Hospiz, which is 17 km away from the Fiescherglacier and at a lower altitude and close to the Grimsellake. This influences the climatic conditions as well as the amount of precipitation. Even if we corrected the data set according to the elevation, inaccurate temperature and precipitation data can still influence the calibration of the DDF.

We calibrated the whole model only on two timepoints, 1980 and 2009, and both of them were generated in the same month (October). Therefore, they can't reflect seasonal differences or extreme events within the time span of those 29 years. More data points could lead to a more robust estimation of the DDF. Furthermore, little errors or uncertainties in one of the datasets already lead to a different result, as there is no alternative data available. For example, it could be that measurement techniques have evolved between 1980 and 2009 so that it is difficult to relate these time points.

Conclusion

It is challenging to determine the direction in which our biases tend to lean, as there exist factors that support an overestimation of DDF as well as factors that support an underestimation. As accumulation is primarily dependent on snowfall, which was incorporated in our model, and there are certain crucial components of the ablation that were not included, such as glacier ice flow, it is possible that we may have underestimated the DDF slightly bit. Nonetheless, our calibrated DDF is within the range of realistic values (see 3.2), so the bias might not be too large.

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Exercise 4: Mass balance reconstruction

Q: What are the (i) cumulative and (ii) average glacier mass balance (in mw.e. and mw.e. a-1, respectively) and what do you observe in the yearly time series? Check whether you can discern trends, and whether there are periods or individual years that stand out.

Cumulative mass balance

To calculate the cumulative glacier mass balance, we followed a grid-based modelling approach.

1. We transformed the DDF (unit: mm water equivalent per day and degree) into a "degree month factor" (unit: m water equivalent per month and degree) by multiplying it by the mean number of days per month (30.42) and dividing it by 1000.
2. For each grid cell and each month from 1935 to 2022, we computed the accumulation and ablation:
   a. Accumulation: If the calculated temperature (as explained in Question 3) was below 2°C, we added the precipitation of that month.
   b. Ablation: If the temperature was above 0°C, we calculated ablation by multiplying the temperature of that month with the degree month factor.
3. We summed up the cumulation and ablation and divided it through the number of grids that were covered by a glacier:

$$mass\ balance_{cumulative} = \frac{\sum_{1935}^{2022} Cumulation - \sum_{1935}^{2022} Ablation}{glacier grids}$$

Result: -25.67 m w.e.

Average glacier mass balance

To calculate the average mass balance, we divided the result through the number of years:

$$mass\ balance_{average} = \frac{mass\ balance_{cumulative}}{\Delta years}$$

Result: -0.3 m w. e. y^{-1}

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Yearly time series

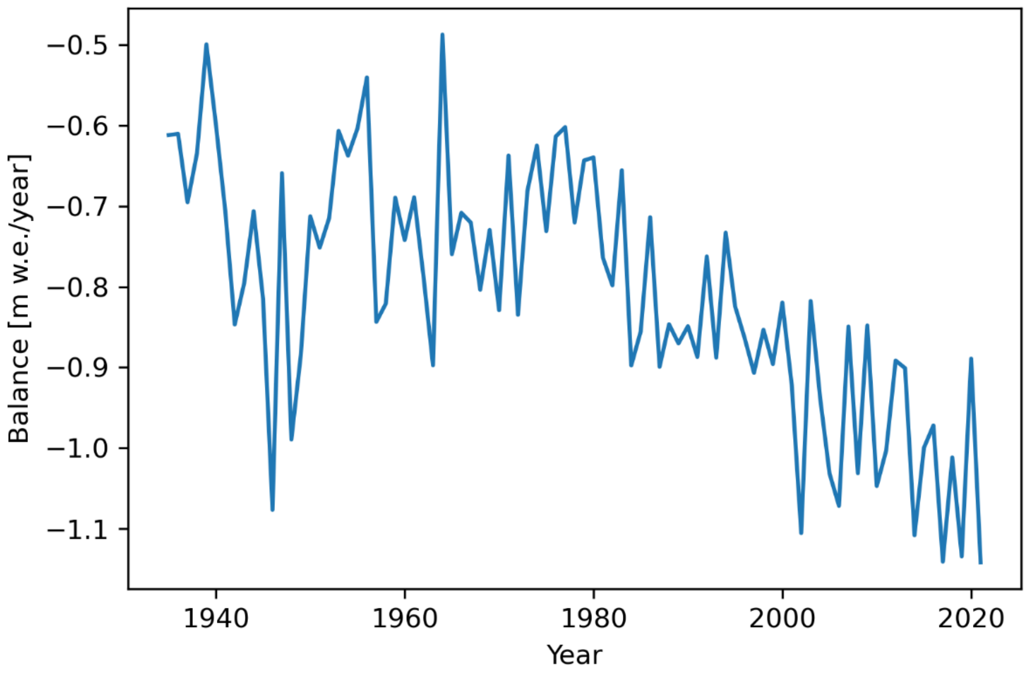

Figure 1: Yearly mass balance of the glacier since 1935

In this plot and the analysis, we consider the hydrological year, which takes from October to September (e.g., our year 1935 covers the period from 1.10.1934, to 30.09.1935). The trend is very clear: the mass balance is negative in all years. This means the glacier is losing ice since the beginning of our time series. From 1935 to 1970 the mean loss stayed at a rather constant level, but they are notably characterized by the largest year-to-year variations in the data. This could be attributed to our backward interpolation from the surface coverage we observed in 1980, relying solely on the available meteorological data. However, it is important to recognize that data collection methods and accuracy improved significantly over the years. Therefore, the substantial fluctuations in the early years could be attributed to less precise measurements during that period, resulting from less advanced data collection techniques.

From 1975 onwards the glacier is losing more ice from year to year. In 2003, the glacier experienced a first exceptionally negative mass balance, likely due to the severe heatwave that affected Western Europe during the summer. However, this extreme value was surpassed in the subsequent two decades, as four different years (2015, 2018, 2020, 2022) experienced even more negative mass balances.

The year 2022 stands out as the glacier's most unfavourable year in terms of mass balance, and once more, this can be attributed to the significant heatwave and that impacted Europe during that particular summer. Furthermore, high temperatures were reached very early in this year and new records were recorded for sunshine duration (MeteoSchweiz, 2022). This also led to a new record of the 0°C-altitude level (MeteoSchweiz, 2022). All these factors lead to the highest negative mass balance of -1.1418 m we/year in our time series.

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Exercise 5: Future projection

Question 5.1

Q: What was the glacier volume in 2009? Express you result in km³.

To determine the glacier volume in 2009, we employed the following equation:

$$V_{2009} = c * A_{2009}{}^{\gamma}$$

This equation can also be found in (Cogley et al., 2011, p. 30)

To get the absolute area in 2009, we summed up the amount of gridcells and multiplied the sum with a factor of 2500, as each gridcell has a size of 50x50m. Our area in 2009 (A_{2009}) has therefore the size of 33,23 km². γ stands for the cold content, meaning "The amount of energy required to raise the temperature of a body of frozen water to the freezing point" (Cogley et al., 2011, p. 30). For the constants c and γ, we utilized the values specified for glaciers, which are c = 0.03 and γ = 1.36 (Bahr et al., 1997).

We therefore get as a result for the glacier volume in 2009 3.519 km³.

Question 5.2

Q: Based on your projection, when (year) will the glacier have lost 50% of the volume it had in 2009? Use "Hint 1" below, and discuss whether the resulting "projection" is likely to be an under- or overestimate, and why.

Based on our projection, the glacier is estimated to have lost 50% of its volume from 2009 after 40.55 years, which means by the year 2050. This projection is calculated using the following formula, which reflects a linear assumption:

$$\Delta years = -\frac{1}{2} * \frac{V_{2009} * \rho_{glacier}}{A_{2009} * mass\ balance_{average,1992to2022} * \rho_{water}}$$

$$Year = 2009 + \Delta years$$

We get the average mass balance from 1992 to 2022 ($mass\ balance_{average,1992to2022}$)by using the procedure described in Question 3. The density of a glacier ($\rho_{glacier}$) is 900 kg/m².

<u>Reasons for over- or underestimation of the year (that the glacier will be half melted):</u>

- **Weather Station Representation:** Our chosen weather station shows a good representation in terms of elevation levels, and temperatures. However, when it comes to precipitation, the station's data may not be as representative. Being located 17 kilometres away from our glacier, the weather station's precipitation values might differ as precipitation has very small-scale local occurrences. Furthermore, Precipitation estimates for high alpine regions are associated to large uncertainties. Also, the station is located next to a lake, which can affect the temperature values. This discrepancy could potentially lead to both overestimation and underestimation of the actual precipitation occurring at our glacier.

- **Temperature Changes:** We assumed that the temperature change per year is linear based on our data from 1992 to 2022. Climate change affects different regions of the world in varying intensities, and Switzerland is one of the areas where the effect is even stronger (*Klimaszenarien Für Die Schweiz*, 2018). It's plausible that the rate of temperature increase is more complex, possibly even exponential, leading to faster ice melt than our linear model suggests. In recent years, we've observed record-breaking temperatures, such as the exceptionally warm October in 2022, surpassed by the even warmer October in 2023. These events suggest an acceleration in temperature changes and, consequently, a more rapid ice melt rate, which was also recorded in the last two years (tagesschau.de, 2022; World Meteorological Organization [WMO], 2023).
- **Albedo Effects:** Our projection doesn't account for factors that influence the albedo, such as changes in the glacier's coverage area (as we also assume the volume as a brick). As glaciers shrink, rocky (darker) terrain is revealed. The darker surface absorbs more heat, which again accelerates the ice melt process. This was not considered in our projection and could further contribute to underestimating the rate of glacier volume loss. Additionally, particles like Sahara dust on the glacier surface can affect albedo and ice melt rates (Gabbi et al., 2015) which we only included indirectly by evaluating the mean over the reference period. However, if this amount increases, our projected year would also be wrong.
- **Hint one:** We did not include change of surface in our calculation. This would be a source of overestimation of ablation in our model as more area is hit by solar radiation. On the other hand, it also leads to an overestimation of accumulation as more gridcells account for the calculation of the accumulation.
- **Glacier movement:** We did not consider the movement of glaciers downwards. This would lead to a higher ablation; we therefore underestimated this value.
- **Ablation:** OUR ABLATION MODEL DOESN'T CONSIDER VARIOUS FACTORS THAT COULD ACCELERATE THE ABLATION PROCESS. THIS INCLUDES ASPECTS LIKE THE IMPACT OF SOLAR RADIATION AND ALBEDO EFFECTS, AS DISCUSSED EARLIER. IT ALSO DOESN'T ACCOUNT FOR WHETHER LIQUID PRECIPITATION, WHICH BECOMES MORE RELEVANT AS TEMPERATURES RISE AND MORE PRECIPITATION TURNS LIQUID, MIGHT EXPEDITE ABLATION. CONSEQUENTLY, OUR MODEL TENDS TO PROVIDE CONSERVATIVE ESTIMATES, UNDERESTIMATING THE ACTUAL ABLATION RATE.

Overall, we think that our accumulation values are fine, but due to the reasons mentioned above we assume that our ablation rate is too low. Therefore, the period until half of the volume of 2009 melted is overestimated.

Question 5.3

Q: Can you think of a strategy that avoids the simplification given in "Hint 1"? Explain how you could avoid the assumption of a constant area, and what additional information, tools, or methods (if any) you would need for that.

With access to more historical data regarding ice coverage, we can perform a detailed evaluation of annual volume changes and corresponding area alterations. This could be reached by following the following steps:

1. **Calculate Volume Change year i:** We need to determine the volume change from year 'i' to 'i+1' based on the glacier's area in year 'i'. This volume change quantifies the alteration in the glacier's ice mass over a one-year period.
2. **Calculate Area Change year i:** We need to calculate the area change in response to the calculated volume change in 1. This step provides information on how the glacier's surface area is adjusting due to shifts in ice volume in this year.
3. **Project Year 'i+1':** we assume that the area of *year i+1* is the area of *year i* – calculated area change and calculate according to step 1 and 2.
4. **Get average change of area per change of volume per year:** calculate for every year the change of area per change of volume, take the mean of all years.
5. **Include this mean in equation of question 5.1 and use an integral**

Moreover, data from the underlying surface or additional depth measurements would enhance our ability to estimate the glacier's volume with greater precision.

References

Bahr, D. B., Meier, M. F., & Peckham, S. D. (1997). The physical basis of glacier volume-area scaling. *Journal of Geophysical Research: Solid Earth*, *102*(B9), 20355–20362. https://doi.org/10.1029/97JB01696

Braithwaite, R. J [Roger J.], Raper, S. C., & Chutko, K. (2006). Accumulation at the equilibrium-line altitude of glaciers inferred from a degree-day model and tested against field observations. *Annals of Glaciology*, *43*, 329–334. https://doi.org/10.3189/172756406781812366

Cogley, J. G., Hock, R., Rasmussen, L. A., Arendt, A. A., Bauder, A., Braithwaite, R. J [R. J.], Jansson, P., Kaser, G., Möller, M., Nicholson, L., & Zemp, M. (2011). *Glossary of glacier mass balance and related terms*. UNESCO/IHP.

Cui, Y., Ye, B., Wang, J., & Liu, Y. (2013). Influence of degree-day factor variation on the mass balance of Glacier No. 1 at the headwaters of Ürümqi River, China. *Journal of Earth Science*, *24*(6), 1008–1022. https://doi.org/10.1007/s12583-013-0394-2

Gabbi, J., Huss, M [M.], Bauder, A., Cao, F., & Schwikowski, M. (2015). The impact of Saharan dust and black carbon on albedo and long-term mass balance of an Alpine glacier. *The Cryosphere*, *9*(4), 1385–1400. https://doi.org/10.5194/tc-9-1385-2015

Klimaszenarien für die Schweiz: CH2018. (2018). BBL, Verkauf Bundespublikationen.

MeteoSchweiz. (2022). *Klimabulletin Sommer 2022.*

Ohmura, A. (2001). Physical Basis for the Temperature-Based Melt-Index Method. *Journal of Applied Meteorology*, *40*(4), 753–761. https://doi.org/10.1175/1520-0450(2001)040%3c0753:PBFTTB%3e2.0.CO;2

Sugiyama, S., Yoshizawa, T., Huss, M [Matthias], Tsutaki, S., & Nishimura, D. (2011). Spatial distribution of surface ablation in the terminus of Rhonegletscher, Switzerland. *Annals of Glaciology*, *52*(58), 1–8. https://doi.org/10.3189/172756411797252185

tagesschau.de. (2022, September 28). *Schweizer Gletscher schmelzen wie noch nie*. https://www.tagesschau.de/ausland/europa/schweizer-gletscher-schneemangel-schmelze-101.html

World Meteorological Organization. (2023). *State of the Climate in Europe 2022*. WMO.