



**University of
Zurich^{UZH}**

Analysing Rockglacier Ground Surface Temperatures between 2001 and 2023 in the Hungerlitelli, Turtmanntal (VS)

ESS 511 Master's Thesis

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26.04.2024

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Abstract

Long-term time series analysis of Ground Surface Temperatures (GSTs) on two active and one inactive rockglacier enables an assessment of periglacial features. The long-term trend of the Mean Annual Ground Surface Temperature (MAGST) for the active rockglacier Huhh1 has a slope of $+0.067^{\circ}\text{C}/\text{year}$ and its long-term MAGST average from 2002 to 2023 is $-0.32 \pm 0.86^{\circ}\text{C}$. The second active rockglacier Huhh3 has an increase of $+0.088^{\circ}\text{C}/\text{year}$ and a long-term MAGST average of $+0.28 \pm 1.11^{\circ}\text{C}$. The slightly larger increase of MAGST on Huhh3 is attributed to the larger amount of fine-grained substrate in comparison to Huhh1, to the exposition and the snow coverage. The inactive rockglacier Huhh2 has a MAGST trend of $-0.0046^{\circ}\text{C}/\text{year}$ and a long-term average of $-1.08 \pm 0.91^{\circ}\text{C}$. Although a higher MAGST was expected since it is an inactive rockglacier, the prevailing conditions of coarse-grained material favouring permafrost and wind driven snow accumulation resulted in the lowest measured long-term average on rockglacier level. The calculation of the Bottom Temperature of the winter Snow cover (BTS) resulted in a minimal increase of $+0.014^{\circ}\text{C}/\text{year}$ on regional scale, which amplifies the independence of GST on air temperature. The Ground Thawing Index (GTI) and Ground Freezing Index (GFI) highlight the rising occurrence of extreme temperatures and loss of snow since the GTI is increasing and the GFI is decreasing. The correlation between the air temperature and the GST is high during snow-free periods and low if snow covers the ground. A high variability between the sites was observed during summer and a low variability in winter due to the insulating effect of snow. The timing, duration and thickness of snow layers strongly influence the value of GST. A start of High Thermal Insulation ($\text{HTI}_{\text{start}}$) in October to November resulted in high winter GST since the summer heat could not leave the system. Late $\text{HTI}_{\text{start}}$ around New Year lead to an efficient cooling of the ground if the air temperature was low. The length of the time gap between the Snow Onset Date (SOD) and the $\text{HTI}_{\text{start}}$ cannot be used for a prediction of the size of BTS. With ongoing climate change, the GST will further rise.

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Acronyms

BTS	Bottom Temperature of the winter Snow cover i, 3, 9, 24, 34, 45, 52, 53, 60, 69, 70, 78–81, 85, 86
GFI	Ground Freezing Index i, 24, 34, 55, 56, 82, 83
GST	Ground Surface Temperature i, 1–3, 12, 18–20, 22–24, 26, 31–34, 37, 38, 43–47, 58–73, 76–78, 82–86
GST_{day}	daily mean Ground Surface Temperature 31–34, 59, 64, 72
GTI	Ground Thawing Index i, 24, 34, 55, 56, 82, 83
HADES	Hydrological Atlas of Switzerland 35, 39
HTI_{start}	start of High Thermal Insulation i, 32, 43–45, 59–70, 72–74, 77, 80, 85
m a.s.l.	meter above sea level 1, 2, 35–38, 41, 71
MAAT	Mean Annual Air Temperature 1, 7–9, 12, 20, 40, 41, 64, 66, 68, 77, 79, 80
MAGST	Mean Annual Ground Surface Temperature i, 1, 3, 9, 12, 20, 24, 33, 34, 47–49, 51, 58, 59, 61–64, 66–69, 73–79, 81, 82, 85, 86
MAP	Mean Annual Precipitation 7, 39, 41
PERMOS	The Swiss Permafrost Monitoring Network 1, 26
SD	Standard Deviation 33, 72
SOD	Snow Onset Date i, 32, 44, 45, 63, 68, 70, 72, 85
UTL	Universal Temperature Logger 2, 26, 27, 29, 33, 84
ZC	Zero Curtain 17, 24, 31–33, 43–45, 60, 63, 64, 66–69, 71–73, 76

1. Introduction

1.1 Motivation

Rockglaciers are common and distinct features of permafrost. Without knowing their existence, they seem to be inconspicuous. But as soon as one crosses the way with a huge and distinct rockglacier, people start to think about what kind of feature this is. Rockglaciers are widespread across the Alps, but due to their inconsiderable appearance, they are much less known in the community. Nevertheless, they are important features of the cryosphere.

My supervisor, Isabelle Gärtner-Roer, collected data about rockglaciers for 22 years from 2001 up to today. Thus, there exists a long-term GST time series of three rockglaciers in the Turtmanntal in the Canton of Valais. Long-term time series are useful and powerful tools for climate analyses. By comparing the GST with climate variables, like the air temperature or precipitation, similar trends and correlations may be detected.

Mountainous areas belong to the fastest changing landscapes (IPCC 2007). Switzerland experiences a warming which is twice as fast as the global mean. The ground-level air temperature increased by about 2°C compared to 0.9°C globally (NCCS 2018). 2014 to 2018 was the warmest 4-year period ever measured in Switzerland since measurements began in 1864 (PERMOS 2019).

The Swiss Permafrost Monitoring Network (PERMOS) measures, analyses and documents the state and changes of permafrost in the Swiss Alps over more than 20 years. The latest report, The Swiss Permafrost Bulletin 2022 (PERMOS 2023) documented that the hydrological year 2022 was the second warmest year ever measured since 1864. The Mean Annual Air Temperature (MAAT) was around 1.5°C over the long-term mean 1981 - 2010 (MeteoSchweiz 2024). As a consequence of these meteorological conditions, the MAGST of the hydrological year 2022 increased for all measurement sites which were covered by PERMOS in comparison to the previous year (PERMOS 2023).

On 25 July 2022, a new record of the zero-degree isotherm was registered at an altitude of 5184 meter above sea level (m a.s.l.) (MeteoSchweiz 2024; PERMOS

2023). Kenner et al. (2024) found that the loss of mountain permafrost corresponds well to the rise of the atmospheric zero degree line.

Permafrost, hence rockglaciers, is a thermally controlled phenomenon (e.g. Biskaborn et al. 2019; PERMOS 2023; Roer 2005), reacts to climatic changes (e.g. Barsch 1996; Marmy et al. 2013; PERMOS 2023) and is one of the essential climate variables (PERMOS 2023). The main factors influencing permafrost occurrence is air temperature, surface characteristics, radiation balance and the thickness and duration of snow cover (Hoelzle 1996; PERMOS 2023; Roer 2005). Snow cover has the ability to insulate the ground from the atmosphere (e.g. Haeberli 1973; PERMOS 2019; T. Zhang 2005). A thick enough snow layer (> 0.8 m) creates a disconnection between permafrost and the atmosphere (Haeberli 1973; Hoelzle 1992; Keller 1994). During snow free or snow-poor periods, permafrost is directly influenced by the atmosphere (Harris & Pedersen 1998; Luo, Jin, & Bense 2019; Scherler et al. 2014). Therefore, the timing of the first snow fall, the duration and thickness of the snow cover and the time when the ground surface becomes snow free (in spring) are relevant (PERMOS 2019; Staub & Delaloye 2017). Accumulation of snow in autumn has a long-lasting effect on inter-annual GST variations, not only because of its insulating effect but also due to snow melt and refreezing (Marmy et al. 2013; Staub & Delaloye 2017). Hence, the energy balance at the ground surface is strongly influenced by the snow accumulation, redistribution and melt (Stocker-Mittaz, Hoelzle, & Haeberli 2002). Rising temperatures and change in the amount and timing of precipitation influence strongly the existence of permafrost (Hoelzle, Haeberli, & Stocker-Mittaz 2003; PERMOS 2019; Staub & Delaloye 2017).

1.2 Objective and Research Questions

In this work, a long-term GST time series from the Hungerlitelli in the Turtmanntal (VS) in the Swiss Alps is analysed. This data set covers the time period from the first of October 2001 to the 30th of September 2023. Within this period, the GST was measured with Universal Temperature Loggers (UTLs) in about 10 different locations. The measurement sites were located on active (Huhh1, Huhh3) and inactive (Huhh2) rockglaciers between 2500 and 2800 m a.s.l. Additionally, from October 2002 to September 2008, several temperature loggers were distributed on a nearby moraine for comparison.

The aim is to document the multi-decadal GST trend, to highlight the inter-annual

1.2. Objective and Research Questions

and seasonal variations and the timing and duration of the snow cover in a local and regional scale. Hence, the following research questions are addressed:

- How does the seasonal and inter-annual ground surface temperature vary?
- How does the duration and timing of the snow cover influence the quantity of the bottom temperature of the winter snow cover?
- How does the bottom temperature of the winter snow cover correlate with the mean annual ground surface temperature?

1.2.1 Ground Surface Temperature

GST analysis on rockglaciers can help to understand the sensitivity of these landforms under changing climate (IPCC 2019). Many studies documented and researched the GST (e.g. Gissnäs et al. 2014; Gubler et al. 2011; PERMOS 2023; Roer 2005; Staub & Delaloye 2017). However, few observations exist on the long-term variability in MAGST on a local scale (Haeberli et al. 2010). Hence, the long-term time series of the Hungerlitelli is processed to gain an overview about the long-term trend on a local GST time series. The first and second research question will be addressed within the GST analysis.

1.2.2 Bottom Temperature of the Winter Snow Cover

The significance of the BTS is well studied, mainly in the early studies of permafrost features (e.g. Haeberli 1973; Hoelzle 1992; Keller 1994; Schoeneich 2011). However, a long-term monitoring is not documented. In this Master Thesis, the trend of the BTS is analysed and evaluated. Likewise, a comparison between the BTS and the MAGST was done to assess a new variable for permafrost detection since the snow cover thickness and duration will be reduced in future climate (NCCS 2018) and cannot serve as a permafrost distribution variable anymore. Thus, the third research question will be answered with the analysis of the BTS.

2. Scientific Background

2.1 High Mountain System

Mountainous terrain, mountain system and high mountain environment all refer to a landscape which have similarities but are slightly different. High mountain landscapes have physiological and ecological characters at different elevations (Troll 1973) and are highly variable due to relief, elevation and exposure (Barsch & Caine 1984). Setting limits where a mountainous terrain starts or ends is essential to distinguish mountain areas. Generally, alpine environments are dominated by steep slopes, tundra plants, rocky outcrops, snow and ice (French 2017).

Many studies define mountain system with different approaches. Barsch and Caine (1984) define mountain terrain with four characteristics. They are elevation, steep gradients, rocky terrain and the presence of snow and ice. They defined four different types of mountain systems by using elevation as an approach. By calculating the altitudinal difference over 5 km distance, the defined systems are hilly terrain (50 – 100 m altitudinal difference), mountainous terrain (100 – 500 m altitudinal difference), mountain system (500 – 1000 m altitudinal difference) and high mountain system with >1000 m altitudinal difference. Using only this strict definition is not adequate to differentiate between various mountain areas due to their large variability over the entire globe. Additional distinctions of mountain areas also result from their elevation, relief and exposure (Barsch & Caine 1984). The topographic position gives a simple example for the difficulty of defining mountainous regions. Mountain environments in mid-latitudes are at higher altitudes than mountain areas at higher latitudes due to the energy received from the sun. High latitudes receive less energy per surface unit than mid-latitudes (French 2017). Thus, the position on the globe makes it impossible to set a definition only by elevation and altitudinal difference. Therefore, more characteristics are needed. Barsch and Caine (1984) used the steepness of the environment to differentiate high mountain areas from mountain environments. High mountain areas in the Alps are characterised by steep topography, dominated by rock walls ($> 60^\circ$) and steep slopes between 35° and 60° . These regimes are normally created by glacial erosion. In addition, other land forms, like glacial troughs and cirques, are as well a result of glacial erosion and

2.1. High Mountain System

represent the state of a former landscape condition. In post-glacial regimes, talus slopes and fans filled the valley floors with sediments (Barsch & Caine 1984). These characteristics can be summarised in a typical high mountain relief for the Alps which is proposed by Barsch and Caine (1984) and can be seen in Figure 2.1.

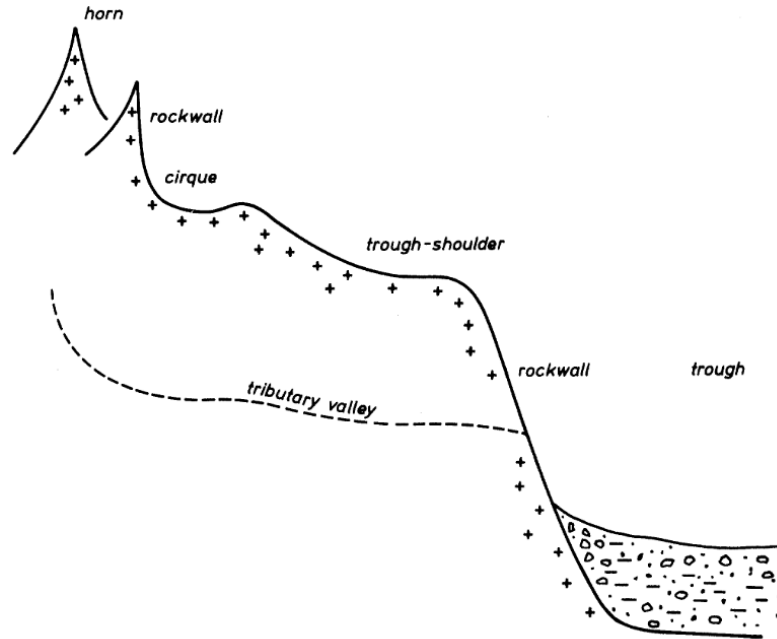


Figure 2.1: Schematic representation of a high mountain environment in the Alps. The bedrock is illustrated with crosses, the filling of the trough represents fluvial sediments. Angular shapes, labelled with horn (in common state of research named as nunatak), represent features above glacial erosion. Rounded forms resulted by glacial erosion, sedimentation from post-glacial processes (from Barsch and Caine (1984): p. 291).

Another approach to distinguish high mountain environment presented Carl Troll (Troll 1973). He defined different ecosystems and their ranges which are only represented in high mountain environments. Those ranges were classified into belts and consist of defined landscape elements. He suggested three criteria to determine the lower limit of high mountain belts: the upper timberline, the cold Pleistocene snow line and the lower limit of solifluction.

The timberline, or also named as tree line, defines a zone with an extent of around 30 to 150 km (French 2017). Above the timberline, trees cannot survive due to the prevailing climatic conditions. The determination of a high mountain system with the upper timberline is only reasonable for all non-tropical, humid mountain system (Troll 1973). In addition, the timberline varies with aspect. It is situated at higher altitudes at south- and west-facing slopes than for north- and east-facing

slopes (French 2017).

The cold Pleistocene snow line was created during the last glaciation, thus it is responsible for the high mountain relief.

The lower limit of solifluction describes the threshold where the processes of cryoturbation and solifluction on sloping terrain can still occur above the limit. Below the limit, frost patterned soil cannot appear due to their temperature limit.

These environments belong to periglacial processes. To sum up, Carl Troll defined a high mountain environment that lies above the timberline, has a glacially engraved relief and is influenced by periglacial processes.

The combination of the different approaches enables a localisation of alpine environment and a differentiation of mountain systems and high mountain environment.

2.2 Periglacial

The word 'periglacial' was first used by Walery von Lozinski in 1909. He described periglacial processes as climatic and geomorphic conditions peripheral to Pleistocene ice sheets and glaciers (French 2017). Thus, his definition relies close to the root of the word 'periglacial' which means 'the ice surrounding'. However, this is not a restriction. Periglacial processes can be found in the surroundings of glaciers but also in large distances to them (Zepp 2014). Nowadays, periglacial environments are only restricted to environments with a cold climate where intense frost processes occur (French 2017). Ground freezing and thawing are the main process which appear in the periglacial environment (French 2017; Zepp 2014). The time scale of freezing- and thawing-cycles varies and can be differentiated in seasonally-frozen or perennally-frozen ground (French 2017).

Periglacial environments can be found in high latitudes and high altitudes. In the Central Alps in Europe, periglacial processes are generally found above the timberline and below the snow line (Barsch 1996; French 2017; Troll 1973).

Troll (1973) defined periglacial environments as the periglacial stage and divided it into two sub-belts of periglacial dynamics. The lower sub-belt is dominated by tied solifluction and lies around the timberline. Thus, the surface is still covered with vegetation and the processes of ground freezing and thawing are influenced and maintained by the vegetation. The upper sub-belt has only sparsely vegetated soils covered by some pioneer plants. This sub-belt mainly consists of bare scree- and debris-soils and is referred as the sub-nival belt. Hence, free solifluction is dominating.

Troll (1944), Haeberli (1983) and French (2017) presented an approach to limit the periglacial stage with the use of MAAT and Mean Annual Precipitation (MAP). Both variables influence the distribution of glaciers and permafrost, thus also the zone of high mountain environment.

At first, Troll (1944) set a definition to restrict the periglacial environment with climate variables. By a global survey of periglacial conditions, he found that characteristic MAATs lie in the range of -15°C and -1°C . The MAP have values between 120 and 1400 mm.

The definition of Haeberli (1983) was created for the Swiss Alps, thus only valid for high mountain environments in the mid-latitudes. The lowest limit of possible permafrost is defined with a MAAT of -1°C to -2°C and MAP of about 2250 mm (Barsch 1996). Regions with $\text{MAAT} > -1^{\circ}\text{C}$ and $\text{MAP} > 2250$ mm do not have periglacial environments. Even if one variable, temperature or precipitation, is higher then its defined limit, periglacial features are rarely present. According to Haeberli (1983), Barsch (1996) created a formula to calculate a possible vertical extension of the periglacial belt. The input variables are the MAAT at the height of the equilibrium line altitude and an air temperature gradient, the output is the vertical extension.

French (2017) generalised the approach by defining the periglacial environment with climate variables. By only using the MAAT, a definition of the periglacial conditions is presented. Wherever the MAAT is lower than -3°C , periglacial conditions are prevailing and frost is dominating. Conditions with MAAT between $+3^{\circ}\text{C}$ and -3°C can have frost-action processes which do not necessarily dominate.

This approach makes it possible to estimate periglacial environments in a large-scale, but due to the few input parameters, the approach is not very accurate. It only gives a rough estimate due to missing influencing parameters like aspect, surface characteristics, radiation balance and the thickness and duration of the seasonally snow cover.

Figure 2.2 illustrates the limits of the periglacial zone. It is clearly visible that a strict limitation is not suitable due to the highly heterogeneous topography and the orientation. The distribution of frozen ground has many influencing factors. It depends on elevation, temperature, aspect, local topography, snow regime and subsurface characteristics (Biskaborn et al. 2019; French 2017; Roer 2005). Thus, different properties influence the micro-climatic conditions which vary considerably at small scales in alpine terrain (Stocker-Mittaz, Hoelzle, & Haeberli 2002). As a

2.3. Permafrost

result, these properties can also vary within local scales, for example, the distribution of snow cover is not only dependent on local precipitation, but also on wind drift and surface properties.

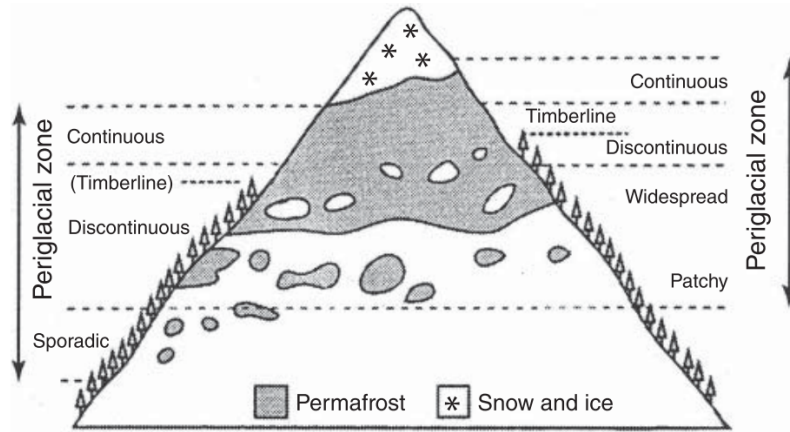


Figure 2.2: Schematic illustration of the periglacial zone in a mountain system. The left side of the mountain is north exposed, the right side is south exposed (from French (2017): p. 4).

2.3 Permafrost

Permafrost is a state of frozen ground if lithospheric material remains at or below 0°C for at least two consecutive years (e.g. Biskaborn et al. 2019; PERMOS 2023; Zepp 2014). Thus, permafrost is a thermally controlled phenomenon (Biskaborn et al. 2019; PERMOS 2023; Roer 2005) and only defined on the basis of temperature (Ferrians, Kachadoorian, & Greene 1969). The presence of water in the soil is not a necessity (Ferrians, Kachadoorian, & Greene 1969; Grotzinger & Jordan 2016). If the ground does not contain water at all, it is defined as dry permafrost (Ferrians, Kachadoorian, & Greene 1969). Permafrost consisting of ice and water can have seasonal variations in the ratio of ice and water. Ice prohibits a deep infiltration of melt water which leads to increased moisture contents (Zepp 2014). Likewise, freeze- and thaw-cycles create typical permafrost patterns. By changing the state of aggregation from water to ice, the volume is increasing by 9% which results in frost heave (French 2017).

Permafrost is subclassified into continuous and discontinuous permafrost. If the MAAT is between -6°C and -8°C , it is continuous permafrost and if the MAAT lies between -1°C and -6°C , discontinuous permafrost is prevailing (Grotzinger & Jordan 2016).

Table 2.1: Probability of permafrost occurrence dependent on BTS (from Hoelzle (1996): p. 13).

	Probability of Permafrost Occurrence
BTS $< -3^{\circ}\text{C}$	probable
BTS $= -2^{\circ}\text{C}$ to -3°C	possible
BTS $> -2^{\circ}\text{C}$	probably no permafrost

Likewise, a division into warm and cold permafrost with mean annual ground temperature is possible. Ground temperatures are measured several meters below the ground surface of permafrost. If the mean annual ground temperature is below -2°C , it is cold permafrost, if the mean annual ground temperature is above -2°C , it is defined as warm permafrost (IPCC 2013).

To differentiate between permafrost of high altitudes and high latitudes, Hoelzle (1996) introduced the names mountain permafrost and polar permafrost. Both forms of permafrost are located in cold regions. In this work, permafrost refers to mountain permafrost.

The BTS can be used as an indicator for the probability of permafrost occurrence (Hoelzle 1996). The BTS describes the temperature below the winter snow cover which exceeds a snow thickness of 0.8 m. The temperature limits of permafrost occurrence and its probability are visible in Table 2.1.

Figure 2.3 represents a temperature profile through permafrost. The lower end of permafrost is called permafrost basis and extends as far down until the temperatures are rising above 0°C due to the heat flow from the Earth’s interior (Grotzinger & Jordan 2016). The upper end of permafrost is labelled as permafrost table and is limited by the maximum penetration depth of the 0°C isotherm (PERMOS 2023). Between the permafrost table and the ground surface is the active layer. The active layer thickness describes the maximum annual thawing depth (PERMOS 2019). Atmospheric conditions and local snow distribution and snow depth influence the active layer thickness (PERMOS 2019). Snow cover creates a surface offset due to its insulating properties (Roer 2005). Surface offset describes the temperature difference between the MAAT and MAGST. The thermal offset specifies the temperature discrepancy between the MAGST and the mean annual temperature at the top of permafrost and results from different thermal conductivity of the active layer (PERMOS 2023). Another important variable is the zero annual amplitude which describes the depth at which seasonal changes in temperature are ≤ 0 to 1°C (Biskaborn et al. 2019).

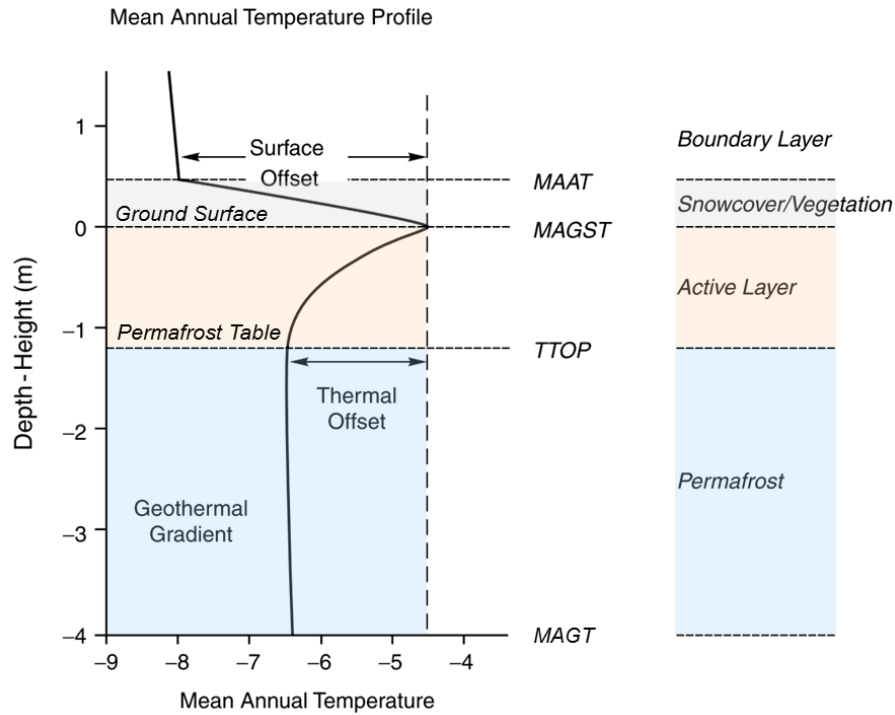


Figure 2.3: Mean annual temperature profile through a permafrost. Modified, after Smith and Riseborough (2002): p. 5.

The distribution of permafrost is highly heterogeneous (Biskaborn et al. 2019). In the Alps, it is a function of topographic and climatic parameters (Keller 1994; Roer 2005). The main factors influencing permafrost occurrence is air temperature (Guglielmin, Worland, & Cannone 2012), thickness and duration of snow cover (Biskaborn et al. 2019; Hoelzle 1996; PERMOS 2023; Roer 2005), direct solar radiation (Hoelzle 1996; Roer 2005) and surface characteristics (Roer 2005).

Mentioning the global extent of seasonally or perennially frozen ground highlights the importance of investigating studies in this field of research. Permafrost covers approximately 24% of the land area in the northern hemisphere (IPCC 2007; T. Zhang et al. 1999). Including the seasonally frozen ground, the long-term average of the maximum extent is 51% of the land area in the northern hemisphere (IPCC 2007; T. Zhang et al. 2003). Thus, frozen ground represents the cryospheric component with the largest extent. However, climate change contributes to increased loss of permafrost areas. More frequent heat waves amplify permafrost thawing (IPCC 2023).

2.4 Rockglacier

First and foremost, the term rockglacier is written as one word to differentiate them from glacial features (Barsch 1992, 1996). Rockglaciers are not glaciers, they are visible expressions of periglacial features and indicate the existence of permafrost (Barsch 1996). Rockglaciers are distinguished into three different kinds: active, inactive and relict rockglaciers. Haeberli (1985) defined active rockglaciers as follows:

Active rockglaciers are the visible expression of steady-state creep of ice-supersaturated mountain permafrost bodies in unconsolidated materials. They display the whole spectrum of forms created by cohesive flows.

Barsch (1996) presented a similar definition, but highlighted the importance of three main characteristics to specify rockglaciers. They are process (1), material (2) and form (3). Process (1) describes the creep of mountain permafrost. The frozen ground is supersaturated with ice, which creates a frost heave due to the volume expansion of ice in comparison to water or pore volume. The deformation of ice, due to gravity driven downslope movement, creates the landform of rockglaciers. The source of the material (2) for rockglaciers are from talus slopes and moraine deposits. Thus, it contains unconsolidated frozen rock fragments, till and debris. The form (3) of rockglaciers are mostly tongue- or lobate-shaped, the surface is characterised by furrows and ridges. The extend is normally restricted by the surrounding topography but it can also be limited by the input of rock fragments or by the inclination.

Active rockglaciers have a distinct appearance. They stand high above the adjacent terrain (at least 10 to 20 m) and their surface is characterized by transverse ridges and furrows, which are bent downslope. Particular large boulders are at the surface, fine material can only be found at the front and side slopes (Barsch 1996). Inactive rockglaciers are similar to actives ones, though nowadays, they do not show movement anymore (Barsch 1996; Ikeda & Matsuoka 2002). However, they still contain permafrost but due to melt processes inducing degradation, the surface starts to subside which decreases the frontal angle of the tongue from around 40° (active rockglacier) to around 35° (inactive rockglacier) (Ikeda & Matsuoka 2002). Relict rockglaciers are past rockglaciers. They consist no longer of ice due to melt. Their surface structures are collapsed, thus their relief is subdued in comparison to active and inactive rockglaciers (Barsch 1996; Ikeda & Matsuoka 2002). The angle of the front at the tongue decreases to values of 30° (Ikeda & Matsuoka 2002).

The distribution of rockglaciers is restricted to climatic conditions. Only low energy input and low precipitation values enables rockglacier formation. Barsch (1996) stated that rockglaciers can only occur at places with MAAT below -1°C to -2°C . Annual precipitation values should not exceed 2500 mm (Haeberli 1983). Thus, the favorable environment for rockglaciers are in dry mountains with low temperatures. Such conditions are found within the periglacial belt (see Section 2.2). Likewise, local relief and microclimatic conditions influence the possibility for rockglacier distribution (Barsch 1996). Local reliefs influence the formation of rockglacier, e.g. talus rockglaciers can only develop below talus slopes.

In the northern hemisphere in mid-latitude mountains, rockglaciers are mainly found in northern exposures from north-west to north-east within the periglacial belt (Barsch 1996).

2.5 Processes and their Parametrisation

2.5.1 Energy Fluxes and Heat Transmission

Energy fluxes define the thermal state of the ground surface. To understand the importance of it, a simple and an extended energy balance model is presented. In section 2.5.2, the influence of seasonality and snow cover is described in detail.

The energy fluxes define the energy balance at the ground surface and thus, the ground surface temperature (Hoelzle 1994). Therefore, the distribution of permafrost is determined by the spatial distribution of the surface energy balance factors and the corresponding thermal conditions of the subsurface (Keller 1994).

The energy balance at the surface is determined by the radiation balance, heat exchange processes at the surface with the atmosphere and ground heat fluxes (Hoelzle 1994; Keller 1994). Surface temperature plays a crucial role, as all involved components depend on it or are influenced by it (Keller 1994). Changes of the MAGST are attributed to site- or climate-specific variations which affects the energy balance. Accordingly, changes of the GST refers to changes of the energy balance components. There exist two regular cycles which are described by daily and yearly repeating patterns of the energy fluxes. Seasonality as well as daily variation results in different amounts of received energy (Hoelzle 1994). Additionally, irregular fluctuations are induced by weather (e.g. clouds), climate, topography (altitude, exposition, mountain shadow, surface roughness) and latitude (length of day) (Hoelzle 1994).

The simple energy balance consists of net short- and long-wave radiation, turbulent fluxes (latent and sensible heat) and ground heat fluxes (Hoelzle 1994; Keller 1994). Equation 2.1 shows the quantification of the energy balance at the earth's surface described by Ohmura and Raschke (2005) with adapted notations.

$$S_{in} - S_{out} + L_{in} - L_{out} \pm Q_H \pm Q_{LE} \pm Q_G \pm Q_M = 0 \quad (2.1)$$

S_{in} , S_{out} are shortwave and L_{in} , L_{out} longwave incoming and outgoing radiation, respectively. Q_H is the sensible heat flux, Q_{LE} the latent heat flux, Q_G the ground heat flux and Q_M the melt energy. Positive signs indicate downward directed radiation which implies energy gain, thus a component which has the ability to heat the surface. Negative signs describes upward directed radiation, thus energy loss (cooling component). Since the direction of turbulent fluxes, ground heat flux and melt energy can be positive as well as negative with time, specific cases have to be defined to clarify their sign. The heat flux changes continuously over time (daily and seasonal) but the sum of the vertical flows (upward and downward directed) remain zero in a steady state over the course of a year (Hoelzle 1994).

At seasonally snow-covered sites, further variables are needed, like the melt energy of snow and the heat flux through the snow cover. Scherler et al. (2014) presented an extended energy balance model which includes the effect of snow and a blocky surface layer. Especially for blocky terrain, they included the net long-wave radiation between the adjacent blocks, the melt and freezing energy within the active layer and the permafrost table as well as the heat storage change. All these parameters influence the energy balance additionally.

The net short- and longwave radiation is dependent on slope angle and exposition (Hoelzle 1994). Furthermore, surface roughness and shadow caused by the shape of the blocks and surrounding terrain can change the radiation density (Scherler et al. 2014). Additionally, the radiation is influenced by the surface albedo. The net shortwave radiation has large spatial and temporal variability. The net longwave has less spatial and temporal variability. It is mainly dependent on the temperature and the emissivity (Hoelzle 1994). Thus, the duration of snow cover is of great importance due to the determination of the albedo (Hoelzle 1994).

Turbulent fluxes consist of latent and sensible heat fluxes. Latent heat is the energy, which is needed or discharged by changing the state of aggregation but without any change of temperature. By transforming ice to water (melt), water to water vapour (evaporation) or ice to water vapour (sublimation), energy is needed. If water vapour or water condensates or freezes, respectively, energy is released. Likewise, if water

vapour directly transforms to ice (deposition), energy is set free. These energy requirements or releases are referred to as latent heat. If the temperature is around the melting point, energy is dedicated for melt and latent heat leaves the environment in form of melt water. Melt, evaporation and sublimation results in lower temperatures in comparison to environments which do not have water available. Latent heat adsorbed in these processes cools the environment (Harris & Pedersen 1998). The sensible heat flux conducts to a temperature change. It correlates with the incoming longwave radiation and thus, with the air temperature. Thereby, the sensible heat flux is influenced by the radiation properties of the ground surface, the heat conductivity of the upper soil layer, altitude and topography (Hoelzle 1994). Both turbulent fluxes are dependent on wind speed and surface roughness. The greater the wind speed and surface roughness, the greater the turbulence, and thus, the greater the mixing of the airmass. In addition, wind is important during snow-free periods due to its ability to increase the turbulent fluxes, which can have large impacts on the temperature. If the air from the ground is directly exchanged with the atmosphere, the temperature change is almost instantaneously (Harris & Pedersen 1998).

The ground heat flux is dependent on the heat conductivity of the soil, thus tributary on the properties of the soil and its composition (ratio of soil, water, ice and air) (French 2017).

The melt energy is important during melt periods. It causes a stabilisation at 0°C at the surface during melt (see section 2.5.3) (Hoelzle 1994).

Convection, advection and conduction are processes of heat transmission, thus important to describe energy fluxes. Convection, or convective process, specifies the transport of energy by a fluid (Wicky & Hauck 2017). It is also referred to as the Balch effect (Harris & Pedersen 1998; Scherler et al. 2014). Due to the temperature dependent densities of air, cold and dense air can displace warmer air within voids of coarse material. Internal air circulation within the upper ground layers can have a cooling effect (Keller 1994). In summer, during periods with high amount of incoming solar radiation, air temperatures at the surface are increasing. Due to the higher temperature of the air, the density is smaller than from the air within the voids. Thus, the warmer air cannot penetrate into the rockglacier. This behaviour results in an insulating effect due to air-filled voids in coarse deposits (Barsch 1996; Haeberli et al. 2006). In section 2.5.4, a special case of convection is described.

Advection, or advective process, describes continuous air exchange between the voids and the atmosphere (Harris & Pedersen 1998).

Conduction refers to the heat transfer by a medium. In the case of periglacial environments, conduction describes the water flow between the blocks (Scherler et al. 2014).

2.5.2 Comparison of Energy Fluxes in Summer, Autumn and Winter

Energy fluxes, thus the incoming and outgoing energy, vary within a year. Figure 2.4 visualises the difference between the seasons and the effect of different snow cover thicknesses.

In summer, when no snow covers the ground, the net radiation is highly positive (Gustafsson, Stähli, & Jansson 2001; Hoelzle 1994; Marks & Dozier 1992). Strongly positive net radiation results from increased receiving solar radiation during summer months in the Alps. The lower albedo of rocks in comparison to snow results in increased absorption of shortwave radiation.

Ice in the active layer is exposed for melting, creating an energy flux directed towards the surface. But meanwhile, cool nights and decreasing temperatures, like in late summer, can cause an opposite direction of latent heat flux. The importance of latent heat flux in coarse rocks over permafrost is not clear yet. Hoelzle (1994) mentioned a reduced importance due to the fast runoff induced by the high porosity.

The direction of the sensible heat flux depends not only on seasonality, but also on daily variation. Sensible heat fluxes are only present if there exist a temperature gradient and they point towards the balancing direction. Temperature gradient can be created by radiation or latent heat fluxes, thus it depends on incoming longwave radiation and air temperature. Due to the highly variable weather appearance and incoming radiation, the direction of the sensible heat flux varies in summer (Hoelzle 1994). Generally spoken, the sensible heat flux is large if there is no or only little water available due to the increased energy available which is not consumed by the latent heat flux.

Advective fluxes are negative in summer, discharging the energy surplus of the net radiation. In winter, they are positive, and compensate the energy deficit (Mittaz, Hoelzle, & Haeberli 2000).

Ground heat fluxes are positive when meltwater starts penetrating into the still frozen ground (Mittaz, Hoelzle, & Haeberli 2000) resulting in heat input (Hoelzle 1994).

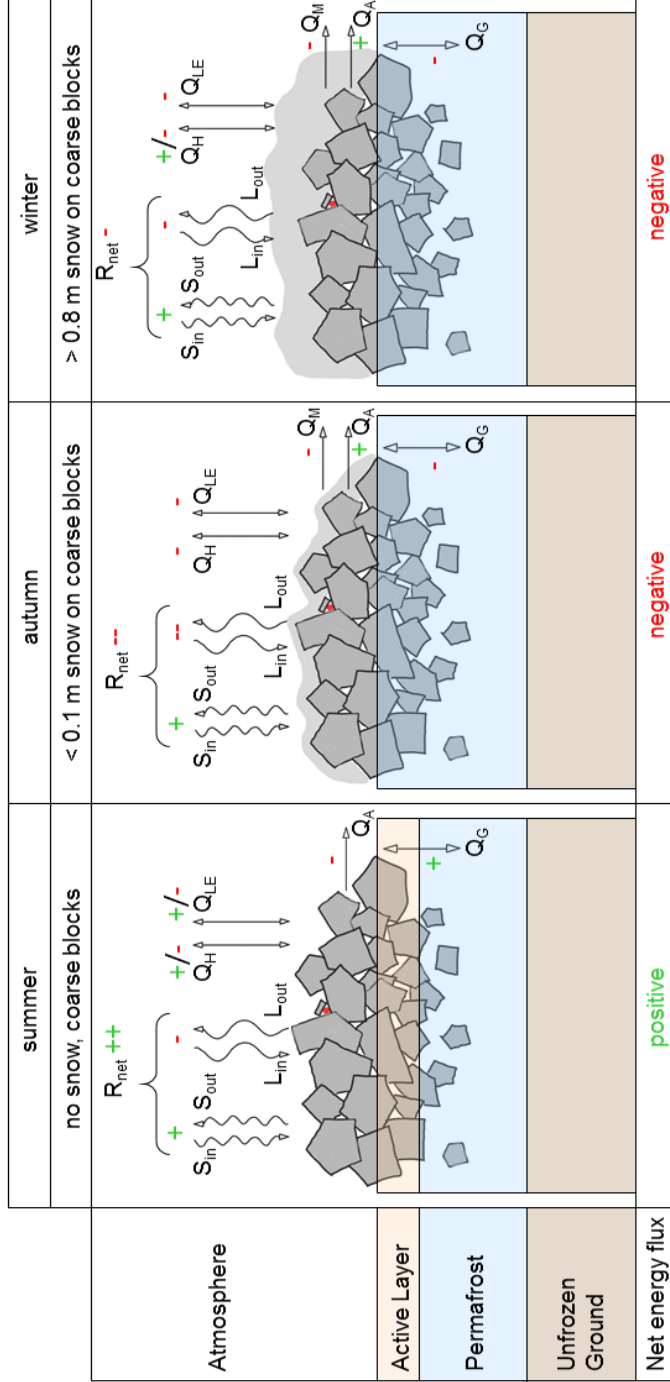


Figure 2.4: Energy fluxes in different seasons on coarse blocks, coarse blocks with < 0.1 m snow cover and coarse blocks with > 0.8 m snow cover. Positive energy fluxes (represented with $+$) indicate the direction towards permafrost, thus, energy gain due to absorption. Negative energy fluxes (represented with $-$) display the direction from permafrost away, hence, energy emission. If there are two plus or minus, the direction is strongly positive or negative, respectively. If the net energy flux is positive, more energy is absorbed than emitted. If it is negative, more energy leaves the system than can be absorbed. S_{in} , S_{out} are shortwave and L_{in} , L_{out} are longwave incoming and outgoing radiation, respectively. R_{net} describes the net radiation. Q_H is the sensible heat flux, Q_{LE} the latent heat flux, Q_G the advective flux, Q_A the ground heat flux and Q_M the melt energy. The red dot within the layer of coarse blocks represent a temperature logger, measuring the GST. Own graphic, data from Cline (1997), Gustafsson, Ståhli, and Jansson (2001), Hoelzle (1994), Marks and Dozier (1992), Mittaz, Hoelzle, and Haerberli (2000), and Sade et al. (2014).

If snow falls on coarse blocks, the thickness of the snow cover defines the direction of individual energy fluxes. If the snow cover has a thickness of < 0.1 m, the greatest difference to no snow or snow cover > 1 m results by the net longwave radiation. This generates a strongly negative energy flux and creates a net radiation which is as strongly negative, indicating an intense ground cooling (Keller 1994). The latent as well as the sensible heat fluxes are both negative, resulting from the decreasing temperatures and the increased importance of the latent heat flux due to the increased water availability. If there is enough energy to melt the snow, melt water and thus melt energy can leave the system (Hoelzle 1994; Sade et al. 2014). In this case, the net energy flux is negative (Mittaz, Hoelzle, & Haeberli 2000).

If the snow cover thickness is > 0.8 m, the insulating effect of the poorly conductive snow layer exceeds the cooling effect of the thin snow cover (Hoelzle et al. 2001; Luo, Jin, & Bense 2019). The net longwave radiation is still negative but does not suppose as small values (Sade et al. 2014). Likewise, the effect of sensible heat flux can have opposite directions. Gustafsson, Stähli, and Jansson (2001) and Mittaz, Hoelzle, and Haeberli (2000) mentioned that the sensible heat flux is an energy loss for the system. On the other hand, Cline (1997), Hoelzle (1994), Marks and Dozier (1992), and Sade et al. (2014) stated that it is an energy source. Thus, the pointing direction is difficult to determine and has to be evaluated individually for each specific case.

The net energy flux is also negative for a thick snow cover, but the energy loss is not as big as for a thin snow cover (Gustafsson, Stähli, & Jansson 2001).

2.5.3 Zero Curtain Effect

The Zero Curtain (ZC) effect describes periods of phase change and can be explained with the latent heat (see section 2.5.1). Hence, the temperature maintains around 0°C over extended periods on freezing or thawing soils (Outcalt, Nelson, & Hinkel 1990) and can be referred to as melting period. Periods with rising temperatures forces the melting of snow on a frozen ground, which mostly takes place during spring (Staub & Delaloye 2017). In autumn, melt of fresh snow on still unfrozen ground occurs in basal melting (Staub et al. 2017). During phases with decreasing temperatures, ground freezing induce a ZC. Likewise, when rain falls on snow, the water percolates through the snow and can refreeze at the bottom (Staub & Delaloye 2017). Gently inclined slopes, which favour snow accumulation, can have a distinct ZC. Steep rock walls or windblown locations show weak or no ZC. Generally, they follow the air temperature variations (Staub et al. 2017).

2.5.4 Chimney Effect

Porous material, like debris accumulations (e.g. talus slopes), can have internal air circulations which strongly influences the internal temperature regime, thus the presence of permafrost (Delaloye & Lambiel 2005; Morard, Delaloye, & Lambiel 2010; Wicky & Hauck 2017). The chimney effect results from convective heat transfer due to the temperature differences between external and internal air of periglacial structures (e.g. Wicky & Hauck 2017). The direction of flow within the debris accumulation depends on the seasonality (Morard, Delaloye, & Lambiel 2010; Wicky & Hauck 2017).

In summer, cold air from top of the slope descends due to the higher density of cold air in comparison to warm air. This comportment is only possible if the external air temperature is higher than the internal air temperature (Delaloye & Lambiel 2005). This results in a gravity driven discharge of cold air at the foot of the debris accumulation. Thus, the GST does not rise significantly higher than 0°C in this area (Morard, Delaloye, & Lambiel 2010) preventing the accumulation of vegetation (Delaloye & Lambiel 2005). In the upper part of the slope, warm air is aspirated.

In winter, the direction of the circulation is inverted. Warm air from the internal structures of the talus slopes ascends, and exits through melt holes in the snow cover, so-called funnels, at the top of the slope. This creates a suction at the foot of the slope which aspirates cold air from the environment, creating a cold reservoir within the scree (Delaloye & Lambiel 2005).

Snow cover on top of debris does not prevent the air to circulate, the air can flow through the pores of the snow. Thus, if the snow cover is porous, it has an insignificant role by considering the chimney effect (Morard, Delaloye, & Lambiel 2010).

The ventilation system has its origin due to phase change of water within the ground (Delaloye & Lambiel 2005) and by the advective energy fluxes (Morard, Delaloye, & Lambiel 2010). Both influence the thermal regime. Large differences between the internal and the external air temperature result in distinct chimney effects (Morard, Delaloye, & Lambiel 2010; Wicky & Hauck 2017). Additionally, if the voids between the blocks have a high connectivity, the effectiveness is high (Wicky & Hauck 2017). The internal air circulation is mostly influenced by the winter air temperature, whereas the summer air temperature and the snow depth have far less influence (Morard, Delaloye, & Lambiel 2010).

At sites with chimney effects, the GST depicts the direction and intensity of the flow when comparing it with the air temperature. If the GST and the air temperature are similar, an aspirating regime is assumed (winter phase). If they differ signifi-

cantly, an expelling phase may be assumed (summer phase) (Morard, Delaloye, & Lambiel 2010). In addition, the GST differs from periglacial features which are not influenced by the chimney effect. Generally, the chimney effect results in decreased GST in comparison to conventional permafrost situations in high altitude (Morard, Delaloye, & Lambiel 2010). Delaloye and Lambiel (2005) stated that a chimney effect may be possible in an inactive or relict rockglacier, depending on the ice content. Low ice content and high porosity favours the creation of a chimney effect. The limiting factor is the capacity for air to circulate.

2.5.5 Snow Cover and Surface Offset

The development of snow cover is highly variable in space and time, it depends on precipitation patterns and is locally influenced by wind, avalanches and radiation (e.g. Gubler et al. 2011; Haeberli et al. 2010; Staub & Delaloye 2017). Strong winds forces snow drift which redistributes snow and thus has the ability to accumulate large snow heights in hollows and bare-blown open areas (Gisnås et al. 2014).

Snow has a high albedo, reducing the incoming shortwave radiation. Hence, it influences the radiation balance at the surface (Gisnås et al. 2014; Hoelzle et al. 2001; Staub & Delaloye 2017). Likewise, snow has a high emissivity, which changes the energy balance of the longwave radiation (Keller 1994).

Snow cover has a low thermal conductivity. Thus, it has the ability to insulate the ground surface from the atmosphere (e.g. Gisnås et al. 2014; Hoelzle et al. 2001; Staub & Delaloye 2017). Especially newly fallen snow has a low thermal conductivity due to low density. With an increasing age of snow, the density increases as well as the thermal conductivity. At a snow height larger than 0.8 m, the ground is effectively insulated from the atmosphere (Haeberli 1973; Keller 1994). Decoupling the surface from the atmosphere influences the thermal regime of the ground (Gisnås et al. 2014) and is substantially dependent on the snow height and density (Keller 1994). In high mountain environments in the Swiss Alps, heat fluxes decrease continuously from January to spring. Once the thermal resistance of a snow depth > 0.8 m is reached, the heat flux fluctuates only minimally even with large changes in air temperature (Keller 1994).

Early snow fall in autumn can have two opposite consequences, depending on the amount of snow. Accumulation of a thick snow cover (> 0.8 m) in autumn prevents the ground from cooling down, resulting in higher GST than without snow cover (Keller 1994). The insulating snow cover has thus an unfavourable effect on permafrost. The stored summer heat in the active layer cannot leave because the

temperature gradients, thus the heat flows, are too small (Hoelzle 1994; PERMOS 2023).

No or only a thin snow cover in autumn enables a cooling of the ground in cold periods (Marmy et al. 2013). A thin snow cover of around 5 cm results in the largest emission of energy in comparison to thick snow covers (> 0.8 m) or no snow (Keller 1994). The heat loss through the emission of longwave radiation prevails the insulating effect of snow cover. This leads to strong cooling of the upper ground layers. This correlation is referred to as the early autumn snow effect. Thus, the accumulation (timing and thickness) of snow in autumn is an important influencing factor on interannual GST variations (Marmy et al. 2013; Staub & Delaloye 2017). In spring, long-lasting and thick snow covers prohibit a warming by sheltering the surface (Hoelzle et al. 2001; Keller 1994). During this season, snow has its maximum insulating effect although old snow has a thermal conductivity of almost three times higher than new snow (French 2017; Johnston 1981; Williams & Smith 1989). Large snow thicknesses compensate the higher thermal conductivity which results in a lower thermal conductivity (Keller 1994).

Hence, the timing of the first snow fall, accumulation of a snow layer > 0.8 m and the duration of the snow cover as well as snow melt strongly influences the thermal regime (e.g. Goodrich 1982; Marmy et al. 2013; Staub & Delaloye 2017; Stocker-Mittaz, Hoelzle, & Haeberli 2002).

Snow melt is not only influenced by radiation but also by the refreezing of melt water within the snow pack and the percolation of water into the snow from rain or surface melt (Staub & Delaloye 2017).

Snow cover influence the local GST and generates a so-called surface offset (indicated in Figure 2.3). The surface offset describes the temperature difference between the MAGST and the MAAT (PERMOS 2019). Accordingly, seasonal variations of snow cover results in a strong interaction with the ground thermal conditions (Stocker-Mittaz, Hoelzle, & Haeberli 2002) and can be described with the surface offset.

2.5.6 Bulk Effect

In snow free periods, like it occurs in late spring and summer, the most important influencing factor on GST is air temperature (Guglielmin, Worland, and Cannone (2012), see section 2.5.7). However, other properties, like shading effects, terrain and subsurface properties describe the remaining spatial variability and should not be neglected (Staub et al. 2017).

Subsurface properties can be described by the bulk density, porosity, moisture con-

tent, degree of saturation and thermal conductivity. Each soil is composed of soil particles, water and air. By varying the amount of the composition, different soil properties prevail.

The bulk density describes the specific weight of the soil and is defined by the total weight divided by the total volume (French 2017). The porosity describes the ratio between the volume of voids and total volume of the soil sample (French 2017; Hendriks 2010). The moisture content is dependent on the porosity. The smaller the voids between particles, the greater are the capillary forces, thus, the more water remain in the soil. In turn, this influences the degree of saturation.

The thermal conductivity depends on the type of the prevailing soil, moisture and ice content (R. Li et al. 2019). Additionally, a temperature gradient is needed (French 2017). Due to the fact that the analysed rockglaciers are composed of the same lithology, the thermal conductivity of the soil can be neglected. This reduces the thermal conductivity to the amount of water, ice and air in the soil. Table 2.2 shows the thermal conductivity dependent on material. The thermal conductivity of ice is approximately four times larger than the one of water and approximately 90 times larger than the one of air. Thus, it is strongly dependent on the variation of soil moisture, ice content and snow cover (French 2017; R. Li et al. 2019).

During a year, distinct patterns due to seasonality can be seen. High thermal conductivities prevail in winter, when the water within the soil is frozen and the ground surface is covered with snow. Low values are found if the pores are filled with water or air, thus in spring or summer (Goodrich 1982). Hence, the thermal conductivity during freeze and thaw cycles can control the energy and moisture exchange between the atmosphere and permafrost (R. Li et al. 2019) and influences the depth of the zero annual amplitude (French 2017). Hoelzle (1994) stated that the soil heat flux is primarily dependent on the thermal conductivity.

At the surface, large blocks and boulders are the main prevailing grain size. With increasing depths, the grain size decreases. At the permafrost table, fine-grained material is predominant (Haeberli et al. 2006). Thus, an increasing gradient of the bulk density from the surface to the permafrost table is defined. Between the blocks, large voids are present which are filled with water, air or snow, dependent on the season. Normally, water percolates to deeper soil horizons and to smaller pore sizes, where the capillary force is strong enough to hold water within the pores. Voids filled with air or snow reduce the thermal conductivity, prohibiting an interaction between the permafrost and the atmosphere (Haeberli et al. 2010; T. Zhang 2005). The effect of a disconnection by snow is larger than by air due to its persistence

(French 2017). Water remaining or leaving the system determines the thermal conductivity as well as the latent heat effect (see section 2.5.1 and 2.5.3).

The stability of permafrost depends on temperature, loading and deformation rate (Nickling & Bennett 1984). Thus, the stability of slopes with unlithified material and permafrost can vary with time. The internal ice content as well as the structural interaction between the soil particles in the frozen ground define the prevailing stability (Haeberli et al. 2010). Hence, increasing temperatures force a thawing of ice which has a major influence on slope stability. With decreasing temperatures, the strength of frozen ground increase. The strength of frozen soils is higher than the strength of unfrozen material due to the cohesion contribution from the ice matrix (Haeberli et al. 2010). Additionally, an increase in ice content in frozen soils enhance the shear strength until a certain critical point, where the behaviour changes its pattern to the opposite (Nickling & Bennett 1984). Hence, the temperature as well as the ice and water content are important quantities for determining the stability of permafrost bodies.

Table 2.2: Thermal conductivity of selected materials. Modified table section from N. Zhang and Wang (2017), data from Bejan and Kraus (2003), Johnston (1981), and Williams and Smith (1989).

Materials	Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
Air (10°C)	0.024
Water (25°C)	0.605
Ice (0°C)	2.23
Fresh snow	0.2
Old snow	0.55
Scree (wet)	1.5
Scree (dry)	0.6

2.5.7 Ground Surface Temperature

The GST is a quantity which is simple to measure. Nonetheless, many processes, influencing factors and parameters can be earned by analysing the GST. The GST results from the energy balance at the ground surface (PERMOS 2023). Hence, measuring the GST provides information about the thermal conditions at the surface. The energy balance, thus the GST, is influenced by the atmospheric conditions (PERMOS 2019), snow characteristics (e.g. Luo, Jin, & Bense 2019; PERMOS 2019;

(Staub et al. 2017) and topography (Luo, Jin, & Bense 2019; Staub et al. 2017) as well as by the elevation and surface properties (Luo, Jin, & Bense 2019). The timing of the first snow fall in autumn, the duration and thickness as well as the time when the ground becomes snow free are relevant (PERMOS 2019).

Fluctuations of GST follows the daily variation of air temperature during snow free periods (Guglielmin, Worland, & Cannone 2012) (Figure 2.5). The spatial variability of GST results from radiation discrepancy, topography (e.g. shading effects, terrain) and subsurface properties (Staub et al. 2017). Large interannual variations can be found at sites which are less influenced by snow (e.g. ridges or steep rock walls) or coarse, blocky or porous ground material, which favours convection (Gisnås et al. 2014; Staub et al. 2017) (see section 2.5.1). These situations can result in an intense ground cooling (Staub et al. 2017).

Surface properties have an impact on GST during the entire year. The surface roughness influences the accumulation of snow in winter, the creation of wind driven turbulence and further circulations like chimney effects (Delaloye & Lambiel 2005; Wicky & Hauck 2017) as seen in section 2.5.4. Different time series of GST depend more on topography and snow characteristics than spatial proximity (Staub et al. 2017).

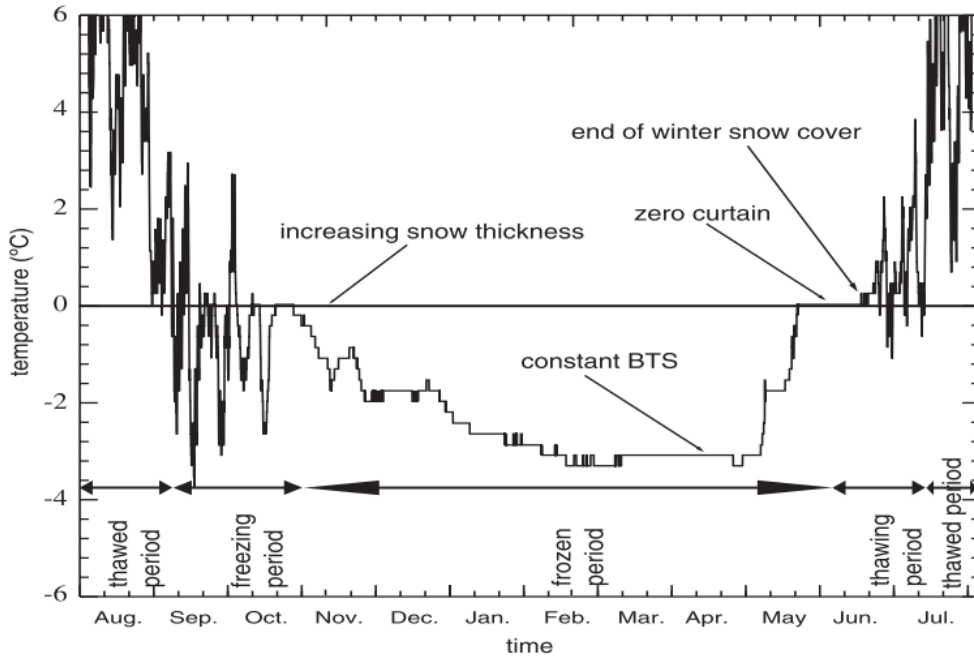


Figure 2.5: Typical annual GST trend from permafrost in the Alps. Characteristic trends are highlighted (from Hoelzle, Haeberli, and Stocker-Mittaz (2003), p. 419).

2.5.8 Bottom Temperature of the Winter Snow Cover

The concept of the BTS was developed by Haeberli (1973). Since then, many studies and measurements were conducted (e.g. Hoelzle 1992; Roer 2005; Schoeneich 2011) to confirm the statements and for further research.

Measuring the BTS enables detection of permafrost distribution (Haeberli 1973; Haeberli & Patzelt 1982; Hoelzle, Haeberli, & Stocker-Mittaz 2003; Hoelzle 1992) (see section 2.3). The BTS describes the ground surface temperature below a thick enough snow layer. It is restricted to sites and time periods with a snow cover larger than 0.8 m of thickness (Haeberli 1973; Hoelzle, Haeberli, & Stocker-Mittaz 2003; Hoelzle 1992; Keller 1994). Thus, this condition is normally given in spring in the Swiss Alps, roughly from February to April (Haeberli & Patzelt 1982). Under this thick enough snow layers, the BTS remains constant if the melting period is not yet reached (Hoelzle 1992). If the snow layer is less than 50 cm, the fluctuations of the BTS are large in comparison to snow layer thicknesses of around 1 m due to the daily variation of air temperature (Haeberli 1973). Thus, the BTS reflects the thermal state of the ground below (Haeberli 1973; Hoelzle 1992; Roer 2005).

The determining factor is primarily the heat flux from the upper ground layers (Haeberli 1973; Haeberli & Patzelt 1982; Hoelzle 1992). Hence, Hoelzle (1992) described that the BTS is a function of the MAGST, which is a function of the different heat fluxes (net radiation, latent and sensible heat, melt and ground heat flux) as described in section 2.5.1.

Continuous measurements of BTS provides parameters such as the snow cover duration, the length of the ZC period, the onset of meltwater percolation, the duration of ground freezing and thawing as well as the mean annual, seasonal or daily GST (Hoelzle, Haeberli, & Stocker-Mittaz 2003). Figure 2.5 illustrates a typical annual GST recording from permafrost in the Alps which highlights characteristics of the GST and BTS.

2.5.9 Ground Freezing and Thawing Indices

The GFI and the GTI are dimensions to quantify how cold or warm a year was at the ground surface (PERMOS 2019). It describes the annual sum of all days with a negative (GFI) or positive (GTI) GST.

The more negative the value of GFI, the more days had a negative GST. Also, the magnitude of the cold season is represented. Very low GFIs indicate a cold season. The same is valid for the GTI but with positive GST. Thus, the size of

2.5. Processes and their Parametrisation

these indices can give information about the duration of an insulating snow cover (PERMOS 2019). Hence, they are indicators of climate change (Frauenfeld, Zhang, & McCreight 2007). Analysing the freezing and thawing indices can provide findings about the changes of the thermal regime of permafrost (Luo et al. 2014).

3. Methods

3.1 Field Measurements

The first measurement of this 22 year long time series started in autumn 2001. The motivation of the GST monitoring was predicated on different projects and served the basis for the dissertation by Isabelle Gärtner-Roer (Roer 2005). The funding depended on running projects and was later handed over to the PERMOS Monitoring Strategy. Due to missing funding in 2008/09, no data retrieval took place.

The data retrieval always occurred in autumn (September to October) each year since 2001, when the first loggers were distributed. The data retrieval follows the course of hydrological years, which lasts from the 1st of October to the 30th of September.

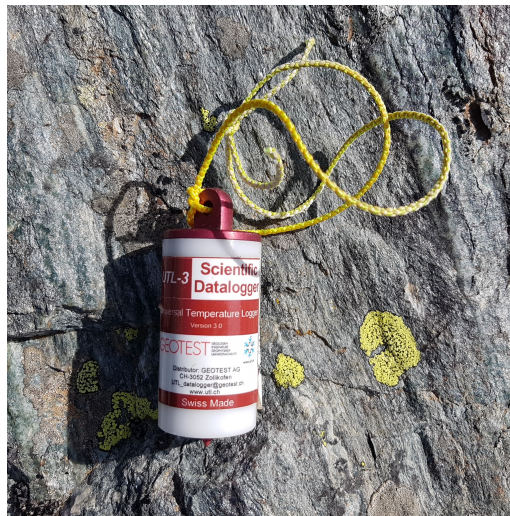


Figure 3.1: Scientific Datalogger (UTL-3) from GEOTEST.

For measuring the GST, Universal Temperature Loggers (UTLs) were used (Figure 3.1). UTLs are powerful miniature data loggers for temperature measurements and logging. The UTL series, UTL-1, UTL-2 and UTL-3, whereupon the current data logger on the market is the UTL-3, are developed by GEOTEST and the Institute for Snow and Avalanche Research (SLF) in Switzerland. Each UTL consists of a small, robust body and lid which locks the body with a screw top.

The following characteristics are valid for UTL-3 and can be found at the webpage

of GEOTEST (2023). Due to their reliable and robust construction, they can measure a temperature range between -30°C and $+40^{\circ}\text{C}$ with an accuracy of $\pm 0.1^{\circ}\text{C}$ at $\pm 20^{\circ}\text{C}$ and $\pm 0.2^{\circ}\text{C}$ at $\pm 40^{\circ}\text{C}$. The data resolution is $< 0.1^{\circ}\text{C}$. The used thermistor in the UTL-3 is YSI 44005 with a typical thermometric drift for $0^{\circ}\text{C} < 0.001^{\circ}\text{C}$ in 100 months. They can collect up to 65'000 data points. The device is running on provided batteries, which have a life time of up to three years.

The UTL-1 and UTL-2 data loggers were the former loggers. They have an operating range between -29°C and $+39^{\circ}\text{C}$ with an accuracy of $\pm 0.1^{\circ}\text{C}$ within the working range. The data resolution is 8 bit, hence, the data is only stored with a resolution of 0.27°C . Thus, the resolution of the UTL-3 ($< 0.1^{\circ}\text{C}$) is prominently improved. The used thermistor for both, UTL-1 and UTL-2, was TMC-1T and the loggers run with a lithium cell lasting for approximately two years.

As measurements began in 2001, UTL-1 were used. In 2015, the first UTL-3 were distributed in the field. However, up to September 2017, some UTL-1 were still in service. From October 2017 up to now, only UTL-3 are in usage. The data loggers were changed to a newer model because the production of the used batteries in the UTL-1 was abandoned. Also, in certain places, the loggers were not detectable anymore in the field. In these cases, the loggers were partially replaced, dependent on the decision if the current location is reasonable to continue. The batteries were changed regularly to prevent data gaps.

The thermistors were all placed as similar as possible. The optimal location is as follows, whereby not all data loggers had the opportunity to be placed like this. Large rocks with sizes $> 2\text{ m}$ were not as sensitive to movement thus only changing their position slowly. The data loggers were placed on the site of big rocks in down slope direction so that they are protected from rocks which may overrun them. Additionally, the chosen place should be in the sun as rarely as possible. Thus, they are mostly situated within a small trough or next to larger rocks which shade the place. Each thermistor is attached with a thin cord to a rock with a width of about 20 to 30 cm. The UTLs are not buried into the ground, they are only placed on the ground with the attached rock on top of it. The height of the rock is mostly around 10 cm. In Figure 3.2, (a) an example of ideal placement is visible, in Figure 3.2 (b), a less ideal placement is shown due to a long exposition to the sun. Figure 3.2 (c) shows how the thermistors were attached to a stone and in Figure 3.2 (d) is visible how the data loggers are placed below the attached stone.

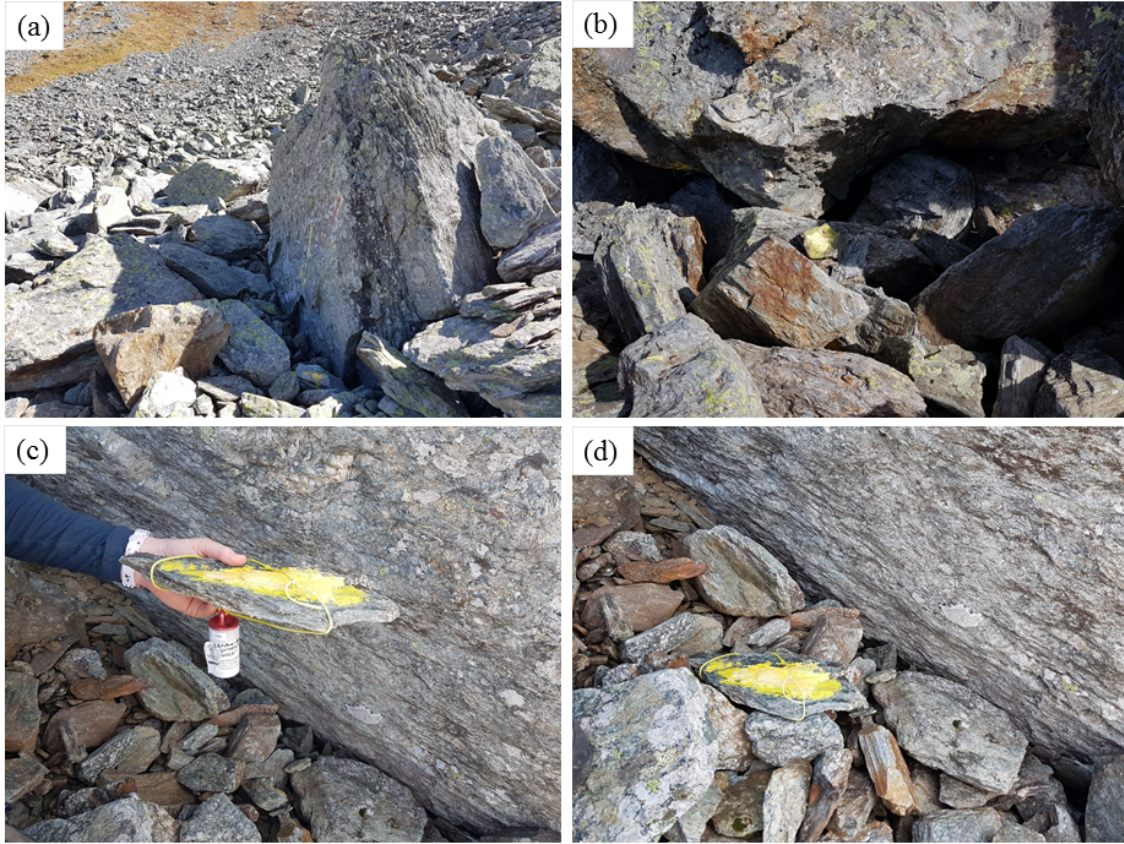


Figure 3.2: (a) Ideal placement of a data logger in front of a big rock in down slope direction. (b) Unfavourable placement of data logger due to direct sun light and no protection of a big rock. (c) Data logger attachment. (d) Placement of data logger.

Each year at the beginning of October, besides 2008, the loggers are read out. In the first few years (from 2001 to 2006), the loggers were launched in the office or in the field before they were placed to their measurement locations. Locations that were already equipped with loggers in the previous year, were mostly replaced with a newly launched logger. Since 2006, in the majority of cases, the data was directly read out in the field. The loggers got connected to a field computer to store the data files. The data on the loggers was then deleted due to the limited storage capacity. Then, they were again placed at the same site as in the previous year. Thereby, the measurement gap during data retrieval was reduced to a minimum. Only if the data loggers did not measure continuously to the end of a measurement period, data gaps occurred.

3.2 Data Specification

The data loggers were placed on two active rockglaciers (Huhh1 and Huhh3) and on an inactive rockglacier (Huhh2) as well as at a moraine at the east side of Huhh1 in the Hungerlitelli. The data acquisition took place continuously from autumn 2001 up to today besides the hydrological year 2008/09. In autumn 2008, no loggers were distributed in the field. Thus, there is a data gap from the 1st of October 2008 to the 30th of September 2009. All other years have at least one logger per landform. On rockglacier Huhh1, the amount of loggers per hydrological year varied between 1 and 15 loggers. The minimal amount of loggers covering rockglacier Huhh1 was in the hydrological year 2005/06 with only one logger. From 2014 to 2017, only two loggers represented the data gathering of Huhh1. Years 2002 to 2004 were covered with the highest amount of loggers with up to 15 loggers. Since October 2017, 7 loggers are distributed on Huhh1.

On rockglacier Huhh3, 2 to 10 loggers were distributed over time. Huhh3 had the fewest loggers in the hydrological year 2006/07 with 2 loggers. 2003/04 represents the year with the maximum amount of loggers distributed on Huhh3 with 10 loggers. From October 2017 up to October 2023, the amount of loggers stayed continuously at 6.

The inactive rockglacier Huhh2 only had up to a maximum of 3 loggers per hydrological year. Several hydrological years are not covered with data loggers (2001/02, 2004/05, 2005/06, 2008/09, 2014/15 and 2015/16). Since October 2016, one logger continuously represents the data gathering for Huhh2.

Due to rockfall or movement of the rockglaciers, several UTL were overrun by rocks, buried or lost. Thus, the number of loggers changed over time.

In addition to the rockglaciers, up to 12 loggers were placed at a moraine at the east side of Huhh1. The data recording on the moraine was between 2002 and 2008 with a data gap in the hydrological years 2005/06 and 2006/07.

A complete table describing the quantity of loggers per hydrological year can be found in the appendix A.1. For detailed information about the location of the loggers, see section 4.1.

3.3 Data Screening

The analysis was done with RStudio (R version 4.3.0), Excel (Microsoft Office Home and Student 2013) and QGIS (Version 3.32.3).

3.3. Data Screening

The two used generations of UTL-loggers have different output files. The generation of UTL-1 loggers have a ".dtf" file format as output. This file can be converted with the software "UTL Management Tool" provided by GEOTEST (2023) to a text file. Since this software is recommend using Windows XP Service Pack 2, an older computer is needed. In addition, if the data files from the UTL-1 loggers are not directly converted with the UTL Management Tool, the standardised output format cannot be transformed easily to a text file format with other software. This is an unfortunate disadvantage since the raw output files cannot be used anymore if the UTL Management Tool is not running. The format of the data file of the UTL-3 generation has the form ".utl" and text file. Thus, when the data from the loggers will be stored on a computer, they will be directly saved as text files. This is a useful improvement since no data format transformation is needed.

The structure of the output files of the UTL-1 and UTL-3 generations differ as well. The output of UTL-1 loggers only contains the information for date, time and temperature, thus reduced to the minimum. If the file name is not chosen appropriate, the data cannot be used anymore since no information about the logger is written within the file. On the other hand, the data screening of those files can directly started with an analysis tool like RStudio because the raw format has a suitable format for further analysis. However, the time is stored to a tenth of a second but the measurement accuracy is limited to seconds. Hence, additional steps are needed to transform the time to a precision of seconds.

The output files of the UTL-3 loggers contain additional information about the project, location, serial number, start and end of sampling date as well as sampling interval and number of total samples within the file. The great advantage of these additional facts besides the sampling time and the temperature is that the information about the logger series number cannot be lost. Additionally, the start and end date can directly be read out as well as the sampling interval. The disadvantage of this format is that the file has to be edited beforehand to reduce the file to the information of sampling date and temperature. Another thing which makes the data screening less efficient is that the column temperature does not have a title. Thus, this has to be added which increases the needed steps to refine the files to an appropriate format.

The design of the data acquisition has changed for most locations since 2006 (see section 3.1). Before 2006, the loggers were not always at their measurement location. The preparation of the used loggers occurred often before field work. Thus, they

3.3. Data Screening

were launched before they were distributed into the field, which needs additional data screening accordingly. The start of measurement does not coincide with the start of distribution onto the field. Hence, these data sets need to be cropped to the start of field measurement. Since the temperature of high mountain environments mostly differ significantly from room temperatures, the data sets can be cropped easily to the actual measurement period without having information about the timing of the field work.

The data was further processed by categorising the years into hydrological years. All data were analysed in the period of hydrological years, which last from the 1st of October until 30th of September. The benefit of this is that it correlates with the timing of the data retrieval. By cutting each measurement period into calendar years, a direct connection between autumn and the subsequent winter and spring does not exist anymore. Especially, the conditions in autumn are very important for analysis due to the dependencies of snow on GST. By analysing the data in hydrological years, the cause (sensitive phase in autumn) and its effect (response of sensitive phase in winter and spring) remain within the same data set.

To prevent including hydrological years with only few measurement observations, the data set is cropped to the hydrological years 2001/02 to 2022/23. Likewise, the data points in the hydrological year 2008/09 were removed due to almost no data.

Because of the variation of the measurement interval (between 1 to 5 hours), the raw GST is aggregated to daily mean Ground Surface Temperature (GST_{day}) values. All analysis and further calculations base on GST_{day} .

By reviewing the measurement accuracy of the data loggers, several logger with temperature drifts were detected. The temperature drift was retrieved by a visual control of GST_{day} over the entire period for each logger during the ZC phase in spring, where it is best developed. The drift occurred only at UTL-1 loggers and they were between -0.31 and $+0.8^{\circ}\text{C}$. The temperature drift seemed to be stable during one measurement period, thus the GST_{day} was adjusted according to the recognised drift by adding or subtracting the value of the drift. For a detailed documentation of temperature drift see appendix A.6.

There was no gap filling routine implemented since the data gaps are small. For at least 319 days per year (87%), data is available, depending on hydrological year

and rockglacier. The count of measurement days and the number of observations for each hydrological year are documented in appendix A.2 and A.3.

3.4 Data Processing

For multi-decennial and inter-annual analysis, the corrected GST_{day} data was used for further analysis.

3.4.1 Thermal Insulation of Snow

Analysing the thermal insulation of snow can give an explanation about the consecutive ZC periods. Being able to classify snow properties into levels of thermal insulation, the period when the ground is covered with snow can be distinguished into sections with no, low or high thermal insulation. However, the used index is not suitable to detect short term snow events like they can occur during summer and autumn (Staub & Delaloye 2017). Nonetheless, for long-term snow events, as it is typical for high mountain environments during autumn, winter and spring, they are useful and suitable to detect the first day with snow in each hydrological year (SOD), the HTI_{start} and the duration of snow cover (Staub & Delaloye 2017).

Staub and Delaloye (2017) proposed three different snow indices to calculate thermal insulation effects of snow. In this study, only one of those three snow indices is used where the input for the snow index is GST_{day} , the formula for it can be seen in equation 3.1. To be able to detect periods with snow, thresholds are needed. The first threshold (th_1) is derived from the 95th percentile of GST_{week} during January to March. This time period was chosen by Staub and Delaloye (2017) because during these months in the Swiss Alps, an insulating snow cover is most likely. The second threshold (th_2) is defined as the 95th percentile of ΔGST_{week} . Both thresholds can differ between periods of higher and lower thermal insulation. Values above the thresholds occur most likely if a thermally insulating snow cover does not exist. The term $GST_{SD\text{week}}$ is used as a variability term. ΔGST_{week} describes the trend of GST over one week. The output values range between 0 and 1, whereas 0 depicts no thermal insulation and 1 maximum thermal insulation. The first date with a snow index > 0 in each hydrological year defines the SOD. The HTI_{start} is initiated by the first value of the snow index which is larger than 0.5 and lasts at least for two weeks. The great benefit of this is that it correlates with the start of a snow depth of around 0.8 m.

$$snowindex[0, ..., 1] = \frac{\left(\frac{-GST_{SDweek}}{th_1} + 1\right) + \left(\frac{-\Delta GST_{week}}{th_2} + 1\right)}{2} \wedge GST_{day} \leq 0.5 \quad (3.1)$$

3.4.2 Zero Curtain Period

To detect the ZC periods, the approach proposed by Staub and Delaloye (2017) was used and can be seen in equation 3.2. The calculation of the ZC are based upon GST_{day} . From the daily means, weekly Standard Deviations (SDs) are calculated in running windows of 7 days aligned at the beginning (GST_{SDweek_prior}) and end (GST_{SDweek_after}) of the period. Due to the thermal resolution of $\pm 0.25^\circ\text{C}$ of UTL-1, a temperature threshold (th_{zc}) with the size of $\pm 0.25^\circ\text{C}$ is included to account for the temperature variation due to the thermal resolution of the measurement devices. During ZC periods, the temperature variation remain constant around 0°C due to phase change of ice. The first part of the equation reviews the size of GST if it is within the range of $0 \pm 0.25^\circ\text{C}$. The second and third part considers the size of the weekly SD at the beginning and end of the period. During ZC periods, the SD should not be greater than the half of the thermal resolution threshold. Hence, if a ZC phase is prevailing, the equation 3.2 prints 1, depicting the presence of a ZC period. Otherwise, zero describes that there is no ZC period due to GST values above 0.25°C or below -0.25°C or large weekly SD.

$$ZC = \begin{cases} 1 & \text{if } |GST_{day}| \leq th_{zc} \wedge \left(GST_{SDweek_prior} \leq \frac{th_{zc}}{2} \vee GST_{SDweek_after} \leq \frac{th_{zc}}{2} \right) \\ 0 & \text{if } |GST_{day}| > th_{zc} \vee GST_{SDweek_prior} > \frac{th_{zc}}{2} \vee GST_{SDweek_after} > \frac{th_{zc}}{2} \end{cases} \quad (3.2)$$

3.4.3 Mean Annual Ground Surface Temperature

The MAGST describes the mean value of all GST_{day} for each hydrological year. Since every hydrological year have data for at least 87% of all days of the year (if calculated for each rockglacier), the MAGST was calculated for every year. PERMOS (2023) used the data for further analysis if the data have at least 85% after gap filling. On a regional scale, most hydrological years have measurements on 365 or 366 days per year (17 out of 22 years). Less measurements with 326 (89%), 333 (91%), 336 (92%) or 363 (99%) days occurred in the hydrological years of 2001/02, 2007/08, 2009/10 and 2015/16 respectively. Hence, no gap filling was implemented since sufficient

data is available. Only few measurement days are recorded in 2008/09, thus no MAGST was calculated.

3.4.4 Detection of BTS Period

As seen in 2.5.8, the BTS period is restricted to sites and time periods with low GST fluctuations. The BTS period is described when the fluctuations of GST are minimal (Nyenhuis 2005). Hence, the BTS period is defined if the GST_{day} fluctuations from February to April does not exceed $\pm 0.5^{\circ}\text{C}$ for at least two consecutive weeks. Following the concept from Nyenhuis (2005), the mean of the GST during the defined BTS period represents the BTS for each year. The aggregation level on regional, rockglacier or logger depends on the scale of interpretation.

3.4.5 Ground Freezing and Thawing Indices

The Ground Freezing Index (GFI) is calculated by summing up all negative GST_{day} for each hydrological year, then divided by the count of measurement days and the count of logger per hydrological year. The Ground Thawing Index (GTI) describes the sum of all positive GST_{day} values per hydrological year divided by the number of measurement days and loggers per hydrological year. The second and third calculation steps enable a comparison between the different years, as various numbers of loggers are used.

4. Study Site

4.1 Turtmanntal and Hungerlitelli

The study site is located in the southern part of the Swiss Alps in the Canton of Valais (Figure 4.1). The analysed rockglaciers are situated in the Hungerlitelli, one of many hanging valleys in the Turtmanntal. The direction of the Turtmanntal is from north to south. The southernmost geological boundary is marked by the Bishorn (4151 m a.s.l.), the northernmost part of the valley ends at Turtmann in the Rhonetal. This geological boundary creates a catchment area of the river Turtmäna. The lower boundary is where the Turtmäna flows into the river Rhône in the community of Turtmann. It covers an area of 112.6 km^2 . The mean altitude of the catchment area Turtmanntal is 2443 m a.s.l., the highest peak is 4447 m a.s.l. and the minimum height is 616 m a.s.l. (HADES 2023). Only 20% of the catchment area lies at lower altitudes than 2000 m a.s.l. (HADES 2023). The top of the valley is covered with two glaciers, the Bruneggletscher and the Turtmannletscher. They contribute to 12% of the entire surface coverage of the valley. Rock surface is represented by 39% and is the main surface coverage of the valley. Other important surface coverages are coniferous forest (18%), grass- and herbaceous vegetation (13%) and unconsolidated rock (12%) (HADES 2023).

The catchment area of the Turtmanntal can be subdivided into a smaller catchment area, called Turtmäna-Gruben with a size of 56.3 km^2 and a mean altitude of 2786 m a.s.l. (HADES 2023). The lowest boundary of this catchment area is defined by the discharge of the stream Grüobbach into the Turtmäna. This estuary is located at Gruben. The Grüobbach is located in the valley located adjacent north of the Hungerlitelli. The upper boundary of this catchment area is the same as the one from the catchment area Turtmanntal. The advantage of this subdivision is that the calculated and aggregated data provided by the Hydrological Atlas of Switzerland (HADES) more precisely represent the in-situ conditions in the Hungerlitelli. The Hungerlitelli is located at the east side of the Turtmanntal, limited by the Giighoru (2749 m a.s.l.), Furggwanghorn (3162 m a.s.l.), Rothorn (3278 m a.s.l.), Hungerlihorli (3008 m a.s.l.) and Brändjispitz (2852 m a.s.l.). Due to the cirque similar shape, the Hungerlitelli has all orientations except for east oriented slopes.

4.1. Turtmanntal and Hungerlitelli

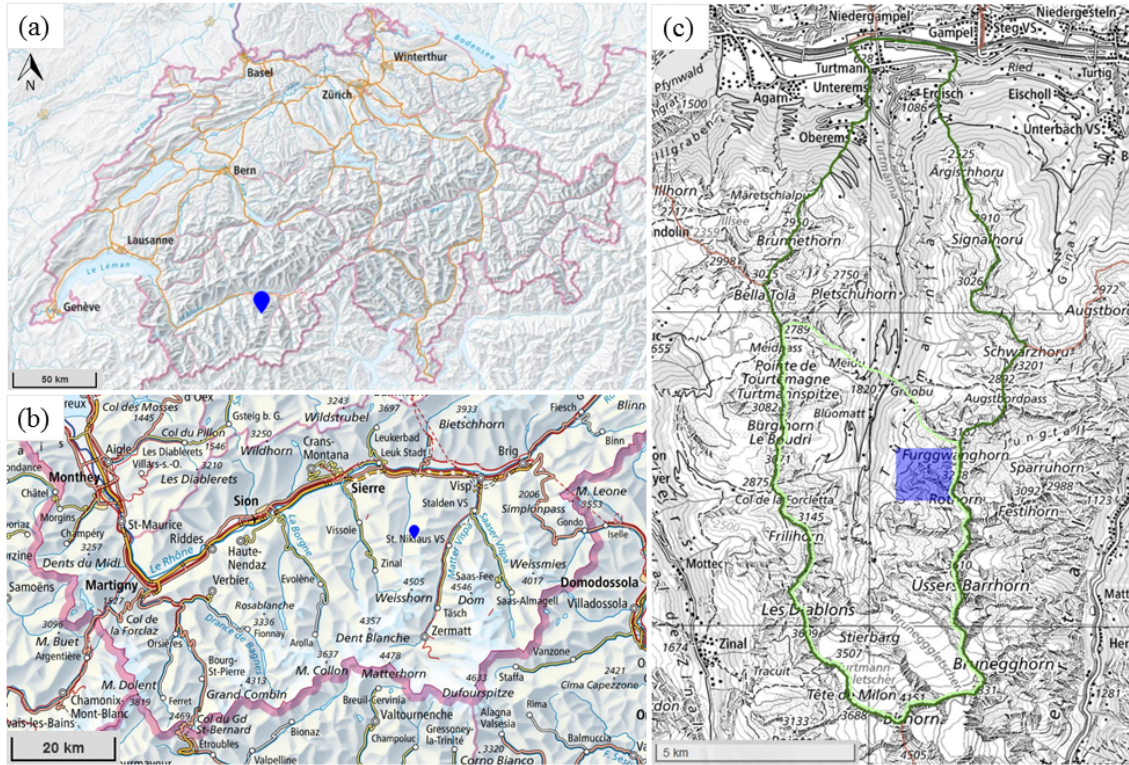


Figure 4.1: (a) Location of the Turtmanntal in the Swiss Alps, Switzerland. The blue pin marks the location of the Hungerlitelli. (b) Enlarged view of the Valais, the blue pin marks the location of the Hungerlitelli. (c) Closeup view of the Turtmanntal. The dark green boundary marks the catchment area of the river Turtmänna and is labelled as the catchment area Turtmanntal. The light green boundary illustrates the catchment area Turtmänna-Gruben. The blue box shows where the Hungerlitelli is located in the Turtmanntal. Map: swisstopo (2023), catchment boundary: HADES (2023).

Rockglacier Huhh1 (Figure 4.2, left) extends from below the very small Hungerli- gletscher (at the east side of Hungerlihorli) at around an altitude of 2800 m a.s.l. down to around 2600 m a.s.l. (Figure 4.3). The surface property persists of a majority of coarse-grained material and large boulders. The boulders are generally unconsolidated but more stable than the boulders on Huhh3. At the tongue, between 2650 and 2670 m a.s.l., the prevailing grain-size is fine-grained (ruggedness ≤ 0.5 m). Further fine-grained material is found at the orographical right side between 2650 to 2700 m a.s.l. and at the orographical side of the root zone (between 2770 and 2800 m a.s.l.) (Figure 5.8 or 5.9). Furthermore, some small patches on the rockglacier consists of fine-grained material. The remaining surface has a ruggedness between 0.5 and 2 m.

Rockglacier Huhh3 (Figure 4.2, right) is located at the west side of the Hungerlihorli



Figure 4.2: Left: Rockglacier Huhh1. Right: Rockglacier Huhh3. The photos were taken in early October 2023 during data retrieval.

and extends from around 2650 m a.s.l. to 2500 m a.s.l. (Figure 4.3). The surface property of Huhh3 consists of fine-grained material to large boulders as well. The lowest extension of the rockglacier forms a distinct and steep front. Many boulders are pushed over the edge which creates an unstable front with loose material. The plateau above the lowermost front as well as the middle part of the rockglacier consist of fine-grained material (ruggedness ≤ 0.5 m). The other areas have a ruggedness between 0.5 and 2.5 m. The lowermost front and four distinct lobes, just above the flat tongue with fine-grained substrate, have the highest measured ruggedness (ruggedness up to 2.5 m, Figure 5.8 or 5.9). The material on all distinct steep fronts is unstable. Flatter parts are better consolidated and mainly consist of coarse-grained substrate. Above the distinct fronts, the surface is more uniformly, with some steeper and less steep slopes. The root zone is formed below a plateau with fine-grained material. The movement of the rockglacier was visible by the tipping of the boulders and due to the rollover of smaller rocks by larger ones.

In addition to Huhh1 and Huhh3, data of an inactive rockglacier, called Huhh2, is gathered as well (Figure 4.3). It is located northwest of Huhh1 on the valley floor of the Hungerlitelli between 2620 and 2570 m a.s.l. Due to the minimal inclination, this rockglacier does not show movement anymore. However, it still contains ice which is visible by the frost heave. The main prevailing ruggedness is ≤ 0.5 m (Figure 5.8 or 5.9). Only up to four different measurement locations are available at Huhh2 (depending on year), thus the data of it serves primarily for comparison.

During the first decade of data retrieval, further GST measurements were gathered at a nearby moraine (Figure 4.3). Thus, the hydrological years 2003, 2004,

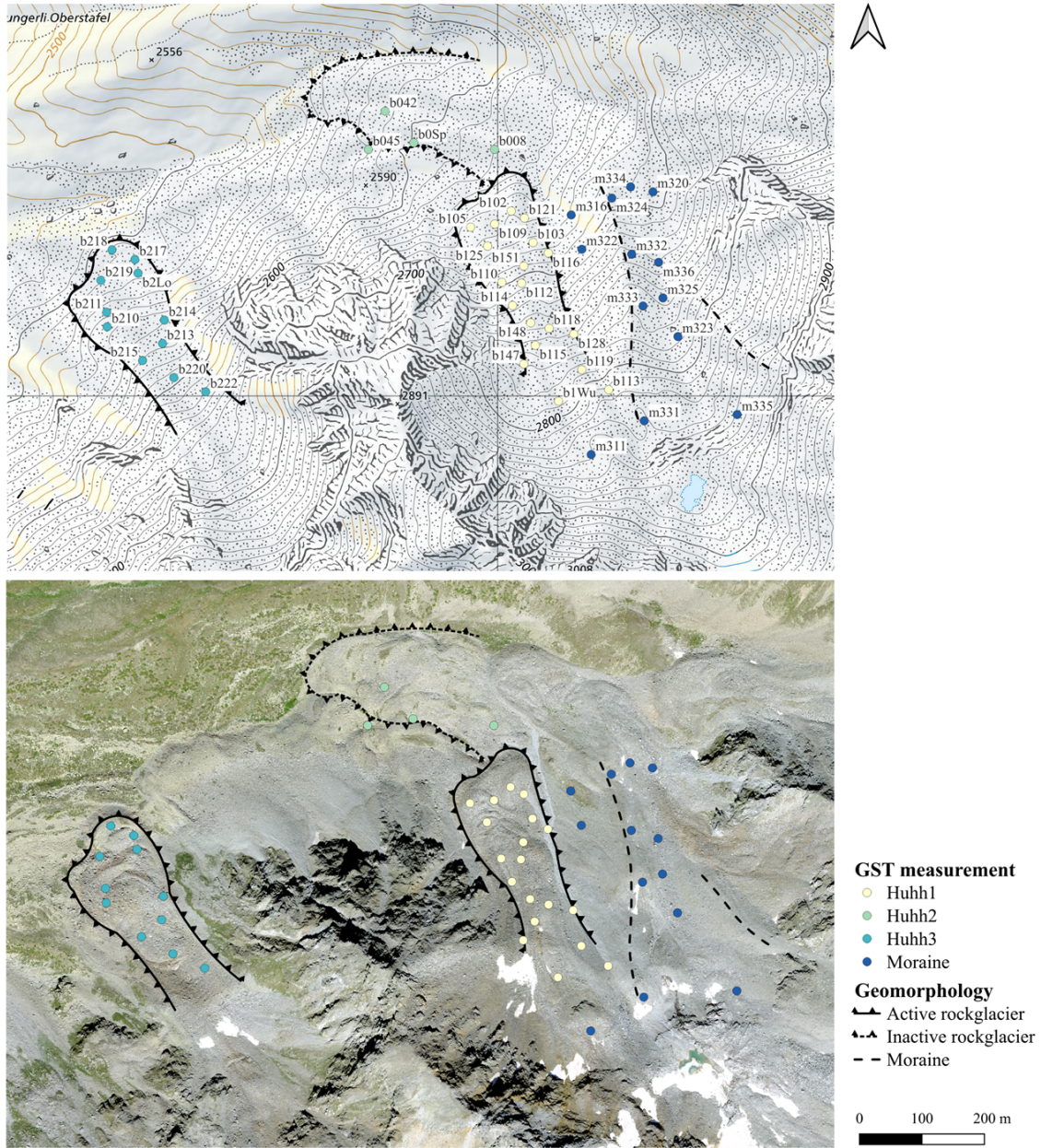


Figure 4.3: Top: Map of the Hungerlitelli, the names of the loggers are labelled. The letter "b" describes the geomorphology for rockglacier, the letter "m" stands for moraine. Bottom: Aerial image of the Hungerlitelli. The activity of the rockglacier is indicated as well as the location of the GST measurements. The active rockglaciers are situated on the east (Huhh1) and west (Huhh3) side of the Hungerlihorli. Huhh2 is located north of the tongue of Huhh1. Map: swisstopo (2023), aerial image: swisstopo (2020).

2005 and 2008 have, in addition to the rockglaciers, data about the GST of a non-permafrost feature. The moraine is located at the east side of Huhh1. The measurement sites were distributed from 2670 to 2850 m a.s.l. The grain size is primarily

fine-grained substrate (Nyenhuis 2005) with a ruggedness of ≤ 0.5 m. Nonetheless, some temperature loggers lay at sites with a ruggedness up to 1.5 m (Figure 5.8).

4.2 Climate

4.2.1 Climatic Conditions Turtmanntal

The Turtmanntal is a side valley from the Rhonetal and lies in the Canton of Valais. The Rhonetal marks an outstanding dry valley in Switzerland since it is well shielded from moist air masses to the north and south. It represents a typical inner-alpine valley in Switzerland (MeteoSchweiz 2024). By analysing the MAP for all of Switzerland, the Valais lies in one of the driest region in Switzerland (Frei, Isotta, & Schwanbeck 2018; HADES 2023). Hence, this region is marked by an arid climate (Roer 2005).

HADES (2023) provides temperature and precipitation data interpolated over the entirety of Switzerland. The used maps from HADES are Mean Air Temperatures 1991 - 2020 and Mean Precipitation 1981 - 2010.

Mean values of the near-ground air temperatures are supplied for the reference period 1991 - 2020 from Meteo Schweiz (MeteoSchweiz 2024). The maps were calculated by means of spatial analysis of temperature normals at climate stations. The used data series were from 88 stations. By spatial interpolation of the station-based temperature normals, the distribution of the annual, seasonal and monthly temperatures can be plotted on a 1 km grid. Due to the actuality that the count of measurement stations are restricted and mathematical interpolations have their limits, several local effects are not recorded and uncertainties of spatial analysis occur. An interpolation error in the winter months in the Alps has a size of 1.6°C, in the summer months 0.8°C (Frei 2022).

Mean precipitation values for the reference period 1981 – 2010 are based on the grid data set of Meteo Schweiz (MeteoSchweiz 2024). The data set is a spatial analysis of precipitation normals, derived from measurements at 418 stations and covers the territory of Switzerland with a spatial resolution of 1.6 km x 2.3 km. Neighbouring measurement stations have a typical distance of 10 to 20 km. Among the stations, a spatial interpolation was applied which results in a relative standard error of $\pm 25 - 30\%$ for the Alps. The highest interpolation errors occurred in inner-alpine valleys like the Valais as well as in high altitudes. Additionally, systematic measurement errors contribute to the accuracy of the data. Generally, the measured values un-

derestimate the actual precipitation amounts (Frei, Isotta, & Schwanbeck 2018).

Aggregated mean air temperatures (1991 – 2020) and aggregated mean precipitation heights (1981 – 2010) are available for the catchment area Turtmanntal and Turtmänna-Gruben (Figure 4.4). The MAAT for the catchment area Turtmanntal is 0.1°C , the annual precipitation sum is 990 mm. January, February and March as well as November and December have mean air temperatures lower than -3°C , thus assuming precipitation is falling as snow (HADES 2023).

In terms of content, the climate graph is created according to Heinrich Walter (Walter 1955). The ratio of the temperature and precipitation scale at which 10°C is made to correspond to 20 mm precipitation (Gaussen 1954) correlates with the temperature dependent evaporation (Hurni et al. 2023).

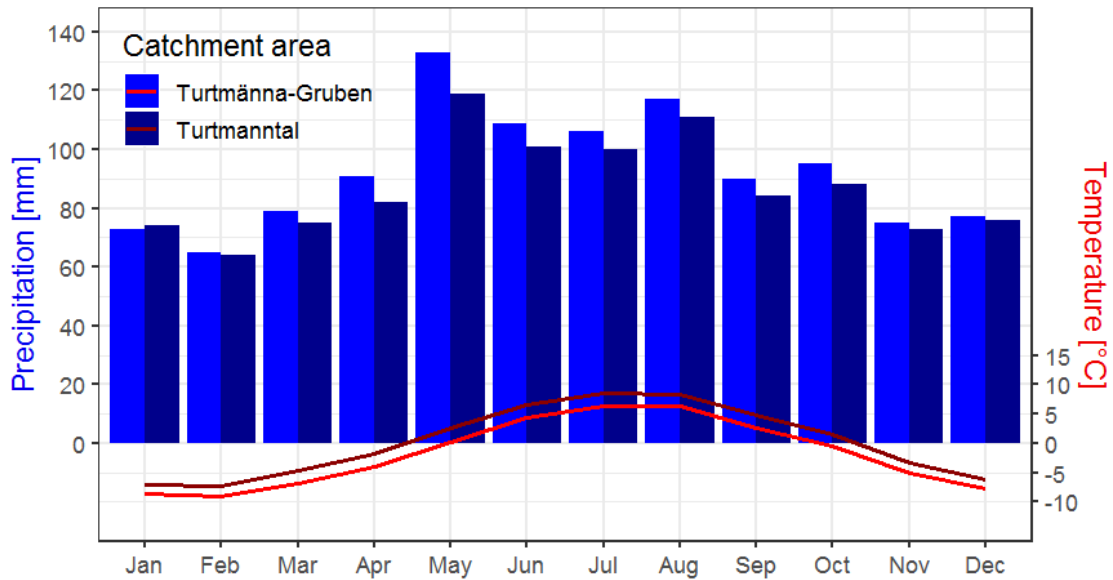


Figure 4.4: Climate graph for the catchment areas Turtmänna-Gruben (light colors) and Turtmanntal (dark colors). Precipitation, indicated with blue bars, represent mean values from 1981 – 2010. Air temperature, illustrated with red lines, represent mean values from 1991 – 2020. Data: HADES (2023) and MeteoSchweiz (2024).

The Turtmanntal is colder in comparison to the surrounding valleys like the Val d’Annivers west of Turtmanntal and the Mattertal in the east. This condition originates from the fact that the Turtmanntal is a valley at high altitudes. Additionally, the air temperature is influenced by the two glaciers at the valley head due to their high albedo and the ability for evaporative cooling.

4.2.2 Climatic Conditions Turtmäna-Gruben

By using the data provided by HADES (2023), the following information was gained. The catchment area Turtmäna-Gruben has a MAAT of -1.9°C (reference period 1991 – 2020). The highest mean monthly air temperatures is represented in August (6.4°C), the lowest in January with -8.5°C (Figure 4.4). January, February, March, April as well as November and December have mean air temperatures lower than -3°C . In total, seven months have a mean air temperatures below 0°C . Positive mean air temperatures were in May to September. The annual precipitation sum is 1030 mm. The largest amount of precipitation falls from May to September with values > 100 mm. February represents the month with the least mean monthly precipitation (65 mm), May with most precipitation (133 mm).

4.2.3 Climatic Conditions Hungerlitelli

The Hungerlitelli is only minimally influenced by a glacier. The small glacier, called Hungerligletscher, is still present but its extent is very small. Nevertheless, different temperature gradients are visible (Figure 4.5 (a)). At the slope eastward of the Hungerlihorli, where the rockglacier Huhh1 and the Hungerligletscher are situated, the gradient of MAAT in the period 1991 – 2020 reaches lower temperatures at lower altitudes in comparison to the westward slope. The -1°C isotherm follows a north-east to south-west direction and lies around 2550 m a.s.l. The -2°C isotherm is around 2750 m a.s.l. At the west side of the Hungerlihorli, at the side of Huhh3, the -1°C isotherm is at altitudes of about 2650 m a.s.l. and the -2°C isotherm is at 3000 m a.s.l. (HADES 2023). Hence, Huhh1 lies in the temperature regime between -2 and -3°C , whereas Huhh3 has a MAAT between -1 and -2°C . Huhh2 lies primarily in the area with a MAAT of -2°C .

The MAP has less variation in the Hungerlitelli (Figure 4.5 (b)). Almost the entire study site has a MAP of 900 mm (reference period 1981 – 2010). Only the root zone of Huhh1 and the uppermost part of the moraine have a MAP of 1000 mm.

Due to the condition that these values (air temperature and precipitation) are only aggregated values and do not stem from close meteorological stations, the precise boundaries should be interpreted with caution.

4.2. Climate

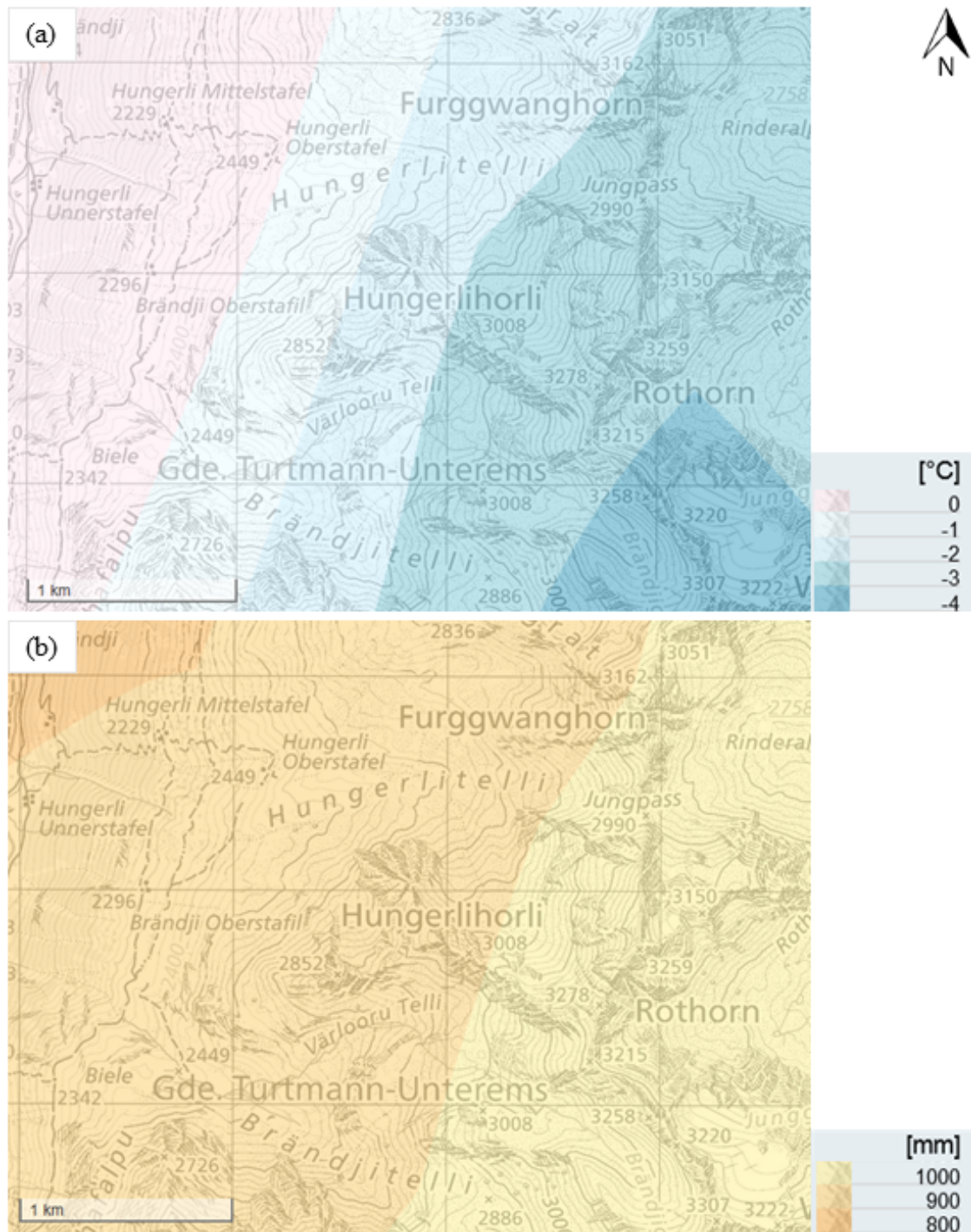


Figure 4.5: Spatial distribution of (a) MAAT and (b) MAP in the Hungerlitelli. The reference period for the MAAT is 1991 – 2020, for the MAP 1981 – 2010. Data: HADES (2023), map: swisstopo (2023).

5. Results

5.1 Daily Mean Ground Surface Temperature

To illustrate different trends during a hydrological year, the time series for logger b222 is plotted in Figure 5.1. This time series is the longest one from rockglacier Huhh3 and the second longest overall. In the subsequent section, trends, anomalies and dependencies are described on the example of logger b222. Further loggers on rockglacier Huhh3, and also on Huhh1 and Huhh2, have these patterns.

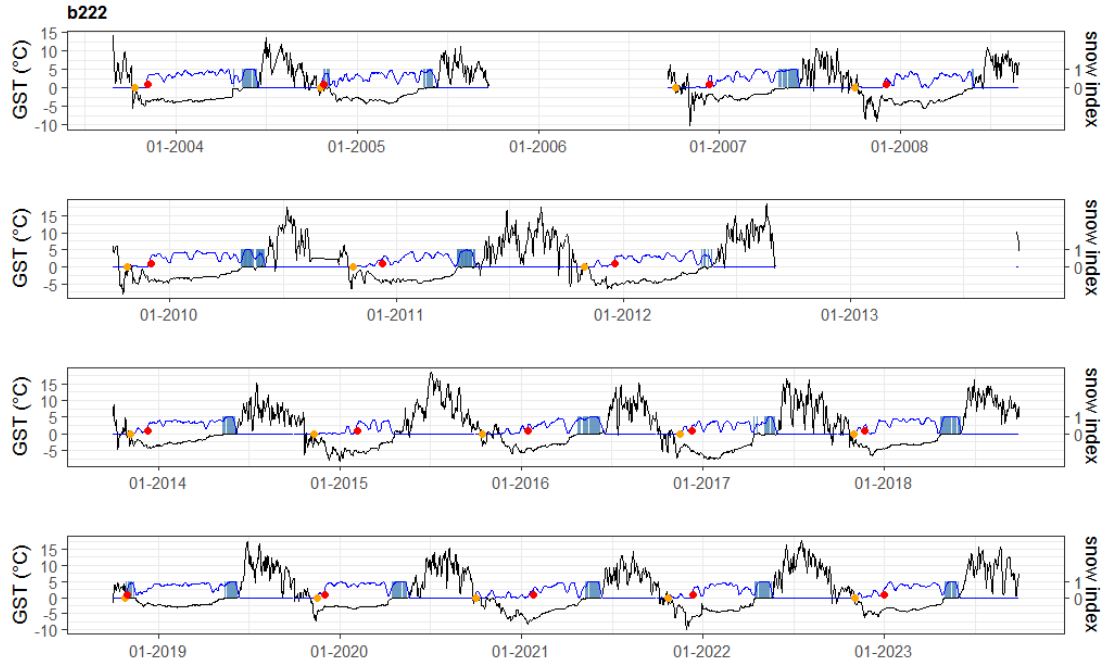


Figure 5.1: Time series for logger b222 of rockglacier Huhh3 from hydrological year 2004 to 2023. The GST_{day} (black line), snow index (blue line), ZC (blue bars), SOD (orange dots) and the HTI_{start} (red dots) are plotted against time.

Looking at hydrological year 2004 (01.10.2003 – 30.09.2004), the influence of early snow is visible. Since the HTI_{start} is early (05.11.2003), the GST did not have the opportunity to cool down for long. Hence, the GST is insulated at a rather high temperature between -3 and -5°C . From the HTI_{start} to just before the ZC, the GST remains constant with only small fluctuations. This resulted from the insulating snow cover for almost the entire winter period. The snow index varies

5.1. Daily Mean Ground Surface Temperature

between 0.5 and 1, indicating a snow cover of a size larger than 0.8 m. In May, the GST increased to 0°C due to a short ZC. Afterwards, the GST decreased again for a short time before the distinct ZC started. During the ZC, the GST remains constant at 0°C due to snow melt (Outcalt, Nelson, & Hinkel 1990). By mid-June, the snow cover is gone and the GST is directly linked to the atmosphere. Large variations of the air temperature are reflected by the GST.

The hydrological year 2005 had a ZC in autumn. Just before the autumn ZC, the SOD and $\text{HTI}_{\text{start}}$ took place. Although the ZC prevents the ground surface to cool down, the GST decreased slightly after the ZC. In this case, the autumn ZC caused that the GST could not adopt to low temperature values in combination with an early snow fall shortly afterwards.

The absence of ZC implies an anomaly. In spring 2015, there was no ZC. The snow index varied strongly and was twice almost at zero. In addition, the $\text{HTI}_{\text{start}}$ was late (in the beginning of February) in comparison to other years. The combination of these factors resulted in the absence of a ZC due to the presence of only little snow.



Figure 5.2: Hydrological year 2011 for logger b210 on rockglacier Huhh3. The GST_{day} (black line), snow index (blue line), ZC (blue bars), SOD (orange dot) and the $\text{HTI}_{\text{start}}$ (red dot) are plotted against time. No ZC and $\text{HTI}_{\text{start}}$ were reported in this hydrological year at the location of b210.

To see the influence of snow on GST, the winter in the hydrological year 2008 is analysed in detail. From the $\text{HTI}_{\text{start}}$ to February, the snow index indicates an insulating snow cover with a constant GST between -3 and -5°C . In early February, the snow index decreased towards zero. The GST decreased as well, highlighting a direct coupling with the air temperature during winter. As soon as the snow cover was again thick enough with a snow index > 0.5 , the GST was again insulated and not influenced by the air temperature fluctuations.

5.1. Daily Mean Ground Surface Temperature

There were some years which did not have a $\text{HTI}_{\text{start}}$. Figure 5.2 shows logger b210 of rockglacier Huhh3 for the hydrological year 2011. In this hydrological year, no $\text{HTI}_{\text{start}}$ took place. In November 2010, the SOD marks the timing of the first snow fall. Since the snow index did not rise, the first snow fall was only a thin layer of snow. During the entire winter, only short snow events were detected. No ZC validate the absence of snow during winter. The GST varied between -17°C and -2°C which is a hint that the ground surface was directly coupled with the air temperature even in winter.

5.1.1 Time gap between Snow Onset Date and start of High Thermal Insulation

The time between the SOD and the $\text{HTI}_{\text{start}}$ differ strongly between the loggers. The influence of a long time gap can be seen in the hydrological year 2021 with logger b222 (Figure 5.1). The SOD was at the beginning of October. From then on, the snow index depicts values between 0 and 0.5 thus too less snow for an insulating snow cover. Hence, the ground is still coupled with the air temperature, resulting in decreasing GST. In February, the snow amount increased, resulting in the $\text{HTI}_{\text{start}}$. Up to then, the GST cooled down to -7°C . Afterwards, the GST increased up to the start of ZC.

Figure 5.3 (a) shows the mean SOD and mean $\text{HTI}_{\text{start}}$ summarised for the entire study site plotted for each hydrological year. Since the timing of an insulating snow cover is of great importance for the BTS, the mean BTS is plotted for direct comparison (Figure 5.3 (b)). Particular early SOD occurred in 2004 (17.10.), 2006 (05.10.), 2019 (16.10.) 2021 and 2023 (both 14.10.). Extraordinary early $\text{HTI}_{\text{start}}$ were in 2006 (21.10), 2014 (09.11.) and 2019 (01.11.). Remarkable late $\text{HTI}_{\text{start}}$ took place in 2002 (30.12.), 2015 (25.12.), 2017 (02.01.) and 2022 (28.12.). The longest time gap between the SOD and the $\text{HTI}_{\text{start}}$ was in 2021 with 68 days, closely followed by 2023 (66 days) and 2022 (64 days). The shortest period occurred in 2006, 2014 and in 2019 with 15 days. A complete table describing the SOD, $\text{HTI}_{\text{start}}$ and the duration of the period between the SOD and the $\text{HTI}_{\text{start}}$ for each hydrological year is reported in the appendix A.10.

5.2. Monthly Mean Ground Surface Temperature

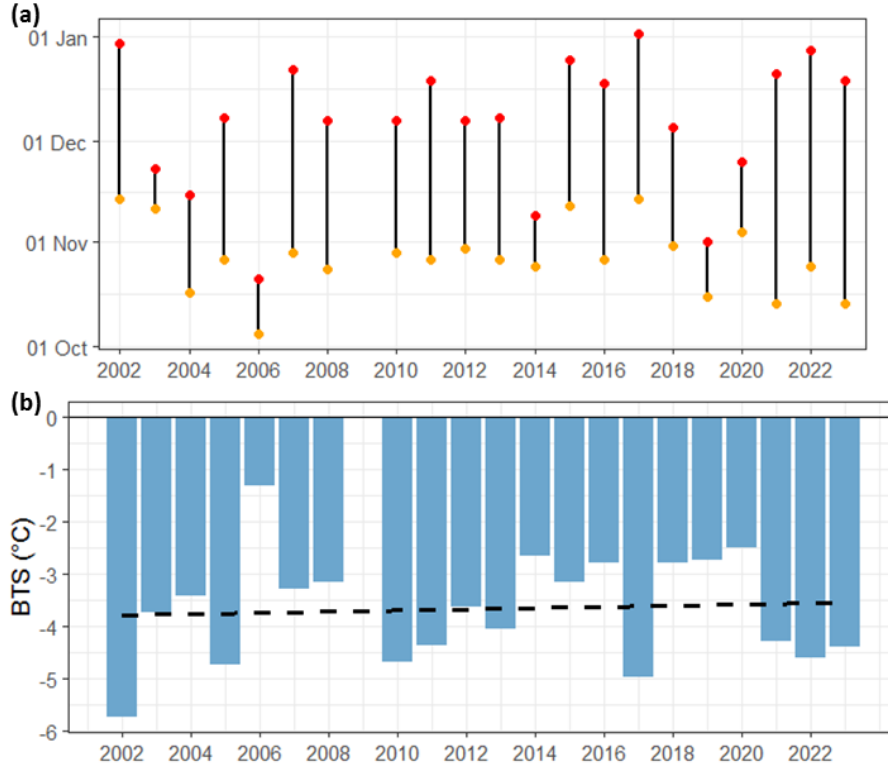


Figure 5.3: (a) Mean SOD (orange dots), mean HTI_{start} (red dots). (b) Mean BTS for each hydrological year. The particular mean is calculated considering all loggers on Huhh1, Huhh2 and Huhh3. The dashed line represents the linear trend for the BTS dependent on time with a slope of +0.014°C/year. Hydrological year 2009 does not have any data.

5.2 Monthly Mean Ground Surface Temperature

Analysing the GST data, categorised in months, helps to understand the dependencies of GST on seasonality (Figure 5.4). The GST from November to April vary only slightly between months and rockglaciers. Outliers are mostly found towards lower temperature values. In May, the data spread is minimal. 50% of the data lie almost at 0°C, indicating a low temperature spread. In June, rockglacier Huhh2 has still a minimal data spread, meanwhile, Huhh1 and Huhh3 have a data spread of about 7°C. Many outliers occur in May and June. From July to September, the data spread remains large in comparison to winter. In October, the data spread has still a greater range than in winter, rather like in summer.

The active rockglaciers have a similar pattern during a year. From November to March, the median of Huhh1 is slightly higher than for Huhh3. From April to October besides May, the median of Huhh1 is lower than for Huhh3. In May, both rockglaciers have a median at 0°C. The inactive rockglacier Huhh2 has almost al-

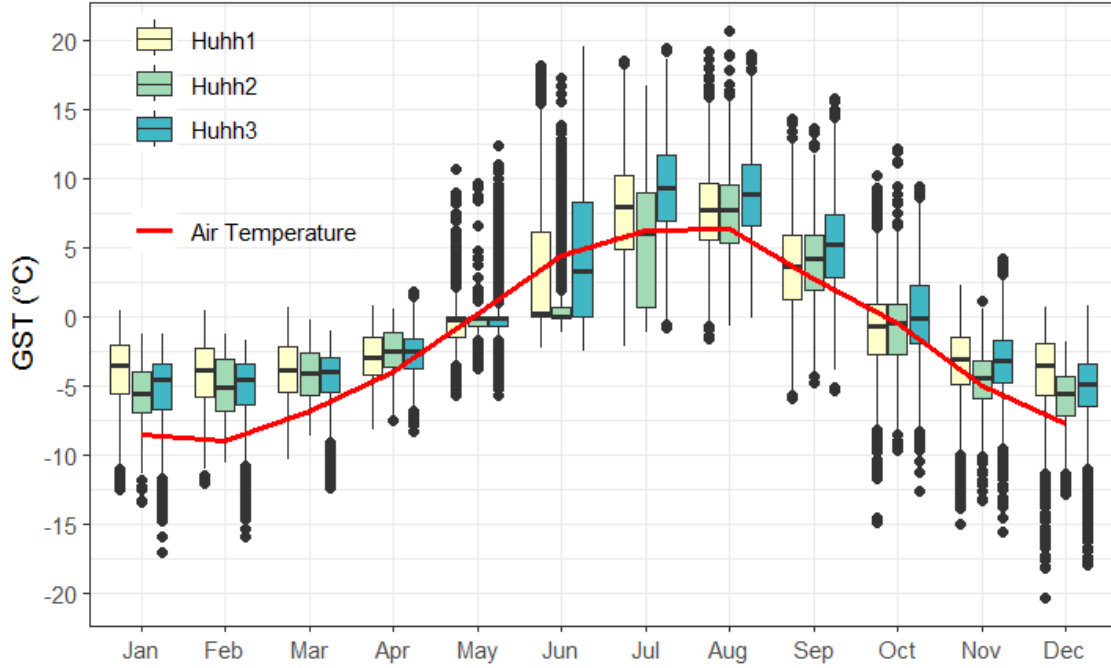


Figure 5.4: Summarised GST_{day} for rockglacier Huhh1, Huhh2 and Huhh3 depending on month. All data for each month and the entire period (2002 – 2023) is represented within one box. The horizontal thick line in the box represents the median, the lower and upper end of the box the 1st and 3rd quartile, respectively. Vertical lines show the range of maximum 1.5 times the interquartile range. Dots are outliers which have values larger than 1.5 times the interquartile range. The red line represents the mean monthly air temperature from the catchment area Turtmäna-Gruben (1991 – 2020). Air temperature data: HADES (2023).

ways a lower median of the mean monthly GST than the active rockglaciers. Only in September, October and April, rockglacier Huhh1 has a slightly lower median of the GST. During the phase of melt, from March to June (besides April), the GST is almost the same among all rockglaciers.

5.3 Mean Annual Ground Surface Temperature

Summarising the GST annually, the MAGST, aggregated for the two active rockglaciers Huhh1 and Huhh3, is plotted for each hydrological year in Figure 5.5. The MAGST average for the rockglacier Huhh1 and Huhh3 aggregated is $-0.23 \pm 0.97^{\circ}\text{C}$. The hydrological year 2015 had the highest MAGST with 1.15°C , 2002 the minimum MAGST with -2.74°C .

By analysing the MAGST for the active rockglaciers over the entire period, a rising

5.3. Mean Annual Ground Surface Temperature

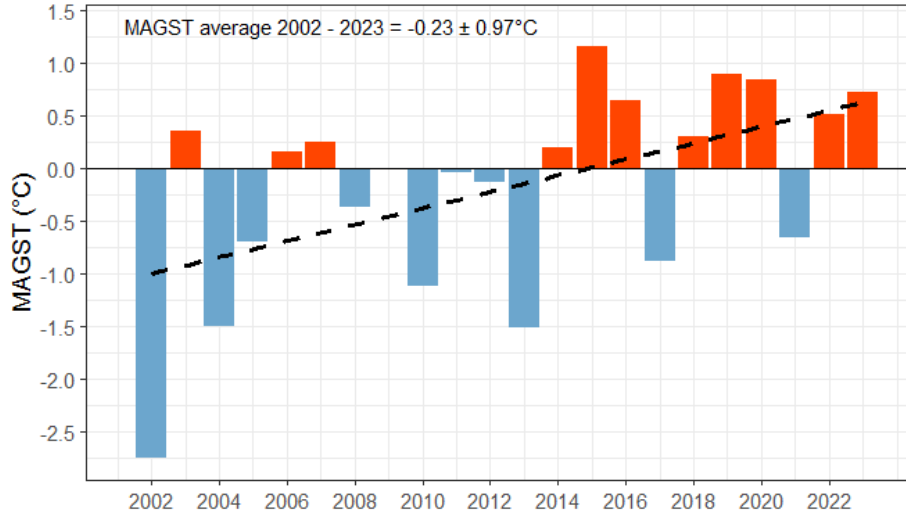


Figure 5.5: Summarised MAGST for Huhh1 and Huhh3 for each hydrological year from 2002 to 2023. The dashed line indicates the linear trend for the time series since 2002. The multiple R-squared is 0.27 and the slope $+0.076^{\circ}\text{C}/\text{year}$. Hydrological year 2009 does not have any data.

trend is clearly visible ($+0.076^{\circ}\text{C}/\text{year}$, Figure 5.5). The first decade, from 2002 to 2012, has typically MAGST below the long-term average thus mainly negative values. The second half of the study period has mostly MAGST above 0°C . The tipping point is between year 2013 and 2014.

Including the inactive rockglacier Huhh2, the average MAGST constitutes $-0.27 \pm 0.96^{\circ}\text{C}$. The quantity of the individual years differ only minimal. In the period of 2006 to 2008, the greatest differences are detected. Hydrological year 2006 has a MAGST of 0.5°C , 2007 -0.1°C and 2008 -0.5°C . The other years do not show any great differences. The multiple R-squared is 0.25 and the slope $+0.072^{\circ}\text{C}/\text{year}$.

Rockglacier Huhh1 has its maximum MAGST in hydrological year 2020 with 0.78°C , the lowest value in 2002 with -2.57°C (Figure 5.6). The MAGST average (2002 – 2023) is $-0.32 \pm 0.86^{\circ}\text{C}$. In Table 5.1, the MAGST averages are calculated for three decades. The long-term trend has a slope of $+0.067^{\circ}\text{C}/\text{year}$.

Rockglacier Huhh3 has its maximum MAGST in 2015 with 1.44°C , its lowest value in 2002 with -3.10°C (Figure 5.6). Both maxima and minima of Huhh3 represent the largest and smallest temperature if analysed on rockglacier level. The MAGST average 2002 – 2023 is $+0.28 \pm 1.11^{\circ}\text{C}$. Not only the MAGST average is higher for Huhh3 in comparison to Huhh1, but also almost every hydrological year has higher MAGST despite 2002, 2010 and 2021. In 2018, Huhh1 and Huhh3 have the same

5.3. Mean Annual Ground Surface Temperature

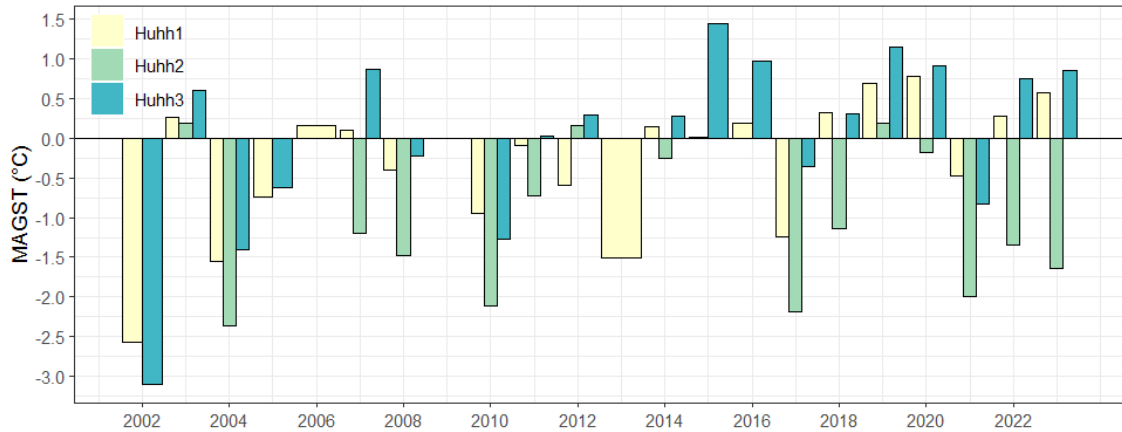


Figure 5.6: MAGST for each rockglacier and each hydrological year from 2002 to 2023. If only one or two bars are printed per hydrological year, no data for the missing rockglacier is available. Hydrological year 2009 does not have any data.

MAGST. Also, the long-term trend for Huhh3 is slightly larger than for Huhh1 with a size of $+0.088^{\circ}\text{C}/\text{year}$.

The inactive rockglacier Huhh2 has its maximum MAGST in 2003 with 0.19°C and the minimum MAGST in 2004 with -2.36°C (Figure 5.6). The long-term average (2002 – 2023) is $-1.08 \pm 0.91^{\circ}\text{C}$. Huhh2 has in each hydrological year the lowest MAGST besides 2012. This is also reflected by the lowest MAGST average comparing to Huhh1 and Huhh3 (Table 5.1). Huhh2 does not have an increasing trend, the slope has a value of $-0.0046^{\circ}\text{C}/\text{year}$.

Table 5.1: MAGST average for three decades and the long-term average depending on rockglacier and the long-term MAAT average for the catchment area Turtmäna-Gruben. Air temperature data: Frei (2022) and HADES (2023).

	Huhh1	Huhh3	Huhh2	Turtmäna-Gruben
2002 – 2011				
MAGST ($^{\circ}\text{C}$)	-0.65 ± 0.94	-0.65 ± 1.27	-1.28 ± 0.93	
2006 – 2015				
MAGST ($^{\circ}\text{C}$)	-0.35 ± 0.58	$+0.20 \pm 0.85$	-0.94 ± 0.83	
2014 – 2023				
MAGST ($^{\circ}\text{C}$)	$+0.13 \pm 0.60$	$+0.54 \pm 0.70$	-1.07 ± 0.89	
2002 – 2023				
MAGST ($^{\circ}\text{C}$)	-0.32 ± 0.86	$+0.28 \pm 1.11$	-1.08 ± 0.91	
1991 – 2020				
MAAT ($^{\circ}\text{C}$)				-1.9 ± 1.6

5.3. Mean Annual Ground Surface Temperature

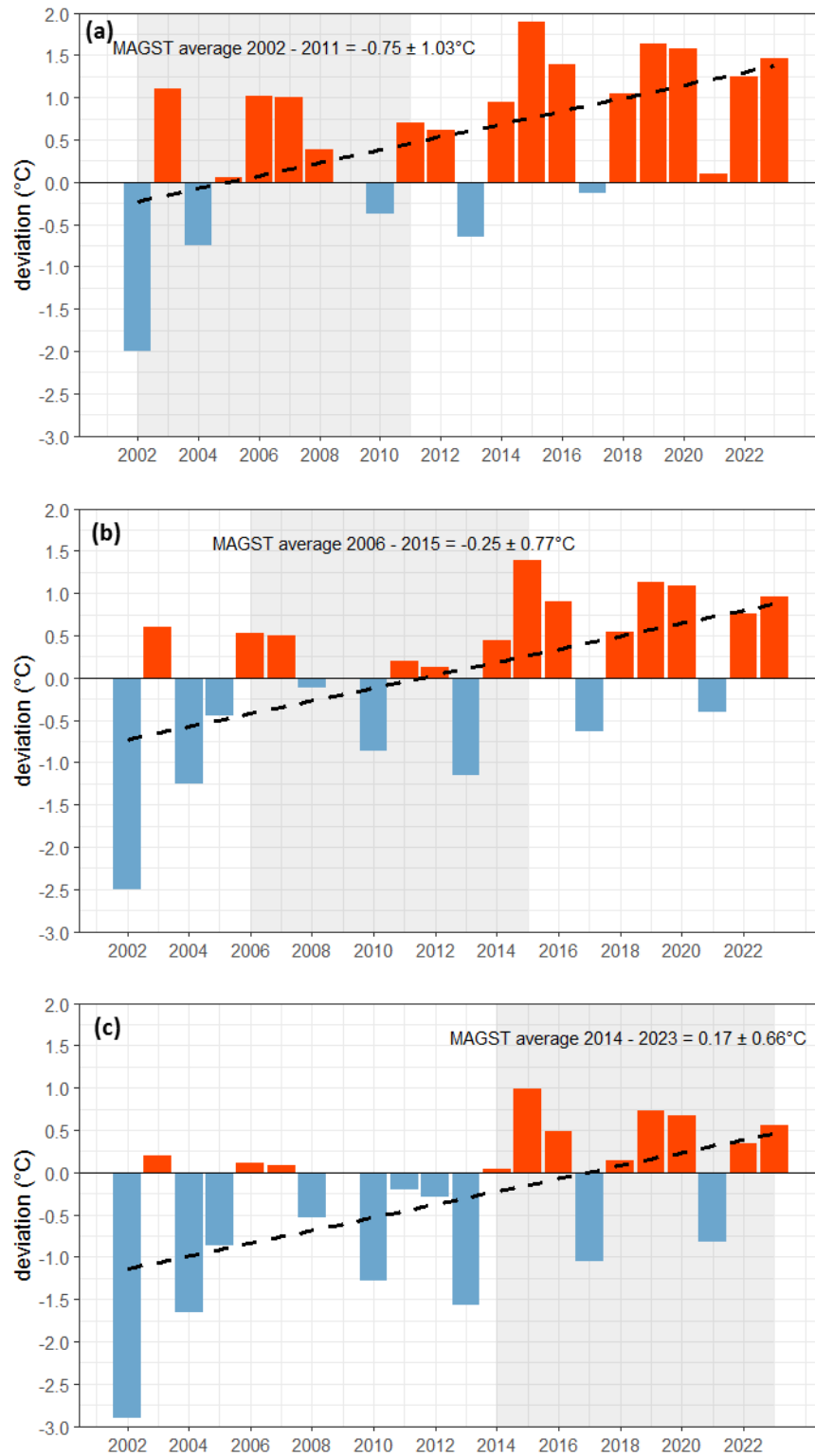


Figure 5.7: Deviation of the MAGST for the period 2002–2011 (a), 2006–2015 (b) and 2014–2023 (c). Data of rockglacier Huhh1 and Huhh3 are summarised, Huhh2 is not represented. The dashed line indicates the linear trend for the time series since 2002. The multiple R-squared is 0.27 and the slope $+0.076^{\circ}\text{C}/\text{year}$. Hydrological year 2009 does not have any data.

5.3.1 Deviation of the Mean Annual Ground Surface Temperature

The deviation of the MAGSTs for rockglacier Huhh1 and Huhh3 for three decades are visible in Figure 5.7. Rockglacier Huhh2 is excluded from this analysis since it is an inactive rockglacier and its MAGST differs from the active rockglaciers.

The deviation is calculated based on the MAGST average for each period. The first decade (2001 – 2011, Figure 5.7 (a)) has a MAGST average of $-0.75 \pm 1.03^{\circ}\text{C}$. Only the hydrological years 2002, 2004, 2010, 2013 and 2017 have a negative deviation of the MAGST average 2002 – 2011.

The intermediate decade 2006 – 2015 has a MAGST average of $-0.25 \pm 0.77^{\circ}\text{C}$ (Figure 5.7 (b)). Eight hydrological years have a negative deviation of the MAGST average 2006 – 2015, 13 hydrological years have a positive deviation.

The last decade, from 2014 – 2023, has a MAGST average of $0.17 \pm 0.66^{\circ}\text{C}$ (Figure 5.7 (c)). The count of hydrological years which have a positive or negative anomaly is 11 and 10, respectively. Five years which have a positive deviation are below 0.2°C , thus only slightly positive.

5.3.2 Spatial Distribution of the Mean Annual Ground Surface Temperature

The distribution of the MAGST average for the first and second decade is illustrated in Figure 5.8. In the first decade (2002 – 2011), the MAGST average on the rockglaciers are almost always lower than on the moraine. The MAGST average on rockglacier Huhh1 and Huhh3 has a data spread between -4.4°C to $+1.6^{\circ}\text{C}$. The loggers on the orographical right side of Huhh1 have higher values than on the orographical left side and at the tongue. On Huhh3, higher MAGST average values are at higher altitudes (e.g. b213, b220, b222), whereas lower values are found at lower altitudes (e.g. b217, b219). Rockglacier Huhh2 has a data spread between -2.9°C and 0°C . The moraine has MAGST averages between -1.4°C and $+3.1^{\circ}\text{C}$. In the second decade (2014 – 2023), the MAGST average only varies between -1.4 and $+1.6^{\circ}\text{C}$. On Huhh1, the highest MAGST average was measured at the tongue (b102 and b105) and at the orographical right side (b103). Higher MAGST average at Huhh3 are at higher altitudes (e.g. b220, b222), whereas the lowest values are found at the tongue (b217, b218) and in the centre (b213) of the rockglacier. Both loggers on rockglacier Huhh2 have increased MAGST average in comparison to the first decade.

5.4. Bottom Temperature of the Winter Snow Cover

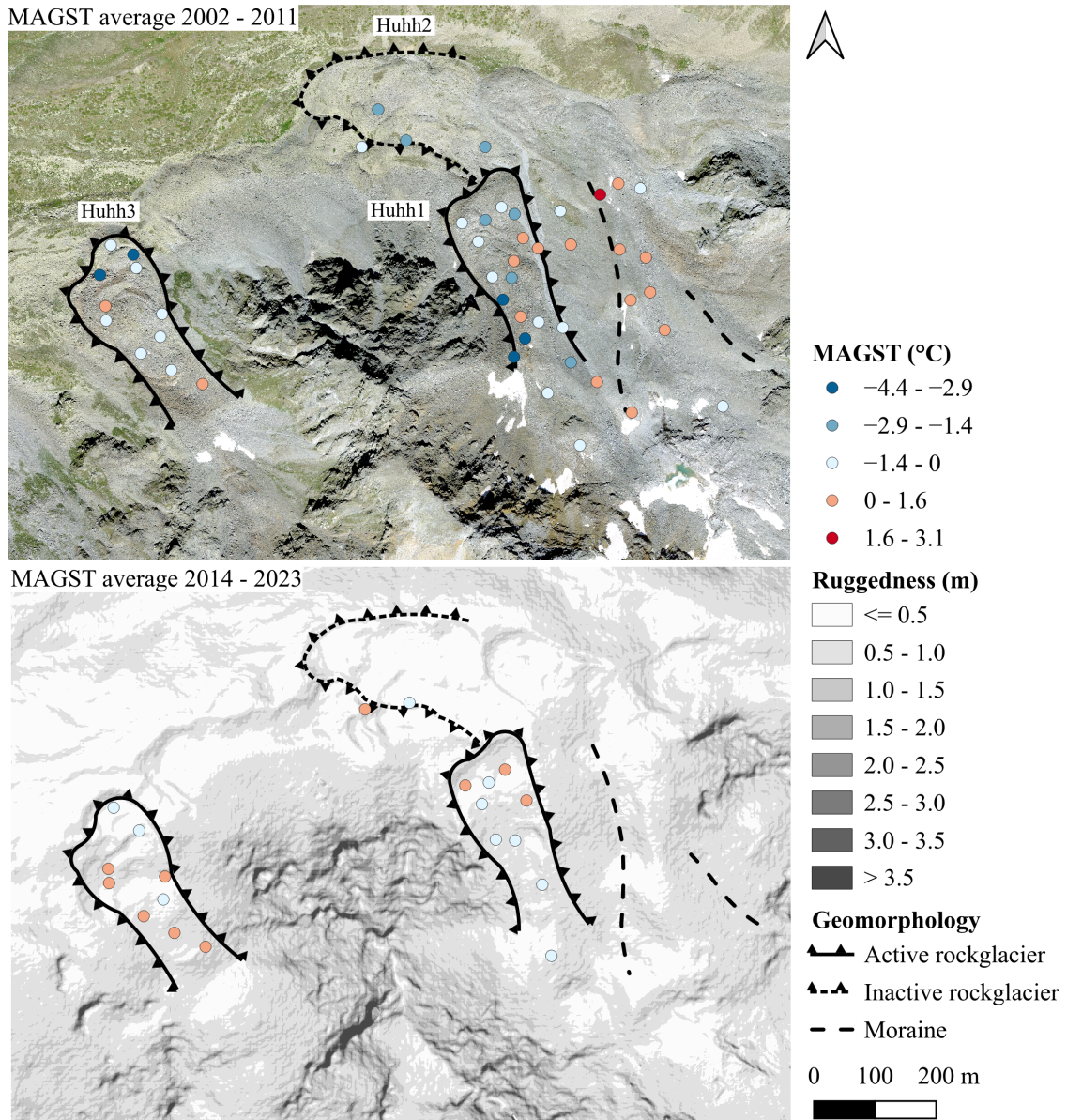


Figure 5.8: MAGST average for the first (2002 – 2011) and second (2014 – 2023) decade. In the second decade, no measurements were taken at the moraine. The background map for the second decade describes the ruggedness of the surface, the higher the ruggedness, the larger the prevailing grain size. Aerial image: swisstopo (2020). Data used for ruggedness map: swissALTI3D from swisstopo (2017).

5.4 Bottom Temperature of the Winter Snow Cover

The BTS is calculated as a regional mean (Figure 5.3 (b)) and for the first and second decade (Figure 5.9).

The regional mean of the BTS only shows a minimal increasing trend of about $+0.29^{\circ}\text{C}$ (value of slope is $+0.014^{\circ}\text{C}/\text{year}$) over the entire study period (Figure 5.3

(b)). However, the BTS is fluctuating from year to year. The highest BTS is measured in 2006 with -1.32°C , the lowest in 2002 with -5.74°C .

In the period of 2002 to 2011, almost all loggers on every rockglacier have a BTS $< -3^{\circ}\text{C}$ (Figure 5.9). Exceptions on Huhh1 are loggers located at the east side and upper part (b103, b113, b116, b128, b148 and b151). Their BTS is $> -2^{\circ}\text{C}$. On the east side of Huhh2, logger b008 has a BTS of -2 to -3°C . Rockglacier Huhh3 has only one BTS (logger b222) which is between -2 and -3°C . The remaining loggers all have a BTS $< -3^{\circ}\text{C}$. All measurement locations on the moraine besides logger m211 have a BTS $> -2^{\circ}\text{C}$.

Looking at the second decade, Huhh1 has three loggers (b102, b125 and b1Wu) which have an increased BTS of -2 to -3°C . Logger b103 has still a BTS of $> -2^{\circ}\text{C}$. Logger b045 on Huhh2 has an increased BTS as well. On Huhh3, three loggers (b211, b214 and b220) differ from the first decade by increasing the BTS to the range of -2 to -3°C . No measurement sites at all rockglaciers have BTS which changed to no permafrost which were in the first decade categorised as permafrost. A detailed table of the BTS for each logger and hydrological year is attached in the appendix A.7, A.8 and A.9.

5.4. Bottom Temperature of the Winter Snow Cover

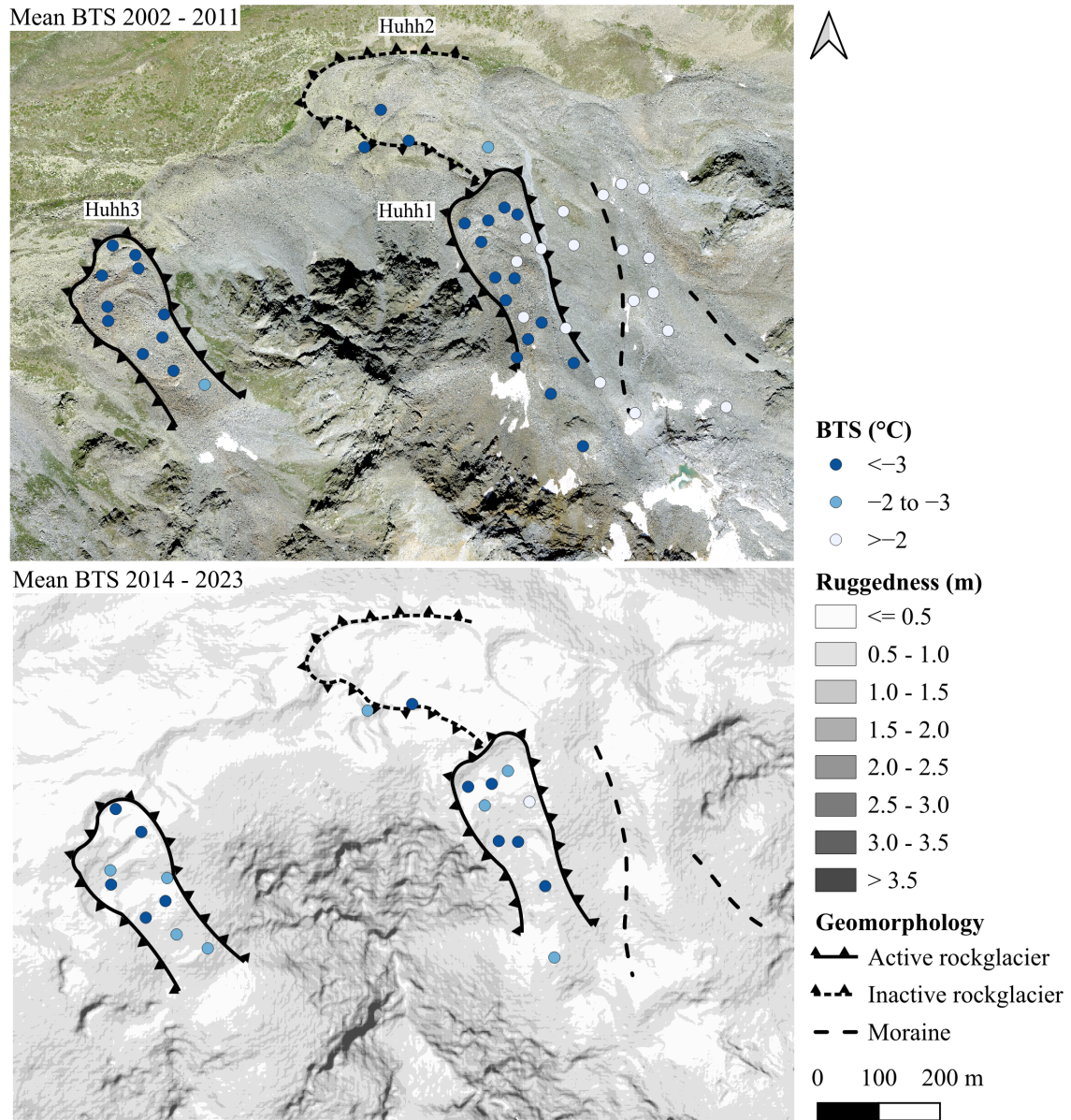


Figure 5.9: The mean BTS for the first decade (2002 – 2011) and for the second decade (2014 – 2023). In the second decade, no measurements were taken at the moraine. The temperature thresholds were chosen according to Hoelzle (1996) to distinguish into the three different states for the probability of permafrost occurrence. The background map for the second decade describes the ruggedness of the surface, the higher the ruggedness, the larger the prevailing grain size. Aerial image: swisstopo (2020). Data used for ruggedness map: swissALTI3D from swisstopo (2017).

5.5 Ground Freezing and Thawing Index

The GTI and GFI are calculated for each hydrological year at a regional aggregation level (Figure 5.10). The GTI indicates an increasing trend from 2002 to 2023. It is increasing with a slope of $+0.076^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}/\text{year}$. In contrast to the GFI, the individual years do not show a distinct pattern with increasing GTI values. The GTI is rather fluctuating with time but showing little evidence towards increasing values. The hydrological years from the second decade more often have larger GTI values than the first decade. The highest value of the GTI occurred in 2022 ($3.2^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$), the lowest value in 2013 ($0.2^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$).

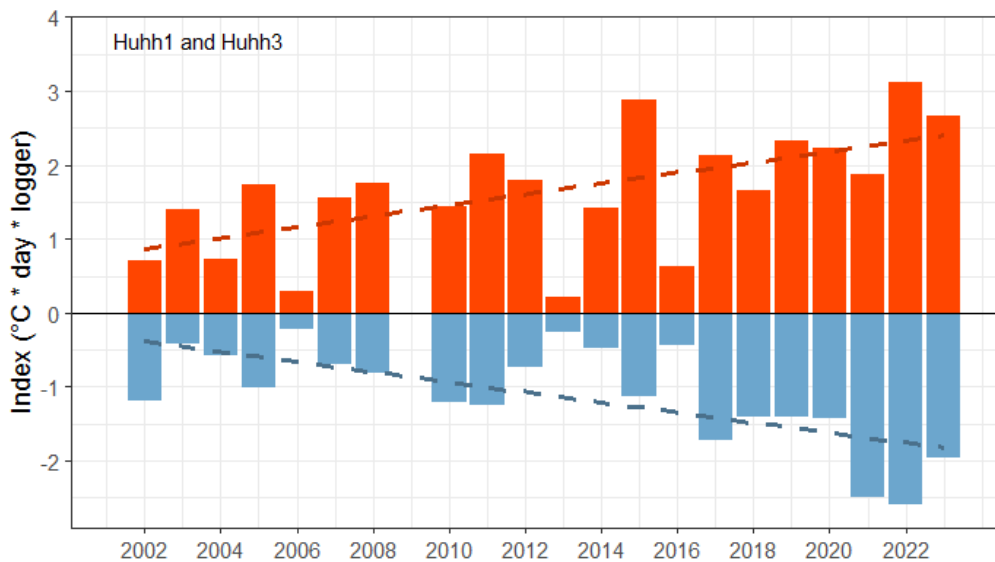


Figure 5.10: GTI (red bars) and GFI (blue bars) summarised for Huhh1 and Huhh3 from 2002 to 2023. Hydrological year 2009 does not have any data.

The GFI shows a decreasing trend over the study period. The GFI is decreasing with a slope of $-0.076^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}/\text{year}$. From the hydrological year 2002 to 2016, the GFI seems to be stable around -0.2 to $-1.2^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$. Since 2017, the size of GFI is between -1.4 and $-2.6^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$. The hydrological year 2006 represent the year with the value closest to zero with $-0.1^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$. The lowest GFI occurred in 2022 ($-2.6^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$), closely followed by 2021 ($-2.5^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$) and 2023 ($-2^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$).

In Figure 5.11, the ground freezing and thawing index is plotted for each rockglacier individually. Rockglacier Huhh1 (Figure 5.11 (a)) shows a trend similar to Huhh1 and Huhh3 being aggregated (Figure 5.10). The main difference represents

the GTI with mostly slightly smaller values. The greatest deviation is in the hydrological year 2015 in which Huhh1 has a GTI of $2.1^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$ in comparison to the summarised index of $2.8^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$. The largest GTI is $2.9^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$ in 2022, the smallest in 2013 with $0.3^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$. The lowest GFI occurred in 2022 with a size of $-2.5^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$, the maximum in 2006 with $-0.3^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$.

Figure 5.11 (b) shows the GFI and GTI for Huhh2. The GFI illustrates a decreasing trend. The lowest value is in 2022 with $-3.5^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$, the highest value in 2003 with $-0.6^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$. The quantity can be categorised into three periods. From 2002 to 2008, the average GFI has a size of $-1^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$. From 2010 to 2014, the average GFI is $-2^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$. The period 2017 to 2023 has an average GFI of $-2.4^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$. The GTI fluctuates from year to year in which no increasing or decreasing trend can be detected. The maximum GTI has a size of $3.6^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$ in 2006, the minimum $0.5^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$ in 2008.

Rockglacier Huhh3 has a distinct trend of the GFI and GTI (Figure 5.11 (c)). The smallest GFI value was in the hydrological year 2021 ($-3.8^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$), the largest in 2013 ($-0.25^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$). The maximum GTI represents the hydrological year 2006 ($3.4^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$) and the minimum in 2013 ($0.3^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$). The magnitude of the GTI is larger and the GFI is the same in comparison to Huhh1. Comparing it with Huhh2, the magnitude of the GFI of Huhh3 is slightly smaller than of Huhh2. The quantity of the GTI for Huhh3 is more frequently at a value of $2^{\circ}\text{C}\cdot\text{day}\cdot\text{logger}$ than for Huhh2.

5.5. Ground Freezing and Thawing Index

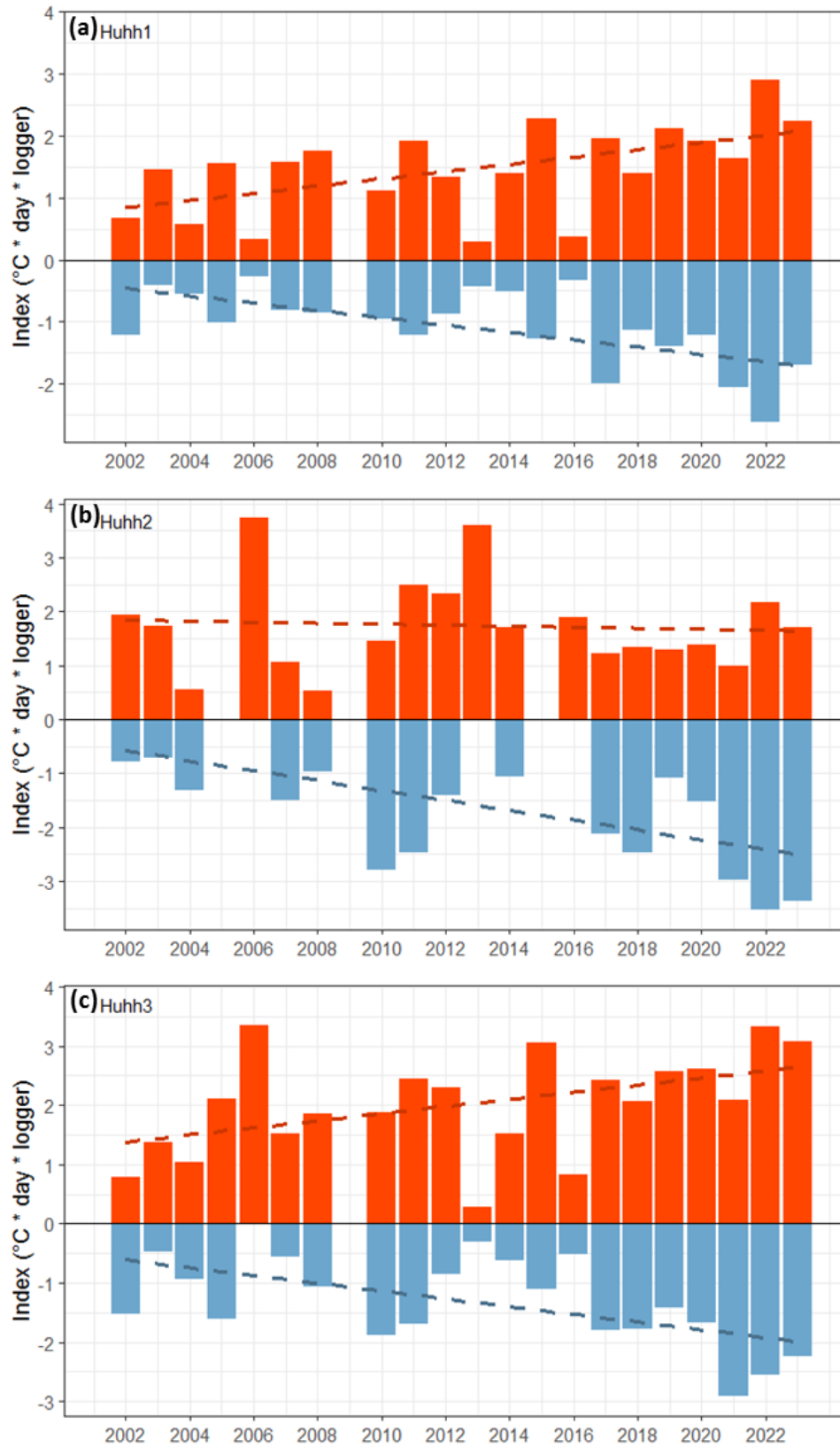


Figure 5.11: GTI (red bars) and GFI (blue bars) for Huhh1 (a), Huhh2 (b) and Huhh3 (c) from 2002 to 2023. Hydrological year 2009 does not have any data.

6. Discussion

6.1 Daily Mean Ground Surface Temperature

6.1.1 Hydrological year 2002

The MAGST of the hydrological year 2002 (01.10.2001 – 30.09.2002) is in comparison to the other hydrological years remarkable low with -2.74°C (Figure 5.5). It represents the lowest MAGST in the study period.

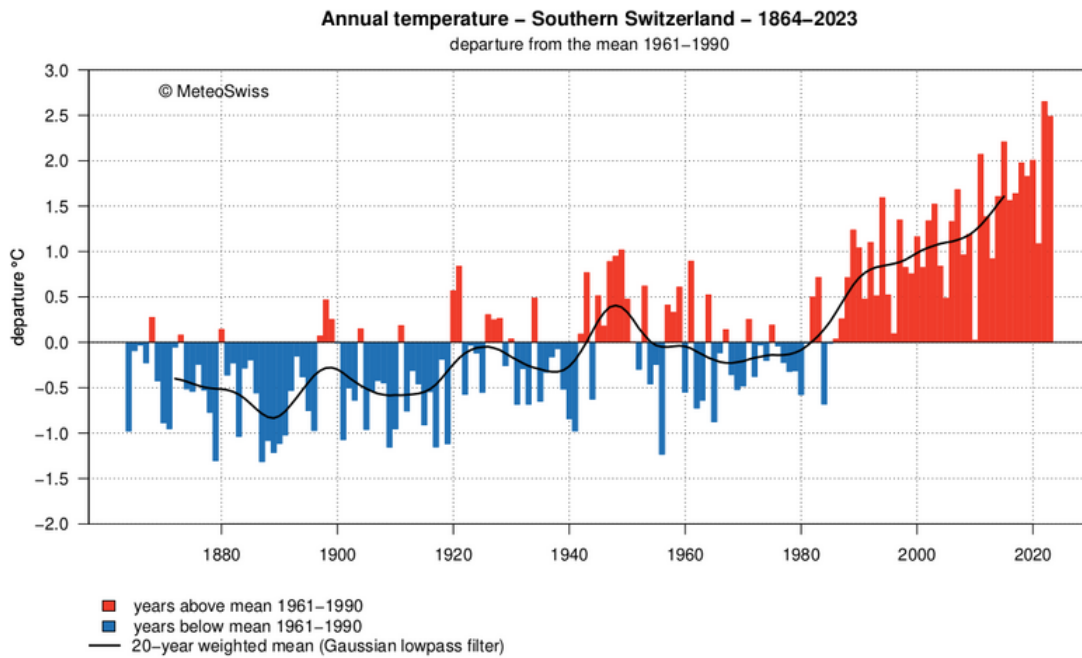


Figure 6.1: Departure from the MAAT 1961 – 1990 for Southern Switzerland (from MeteoSchweiz (2024)).

The departure from the annual air temperature in 2001 is just below the 20-year weighted mean and in 2002 slightly above (MeteoSchweiz 2024) (Figure 6.1). In comparison to the study period, the air temperature in the hydrological year 2002 represents a rather cold year, especially by analysing the summer months from April to September separately. Summer 2002 was the year with the third lowest departure from the mean 1961 to 1990. Low summer air temperatures cause lower GST values due to the direct influence of air temperature on GST (Guglielmin, Worland, & Cannone 2012; Hoelzle 1994). Hence, the GST did not rise as high as in other

6.1. Daily Mean Ground Surface Temperature

years which resulted in less energy flux at the ground. Less available energy at the ground causes less distinct active layer thicknesses (Haeberli et al. 2006; PERMOS 2023).

To see more details, an analysis on the basis of GST_{day} helps to see the cause and effect. The mean $\text{HTI}_{\text{start}}$ was at the 30th of December 2001 (Figure 5.3). Up to the $\text{HTI}_{\text{start}}$, the GST had the opportunity to cool down which resulted in low GST values (Biskaborn et al. 2019; Gubler et al. 2011; T. Zhang 2005). The snow index confirms the absence of snow during autumn and only little snow in December. From the $\text{HTI}_{\text{start}}$, the GST was insulated at low temperatures of around -5 to -10°C , depending on the location of the logger.

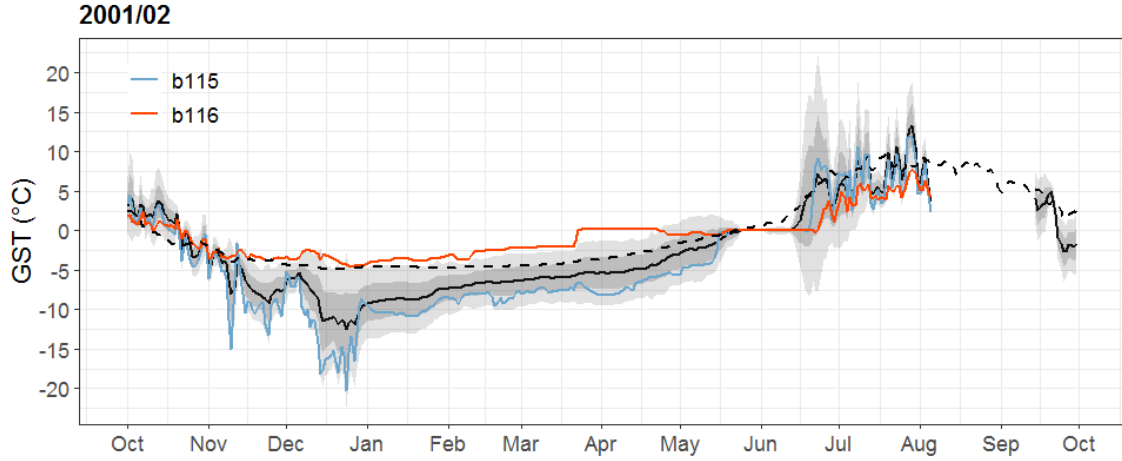


Figure 6.2: GST in the hydrological year 2002 for logger b115 and b116. The black line is the mean GST for all loggers on Huhh1 and Huhh3 for the hydrological year 2002, the dark grey area is the 68% percentile, the light grey area the 95% percentile. The dashed line is the multi-decadal mean for 2002 – 2023 with all rockglaciers aggregated. Between August and mid of September, no data is available for the hydrological year 2002.

Figure 6.2 describes the mean GST trend in the hydrological year 2002 with two selected loggers b115 and b116. Logger b115 represents the logger with the lowest GST course in winter. Logger b115 had its $\text{HTI}_{\text{start}}$ at the 5th of January 2002, which is visible by the stabilisation of the GST fluctuations at the beginning of January. Before, the GST decreased to values of up to -20°C . A GST of -20°C is extraordinary low, it represents the lowest measured GST in the study period. As visible in Figure 6.2, the mean MAGST for the entire study period from December

to April is around -5°C . Thus, the mean GST for the hydrological year 2002 was far below the long-term average. Many loggers had GSTs between -12 and -20°C , which is rather rarely the case in all other hydrological years.

Logger b116 does not follow the general GST trend in the hydrological year 2002. The $\text{HTI}_{\text{start}}$ occurred in early autumn thus the GST was insulated from low autumn and early winter air temperatures (Biskaborn et al. 2019; T. Zhang 2005). The GST reached its lowest value of -5°C and remained constant until the ZC phase in spring. The GST in winter is almost always larger than the 95% percentile (Figure 6.2). Hence, this logger distinguishes from other loggers in the hydrological year 2002 due to low GST fluctuations and no low values down to -12°C . Gislén et al. (2014) and Staub et al. (2017) stated that differing GST can be explained by the variation in snow height but also the exposition to the sun, the shading from surrounding terrain and ground properties. Nyenhuis (2005) described that logger b116 did not lie on coarse debris but on fine-grained material. The ruggedness analysis with a high-resolution digital elevation model (Figure 5.8) confirms this statement. The logger lies on the finest measurable grain size. However, the close surrounding has a higher ruggedness of up to 1 m.

The remaining loggers on the rockglaciers lie on coarse debris. Thus, this difference additionally influences the GST, although it lies directly next coarse-grained substrate. Small-grained material is unfavourable for permafrost (Nyenhuis 2005). Since fine-grained material can store more water due to the larger capillary forces, the thermal conductivity is larger compared to coarse debris where the voids are filled with air or snow (see section 2.5.6). Thus, the ground is not insulated during snow free periods. An insulating effect can be the case if the prevailing grain size is coarse due to the insulation of air (see section 2.5.6) and convective heat fluxes (see section 2.5.1). In addition, the $\text{HTI}_{\text{start}}$ occurred early at the location of b116 which is a reinforcing effect for a higher GST. The BTS for b116 in the hydrological year 2002 was -1.35°C indicating that there was probably no permafrost according to the definition of Hoelzle (1996). This assumption can be confirmed with the earlier data analysis by Roer (2005).

By comparing the hydrological year 2002 with other years, the mean GST had the lowest course (Figure 6.3). The hydrological years 2006 and 2017 also had low GST during winter. They had a mean GST down to -10 and -8°C , respectively. Since the time period with low GST is not as long and not as low as in 2002, the hydrological year 2002 had a remarkable low trend of GST in winter. Also, the

6.1. Daily Mean Ground Surface Temperature

quantity of this course is exceptional, only one logger (b116) out of 12 loggers total does not follow the mean GST. Such a constant trend is remarkable.

To conclude, low summer air temperatures, little snow in autumn and a late $\text{HTI}_{\text{start}}$ resulted in the lowest measured MAGST.

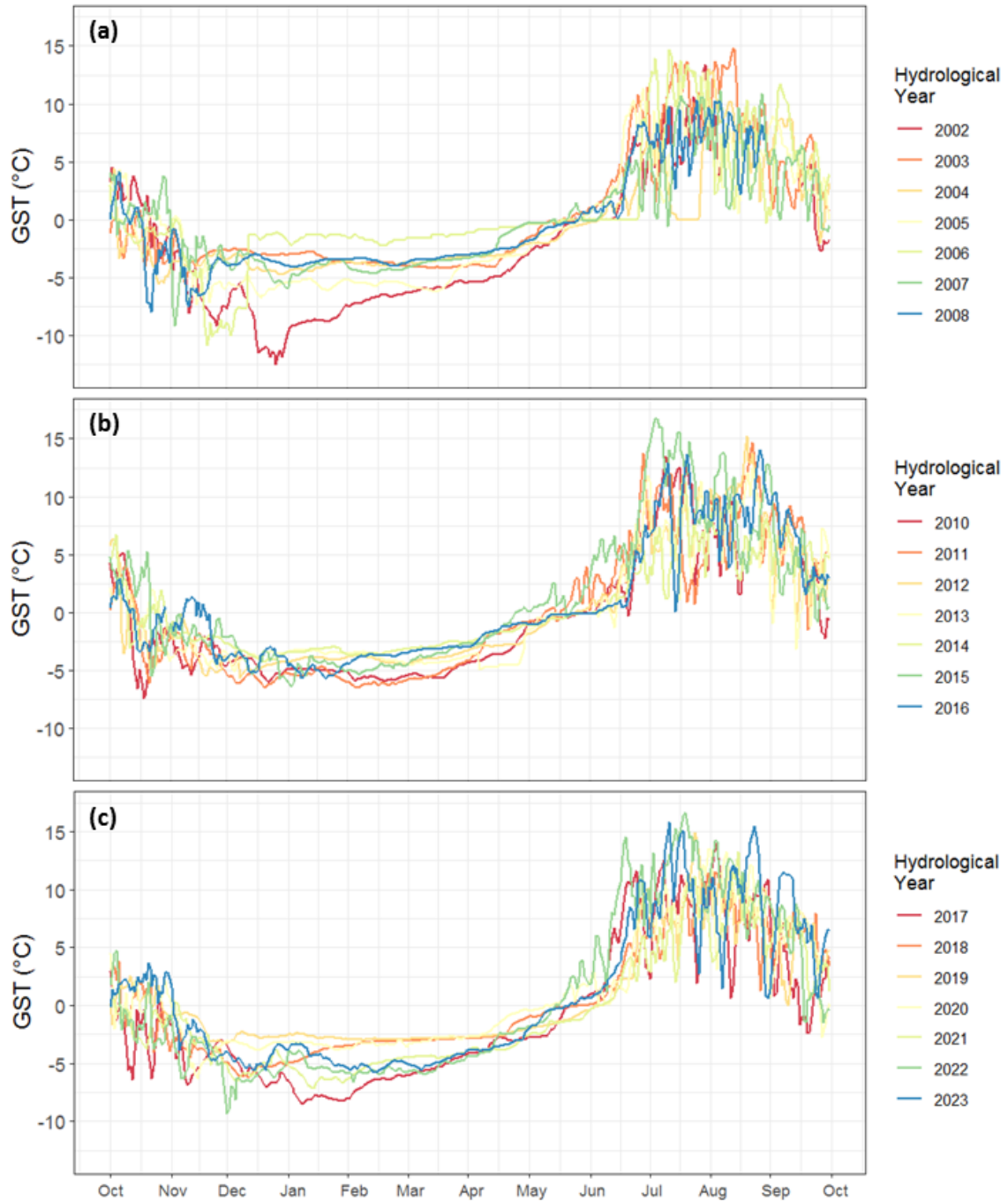


Figure 6.3: Mean GST_{day} for the hydrological year 2002 to 2008 (a), 2010 to 2016 (b) and 2017 to 2023 (c).

6.1.2 Hydrological year 2003

The hydrological year 2003 (01.10.2002 – 30.09.2003) had the warmest summer on record with 2.6°C above the mean from 1981 – 2010 (MeteoSchweiz 2024; PERMOS 2023). The meteorological winter was rather cold. In the period of 2001 – 2023, the winter 2002/03 had the sixth lowest departure compared to the mean of the climatological reference period 1961 – 1990 (MeteoSchweiz 2024).

The MAGST of the hydrological year 2003 (0.36°C) was high in comparison to the decade where it is within (Figure 5.5). Overall, the MAGST belongs to the hydrological year with the seventh highest MAGST.

Rockglacier Huhh1 had a MAGST of 0.26°C , Huhh3 0.59°C . Hence, Huhh3 had a MAGST more than two times larger. By comparing the MAGST of 2003 with the multi-decadal average 2002 – 2023, it is visible that the MAGST of 2003 is higher in winter and summer. In summer (July to end of August), the 95% percentile is almost always above the 2002 – 2023 average. This confirms that the extraordinary high summer air temperatures increased the GST in this period (Figure 6.4).

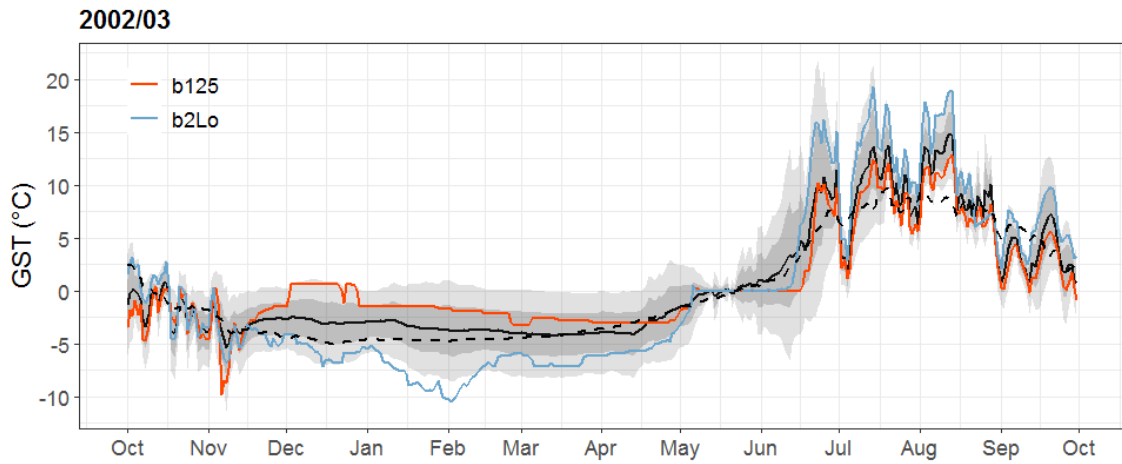


Figure 6.4: GST in the hydrological year 2003 for logger b125 and b2Lo. The black line is the mean GST for all loggers on Huhh1 and Huhh3 for the hydrological year 2003, the dark grey area is the 68% percentile, the light grey area the 95% percentile. The dashed line is the multi-decadal mean for 2002 – 2023, all rockglaciers aggregated.

The loggers on Huhh1 ($n = 12$) mostly had an early $\text{HTI}_{\text{start}}$, between the 7th of November (b102) and 5th of December (b118). Thus, the GST could not adapt to low temperatures since the time to cool down was limited. Only logger b125 had its $\text{HTI}_{\text{start}}$ on the 1st of January. The loggers b118, b125, b148 and b151 had in

6.1. Daily Mean Ground Surface Temperature

all measured years high GSTs during winter even though late (around New Year) $\text{HTI}_{\text{start}}$ occurred in other years. Those late timings of an insulating snow cover resulted only in a minimal reduction of the GST. Thus, these loggers may not be representative for a validation of the importance of a long time gap between the SOD and $\text{HTI}_{\text{start}}$ and a late $\text{HTI}_{\text{start}}$. Other factors, like the bulk effect or convection, may play a greater role for them. Although logger b125 had a late $\text{HTI}_{\text{start}}$, the GST did not decrease to low temperatures due to a ZC phase in December (Figure 6.4). At the end of December, the $\text{HTI}_{\text{start}}$ occurred so that the GST could not decrease.

Four loggers on rockglacier Huhh3 ($n = 5$) had a $\text{HTI}_{\text{start}}$ between the 15th (b211) and 21st (b214) of November. Logger b2Lo had a rather late $\text{HTI}_{\text{start}}$ on the 28th of December. Thus, the winter GST did not decrease to low values besides b2Lo and b218. Since b2Lo had a late start of insulation, the GST decreased to -10°C (Figure 6.4).

Logger b218 had GSTs down to -6°C despite an early $\text{HTI}_{\text{start}}$ (15.11.). The snow index refers to strongly fluctuating snow amounts in autumn. This resulted in a ground cooling even with a thin snow cover, resulting in lower GST. Keller (1994) found that a thin snow cover of around 5 cm results in the largest emission of energy. This can lead to a strong cooling of the upper ground layers as it is represented by the GST measurements. In this case, logger b218 constitutes the early autumn snow effect with only little snow. Since no measurements are available about the snow thicknesses on this specific location, the statement cannot be validated and only based on the temperature measurement of the ground surface.

The loggers b210, b211 and b214 all had a constant GST trend between -3 and -5°C . The snow index does not have a large variability thus the snow cover had an insulating effect on the ground. However, b211 had no ZC which is an indicator for only little snow. Since the GST is not fluctuating during winter, an insulating layer was existent. The GSTs were constant at 0°C for a short time period in spring, indicating a short ZC (< 2 weeks).

The rockglacier Huhh2 ($n = 3$) had a MAGST of 0.19°C . Thus, it represents the lowest MAGST in the hydrological year 2003. The $\text{HTI}_{\text{start}}$ was for logger b045 on the 17th of November, for the loggers b042 and b0Sp on the 20th of November. The SOD was for b042 seven weeks before the $\text{HTI}_{\text{start}}$. The other loggers did not have such a long period between the start of snow and an insulating snow cover (24 days for logger b045 and only 8 days for logger b0Sp). However, the GST did not

6.1. Daily Mean Ground Surface Temperature

differ strongly between the loggers, they all had a decreasing GST in autumn with a stabilisation around -5°C .

In summary, an extraordinary high summer air temperature caused high summer GSTs. A rather cold winter could decrease the GST, however, the $\text{HTI}_{\text{start}}$ was early for almost all loggers. Thus, the summer heat could not leave the system and was insulated in the ground during the winter, resulting in rather high winter GST. Hence, the hydrological year 2003 had an especially high MAGST for the first decade.

6.1.3 Hydrological year 2010

The hydrological year 2010 (01.10.2009 – 30.09.2010) was the year within the calendar year 2010 which had the lowest MAAT in my study period. Likewise, the meteorological winter 2009/10 was the coldest one with a negative anomaly of -1.3°C from the mean 1961 – 1990. Dividing the year into a summer and winter half-year, the summer half-year (April to September) was the sixth coldest summer in the period of 2001 to 2023. The winter half-year was the second coldest winter (MeteoSchweiz 2024).

By comparing the mean GST_{day} from the hydrological year 2010 with other years, the GST was not especially low or high (Figure 6.3). During winter, the mean GST was at -5°C . Many other hydrological years, for example 2002, 2005, 2017 or 2021 had lower GSTs in winter. However, the hydrological year 2010 had the fourth lowest MAGST (-1.12°C) in my study period.

The loggers on rockglacier Huhh1 ($n = 8$) had a $\text{HTI}_{\text{start}}$ between the 27th of October and 2nd of December. Only logger b118 had a late $\text{HTI}_{\text{start}}$, at the sixth of January. Since the time gap between the different starts of insulation differ by about two months, the ground cooling depends on the timing of the $\text{HTI}_{\text{start}}$. Late $\text{HTI}_{\text{start}}$ resulted in a ground cooling. The snow index was constant at almost every site, thus the GST could not decrease to low temperatures. Logger b198 represents the logger with one of the highest GST during winter (Figure 6.5). From the $\text{HTI}_{\text{start}}$ (07.11.2009) until the ZC, the GSTs remained constant.

Rockglacier Huhh3 ($n = 8$) had a slightly different pattern in the GST trend. The $\text{HTI}_{\text{start}}$ for most loggers was between the 2nd of December and 8th of January. Thus, these locations had enough time to adapt to low air temperatures which is reflected by the trend of the GST. Loggers b218 and b220 had a $\text{HTI}_{\text{start}}$ at the 26th

6.1. Daily Mean Ground Surface Temperature

of October. As a result, logger b220 had a rather high GST (minimum of -5°C). Despite an early insulation at the site of logger b218, the GST was not insulated enough to prevent the ground to cool down. The minimum GST was -10°C , which is rather low. The strongly fluctuating snow index explains a possible lowering of the GST.

A special case was found at the site of logger b210. The GST strongly varied during winter (Figure 6.5) due to very little snow recorded by the snow index. Its $\text{HTI}_{\text{start}}$ was at the 26th of March, thus no insulating snow layer prevented the ground from cooling down. During winter, many loggers on Huhh3 had a strong fluctuating GST. This is an opposite behaviour in comparison to the loggers on Huhh1. Since the snow index varies at many loggers on Huhh3 but not on Huhh1, the snow redistribution depending on rockglacier site defined the amount of snow and thus, the insulating effectiveness (Biskaborn et al. 2019; French 2017). Snow redistribution can vary within local scales in alpine terrain due to snow drift, surface properties and avalanches (Gisnås et al. 2014; Stocker-Mittaz, Hoelzle, & Haeberli 2002).

The mean GST in comparison to the long-term mean only differs during summer from mid of June to mid of July. In this period, the mean GST of 2010 was higher than the long-term average.

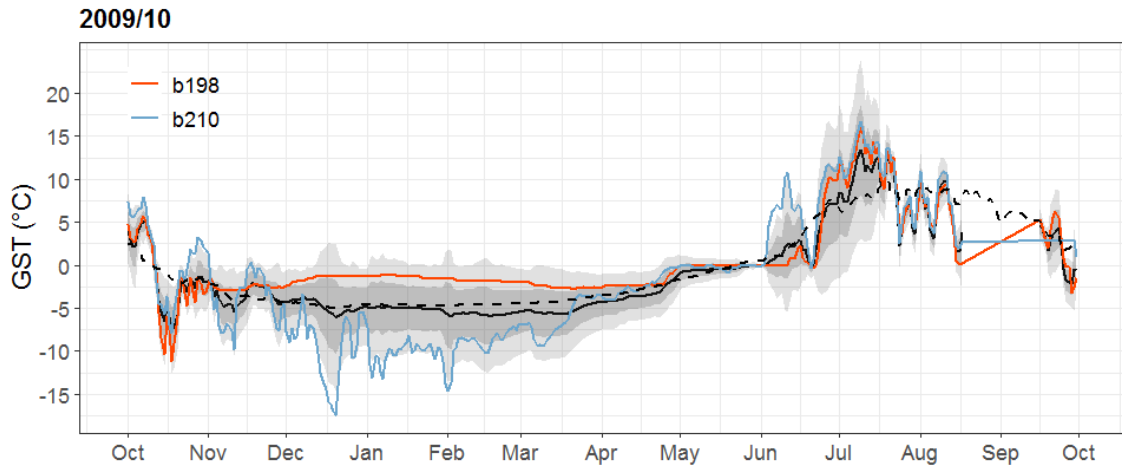


Figure 6.5: GST in the hydrological year 2010 for logger b198 and b210. The black line is the mean GST for all loggers on Huhh1 and Huhh3 for the hydrological year 2010, the dark grey area is the 68% percentile, the light grey area the 95% percentile. The dashed line is the multi-decadal mean for 2002 – 2023, all rockglaciers aggregated. From August to mid of September, no data for the hydrological year 2010 was available. The straight lines from mid of August to mid of September for both loggers are linear interpolations between measurements.

In summary, a cold summer half year in combination with a cold winter, enabled the GSTs to adapt to low temperatures, depending on the timing and amount of snow cover. Even though the year 2010 was the coldest on record in my measurement period (MeteoSchweiz 2024), no very low GST were measured. Thus, the timing and the thickness of snow has at least the same importance than extraordinary low air temperature to get low MAGST. This was also found by Gislén et al. (2014), Gubler et al. (2011), and T. Zhang (2005). However, since no measurements are available between mid of August and mid of September, the MAGST is less influenced by high air temperatures. Only on 332 (Huhh1) and 326 (Huhh3) days were measurements available. Since this is still 91% and 89% respectively, the calculation of the MAGST is valid.

6.1.4 Hydrological year 2015

The hydrological year 2015 (01.10.2014 – 30.09.2015) has the highest observed MAGST of 1.15°C (Figure 5.5). Looking at the GST development of the individual loggers, two different behaviours are detected. The loggers on rockglacier Huhh1 ($n = 2$) generally had an early $\text{HTI}_{\text{start}}$ at the beginning of November. Thus, the GST could not cool down before the snow had its insulating effect. During the entire winter, the GST did not decline to lower temperatures as they were at the $\text{HTI}_{\text{start}}$. Although the snow index indicates a variable amount of snow, the GST remained constant. Logger b103 did not have a ZC in spring, which indicates little snow. However, logger b103 had the highest GST trend in winter although little snow could have lead to a cooling of the ground surface (Figure 6.6). Logger b103 lies on fine-grained material (Figure 5.8, personal communication) which influences the trend of GST.

The loggers on rockglacier Huhh3 ($n = 3$) quantified an opposite behaviour. Their $\text{HTI}_{\text{start}}$ was between mid-January and the beginning of February. As a result, their GST was lower in comparison to Huhh1 in winter. Though, no logger on Huhh3 had a ZC in spring. Logger b210 had the lowest trend of winter GST (Figure 6.6).

Comparing the mean GST of 2015 with the long-term mean (2002 – 2023) shows that the GST in winter was at the long-term average. However, from June to the end of August, the mean GST of 2015 was considerably higher (Figure 6.6).

The departure from the mean 1961–1990 of the MAAT 2015 had the third largest anomaly (+2.2°C) (MeteoSchweiz 2024), indicating a warm year (PERMOS 2023). Reducing the period to the six winter months (October to March) results in the

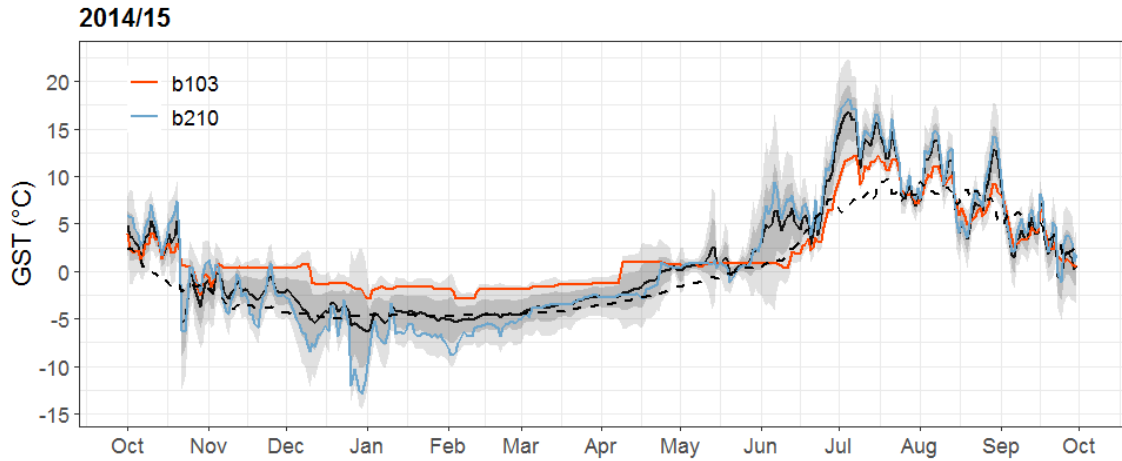


Figure 6.6: GST in the hydrological year 2015 for logger b103 and b210. The black line is the mean GST for all loggers on Huhh1 and Huhh3, the dark grey area is the 68% percentile, the light grey area the 95% percentile. The dashed line is the multi-decadal mean for 2002 – 2023, all rockglaciers aggregated.

winter with the fourth largest anomaly of the mean 1961 to 1990. If looking only at three summer months indicates that the months from June to August had the fourth largest mean anomaly (MeteoSchweiz 2024).

High air temperatures due to warm summer and winter were the most influencing factors for the hydrological year 2015 that caused the highest measured MAGST. Having two opposite timings of the HTI_{start} confirms that the winter was not a cold winter. Since the loggers on rockglacier Huhh3 were not insulated at a snow thickness of > 0.8 m, the GST could have adopted to low values if the air temperature made it possible (Goodrich 1982; Haberkorn et al. 2021; T. Zhang 2005). However, the GST did not decrease to a value worth mentioning.

Kenner et al. (2024) stated that the year 2015 was a snow-poor winter which can be validated with the absence of ZC periods at four out of five loggers. Even though the timing and duration of a snow cover additionally accounts to the main factors influencing GST (Hoelzle 1996; PERMOS 2023; Roer 2005). In the case of the hydrological year 2015, it can be neglected. If the air temperature in winter does not decrease to low temperatures, the importance of a late insulating effect due to snow is low. Only if the snow cover prevents the ground from cooling down, the snow cover has to be included in the interpretation of the GST trend.

6.1.5 Hydrological year 2022

The hydrological year 2022 (01.10.2021 – 30.09.2022) is the second warmest hydrological year ever measured in Switzerland (PERMOS 2023). Furthermore, it is within the period of the warmest year concerning air temperature (MeteoSchweiz 2024). The MAAT of the calendar year 2022 was as high as never before since the start of the measurements in Switzerland (MeteoSchweiz 2024). Three heat periods lead to the second warmest summer on record. Only summer 2003 had higher air temperatures (MeteoSchweiz 2024; PERMOS 2023). Likewise, the winter 2022 was warmer than the long-term mean 1981 – 2010 (PERMOS 2023).

The MAGST of the hydrological year 2022 was high (0.51°C) but for the period where it is within it is not extraordinary high (Figure 5.5). The mean GST was lower in winter but was strongly above the long-term average for 2002 – 2023 in summer (Figure 6.7). From mid-June, the 95% percentile is above the long-term average until mid-August. This reflects the second warmest summer on record.

Seven loggers on rockglacier Huhh1 were distributed. All loggers, besides logger b103, have a strong fluctuating GST between the SOD and the $\text{HTI}_{\text{start}}$. Thus, the GST could decrease to temperatures of -7°C . From the $\text{HTI}_{\text{start}}$ to the ZC, the temperature trend remained more or less constant. Only logger b110 had a fluctuating GST trend. Even though logger b103 was not directly insulated at the beginning of the cold phase, the GST did only decrease to -2°C and remained constant until the ZC. Logger b1Wu represents the highest located logger on Huhh1. Since the GST depends on altitude (Gubler et al. 2011), the expected GST trend would have been lower (Figure 6.7). However, since b1Wu had a rather early $\text{HTI}_{\text{start}}$ (15.12.) in comparison to other loggers, the GST was early insulated from the atmosphere. Nevertheless, logger b112 had its $\text{HTI}_{\text{start}}$ five days earlier than b1Wu and its GST trend achieved lower temperatures. However, b112 had no ZC in spring which indicates that the snow cover was probably thin. Logger b1Wu had a short but distinct ZC.

The logger on rockglacier Huhh2 has the same pattern like the majority of the loggers on Huhh1. From the SOD (06.10.) to the $\text{HTI}_{\text{start}}$ (20.12.), the GST decreased to -7°C and remained constant until the ZC, which was rather short.

On rockglacier Huhh3 six loggers were distributed. The pattern of all loggers, besides b210, follow the same trend as the loggers on Huhh1 and Huhh2. Logger b210 did not have a $\text{HTI}_{\text{start}}$ thus the GST in winter was strongly fluctuating (Figure 6.7). The subsequent ZC was short, but existent.

6.1. Daily Mean Ground Surface Temperature

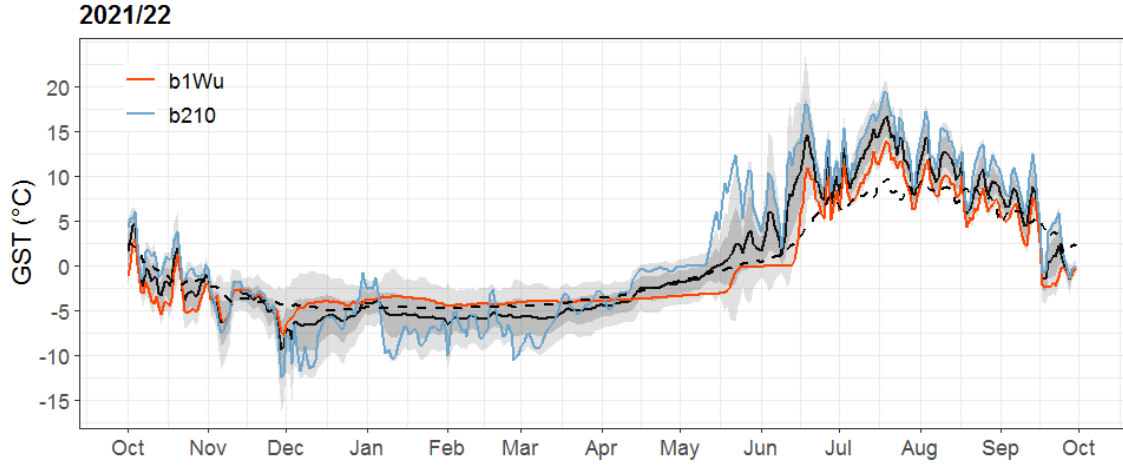


Figure 6.7: GST in the hydrological year 2022 for logger b1Wu and b210. The black line is the mean GST for all loggers on Huhh1 and Huhh3, the dark grey area is the 68% percentile, the light grey area the 95% percentile. The dashed line is the multi-decadal mean for 2002 – 2023, all rockglaciers aggregated.

In summary, snow fall around New Year insulated most of the loggers on all rockglaciers. Up to the $\text{HTI}_{\text{start}}$, the GST decreased to a minimum temperature of -7°C . At most sites, the snow cover had an insulating effect resulting in constant GST during winter at rather high temperatures between -2 to -7°C . The warm winter in combination with a warm summer period resulted in the fifth highest MAGST in the study period. Even though the summer was the second warmest on record, the effect on the mean GST was greater than in the hydrological year 2003 (Figure 6.4 and 6.7), resulting in a higher MAGST.

However, there was no evidence found why the hydrological year 2022 had not an extraordinary high MAGST since it is within the warmest year concerning air temperature and recorded the second warmest summer. Further analysis considering the timing and duration of the ZC or the snow disappearance date in spring may provide explanations.

6.1.6 Time gap between Snow Onset Date and start of High Thermal Insulation

A late $\text{HTI}_{\text{start}}$ is crucial for low GST during winter (PERMOS 2023) and thus, for the BTS (Marmy et al. 2013; Schoeneich 2011; T. Zhang 2005). As visible in Figure 5.3, a late $\text{HTI}_{\text{start}}$ correlates with low BTS since snow has an insulating effect on the surface (G. Li et al. 2021; Marmy et al. 2013; T. Zhang 2005). The hydrological

year 2002 has the lowest BTS and the second latest $\text{HTI}_{\text{start}}$. In combination with a long time gap between the SOD and the $\text{HTI}_{\text{start}}$ (46 days), the ground could cool down during the sensitive phase for permafrost in autumn and early winter.

The hydrological year 2006 confirms the assumption by the opposite behaviour. The highest measured BTS took place after the earliest measured SOD, $\text{HTI}_{\text{start}}$ and the shortest time gap. An insulating snow cover from the 21st of October prevents the ground from cooling down (G. Li et al. 2021; PERMOS 2023; Schoeneich 2011; T. Zhang 2005). Thus, the stored summer heat in the active layer could not efficiently leave the system (PERMOS 2023).

However, not all years follow this assumption. Looking closer at the period of 2014 to 2016, neither the $\text{HTI}_{\text{start}}$ nor the length of the time gap can explain the size of the BTS. In 2014, an early $\text{HTI}_{\text{start}}$ (09.11.) resulted in a rather high BTS (-2.67°C) whereas the time gap had a duration of only 15 days. In contrast, the hydrological year 2016 had a late $\text{HTI}_{\text{start}}$ (25.12.) and the time gap lasted 43 days. This would imply a low BTS. However, the BTS was only slightly lower than in 2014. Thus, other factors affected the size of BTS in 2016.

Generally spoken, a late $\text{HTI}_{\text{start}}$ results in a low BTS. Though the length of the time gap having a major role cannot be confirmed since the combination of a short time gap between the SOD and the $\text{HTI}_{\text{start}}$ whereas the $\text{HTI}_{\text{start}}$ is late, did not occur in the study period. The timing of the SOD seems to play a minor role since an early (e.g. 2021) or late (e.g. 2002) SOD can result in a low BTS.

6.2 Monthly Mean Ground Surface Temperature

The low variability between November and April is caused by the insulation of snow (Figure 5.4). If the loggers are covered by a snow layer with a thickness > 0.8 m, the GST remain constant (Gisnås et al. 2014; Haeberli 1973). Because the loggers are all distributed within a small region, the timing and thickness of the snow cover does not vary strongly at an aggregation on rockglacier level. Only by analysing loggers individually, differences in the timing of the $\text{HTI}_{\text{start}}$ are detected due to the importance of the topographic variability (Gubler et al. 2011).

The snow free period has the largest variability between the loggers and sites. If the ground is free from snow, the GST is directly coupled with the atmosphere (Guglielmin, Worland, & Cannone 2012; Hoelzle 1994). Thus, the exposition, the surface properties and the amount of direct incoming solar radiation are the dominant influencing factors (Hoelzle 1996; Kenner et al. 2024; PERMOS 2023). If a

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logger is placed unfavourably, it may be exposed to direct solar radiation, which can distort the recorded measurements. However, this results in small-scale variability of GST during snow free periods.

In May, a very low variability is detected. The median of the GST and its variation is almost 0°C . During May, many measurement sites are at their ZC period. Since the incoming energy is transferred to latent heat due to melt of snow, the GST remains constant at 0°C (Gisnås et al. 2014; Outcalt, Nelson, & Hinkel 1990; Staub & Delaloye 2017). In June, the variation between the rockglaciers starts to increase. The large data spread in June and July can be reduced to the heterogeneous surface albedo. During snow melt in spring, the distribution of snow disappearance is highly variable (Hoelzle 1992). The duration of the ZC depends on the snow thickness (Gubler et al. 2011). The thicker the snow layer, the longer the ZC period (T. Zhang 2005). Due to the small-scale variability of snow cover on rockglacier scale, the duration of the ZC can be explained by the diverse thicknesses of snow cover. Since the distribution of snow depends on topographic landforms, inclination and small-scale surface properties, the amount of snow may differ significantly. Huhh1 is located at the east side of the Hungerlihorli, hence it receives less direct incoming solar radiation in the afternoon in comparison to Huhh2 or Huhh3. This could lead to increased amounts of snow due to less melt energy. In June, only Huhh3 had a median $> 0^{\circ}\text{C}$, indicating the earliest timing of snow-free period. The data spread of Huhh1 starts to increase in June towards a positive GST indicating the timing of the melt out date. Since the median still remains at 0°C , Huhh1 has its melt out date between June and July for the majority of the years. Huhh2 has the latest melt out which may result from the marginal inclination which favours snow accumulation (Gisnås et al. 2014).

Gisnås et al. (2014) found that the largest variability of monthly mean GST was during the winter months with a developed snow cover (January to April). They stated that the variation in snow cover is the dominating factor of influencing spatial variability in GST. During snow free periods, they observed low spatial variability. Since their study area was in high latitudes and low altitudes (500 – 600 m a.s.l.), their findings may differ from this study.

The study from Staub and Delaloye (2017) found results similar to this study. The used data are from a rockglacier in the Lower Valais, called Alpage de Mille. They observed a large data spread of GST during snow free periods and a small data spread during snow covered periods. An insulating snow cover reduces the standard

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deviation SD of the mean GST_{day} by a factor of at least five to ten. In addition, they compared the mean GST_{day} with the daily mean air temperature. During snow free season, the daily SD of GST is of the same order like the daily SD of the air temperature.

Comparing the monthly mean GST with the monthly mean air temperature (Figure 5.4) depicts that the air temperature has lower values in winter and summer. Only during the snow melt phase (May and June), the air temperature is higher than the GST. In autumn, the air temperature correlates with the GST. The monthly mean GST and the the monthly mean air temperature in October and November are pretty similar. The mean SOD is at the end of October (27.10.), and the mean $\text{HTI}_{\text{start}}$ is at the beginning of December (06.12.). Hence, indicating that the ground is directly coupled with the atmosphere until December (Gubler et al. 2011; Staub et al. 2017).

Since the GST during winter (from December to April) is insulated by a snow cover, the GST is higher than the air temperature (Hoelzle et al. 2001; PERMOS 2023; T. Zhang 2005). The air temperature is below -3°C during these months for the catchment area Turtmännen-Gruben (HADES 2023), indicating that precipitation falls as snow (see section 4.2, Figure 4.4).

From May until September, the mean monthly GST is lower than the mean monthly air temperature. In this period, the air temperature is above 0°C (HADES 2023). In May, during the ZC phase, the GST remain at 0°C due to phase change (T. Zhang 2005). Since snow melt can only occur if the air temperature rises above 0°C (French 2017) or precipitation falls as rain (Gustafsson, Stähli, & Jansson 2001), the mean monthly air temperature is larger than the GST. French (2017) found that the spring thaw occurs during the first five weeks of air temperature rising above 0°C . Substrate consisting of coarse material has a rapid thaw because percolation is easy and the thermal conductivity is high (French 2017). Thus, the period of phase change is not sensitive to long time periods since the rockglaciers consist of coarse-grained substrate.

From the point when the snow cover is depleted (July), the mean monthly GST is higher than the mean monthly air temperature. Low albedo at the ground surface heats the adjacent terrain which results in a higher GST in comparison to the air temperature (Gustafsson, Stähli, & Jansson 2001; Hoelzle 1994; Hoelzle et al. 2001; Keller 1994).

To conclude, the direct influence of the air temperature depends on season. It is reduced during periods with snow (Guglielmin, Worland, & Cannone 2012; Haeberli et al. 2010; Hoelzle et al. 2001), whereas the timing and thickness play a crucial role for the size of the GST during winter (Guglielmin, Worland, & Cannone 2012; PERMOS 2023). However, the data spread between the sites is low since the snow distribution is rather uniform and has a long-lasting effect on GST. During snow free periods, the air temperature is depicted as the dominant driver for the GST (e.g. Guglielmin, Worland, & Cannone 2012; Haeberli et al. 2010; PERMOS 2023). This results in the highest GST variability in snow free periods.

6.3 Mean Annual Ground Surface Temperature

The MAGST increased during the study period with a size of $+0.076^{\circ}\text{C}/\text{year}$ (Figure 5.5, total increase of $+1.6^{\circ}\text{C}/21$ years) which results from rising air temperatures and changing precipitation patterns due to climate change (Biskaborn et al. 2019; IPCC 2013, 2019; Kenner et al. 2024). The results presented by PERMOS (2023) from two rockglaciers in the Lower Valais showed an increase of $+0.036^{\circ}\text{C}/\text{year}$ and $+0.047^{\circ}\text{C}/\text{year}$. Hence, the rockglaciers in the Hungerlitelli experienced a larger increase of MAGST than the ones in the Lower Valais. However, the flat and steep bedrock on Corvatsch in the Engadine also had a MAGST increase of $+0.092$ and $+0.085^{\circ}\text{C}/\text{year}$, respectively (PERMOS 2023).

The interpretation of the MAGST depends on various factors. In this study, the MAGST depended on internal factors (e.g. topographic variability). The timing of the $\text{HTI}_{\text{start}}$, the snow thickness and the end of the ZC phase were of great importance. Years with considerable low (e.g. hydrological year 2010) or high (e.g. summer in hydrological year 2003) air temperatures did not correlate with outstanding low or high MAGST, respectively (Figure 5.5). Many studies, (e.g. Gubler et al. (2011) and Luo, Jin, and Bense (2019)) confirm that large MAGST variability can be explained with the topographic variability. In addition, they found that the MAGST varied stronger at sites with large boulders, steep terrain and variable snow distribution.

6.3.1 Deviation of the Mean Annual Ground Surface Temperature

Along the lines of the Swiss Permafrost Bulletin 2022 (PERMOS 2023), the deviation of the MAGST was calculated (see section 5.3.1, Figure 5.7). PERMOS (2023) analysed two rockglacier sites in the Lower Valais (Aget and Alpage de Mille, Figure 6.8). They calculated the deviation of the MAGST for the period 2006 – 2015 for each hydrological year since 2000. In most hydrological years, the deviation of the MAGST has the same algebraic sign in comparison to the Hungerlitelli. If the algebraic sign is the opposite, the anomaly is small around 0°C.

Exceptions are the hydrological years 2006 (Hungerlitelli vs. Aget and Alpage de Mille), 2013 (Hungerlitelli vs. Alpage de Mille) and 2016 (Hungerlitelli vs. Aget). In 2006, both rockglaciers in the Lower Valais had a negative anomaly of slightly larger than -1°C . The rockglaciers in the Hungerlitelli had a positive anomaly of $+0.5^{\circ}\text{C}$. The same behaviour was detected in 2016 by comparing the Hungerlitelli with rockglacier Aget. In 2013, the rockglaciers in the Hungerlitelli had a negative deviation from the MAGST. However, rockglacier Alpage de Mille had a positive deviation of the MAGST.

The MAGST strongly depends on seasonal atmospheric variations and snow conditions ($\text{HTI}_{\text{start}}$ and snow disappearance date) (PERMOS 2013), the prevailing grain size (Haeberli et al. 2006; Nyenhuis 2005; Roer 2005) and the exposition (Gubler et al. 2011; Hoelzle 1994; Keller 1994). Since the rockglaciers are all located in a similar climate, the atmospheric conditions differ minimal. However, small-scale variations are not related since the rockglaciers are located in different valleys. The timing and duration of the snow cover has a major influence on the MAGST (Gubler et al. 2011; PERMOS 2013) thus the variation of anomalies can be explained by the small-scale variability of snow. Likewise, the grain size may differ which, is also an important factor influencing the existence of permafrost (Haeberli et al. 2006; Nyenhuis 2005; Roer 2005). During snow-free periods, an exposition orientated towards a sun exposed direction in combination with fine-grained material can reinforce unfavourable permafrost conditions (Gubler et al. 2011; Hoelzle 1994).

In addition to the reference period 2006 – 2015, the deviation of the MAGST for the first and last decade was calculated (Figure 5.7). The MAGST average for the first decade (2002 – 2011) is considerably lower in comparison to the intermediate and last decade. Thus, the MAGST anomaly is high, especially in the last decade. If the deviation of the MAGST average in the period 2006 – 2015 is calculated, the

6.3. Mean Annual Ground Surface Temperature

first decade exhibited negative anomalies more frequently than the last decade. The deviation of the MAGST 2014 – 2023 points out that this decade had high MAGST since almost all hydrological years ahead of the last decade have negative anomalies. Likewise, the last decade is the first one which had a positive MAGST average. This shifting of the MAGST average highlights the trend towards increasing MAGST. Although the snow distribution, thickness, timing and duration of an insulating snow layer are of great importance on an interannual scale (Gisnås et al. 2014; Goodrich 1982; Gubler et al. 2011; Haberkorn et al. 2021), an increase in permafrost temperatures over multi-decadal periods is a consequence of rising air temperatures (Biskaborn et al. 2019; IPCC 2019; Kenner et al. 2024).

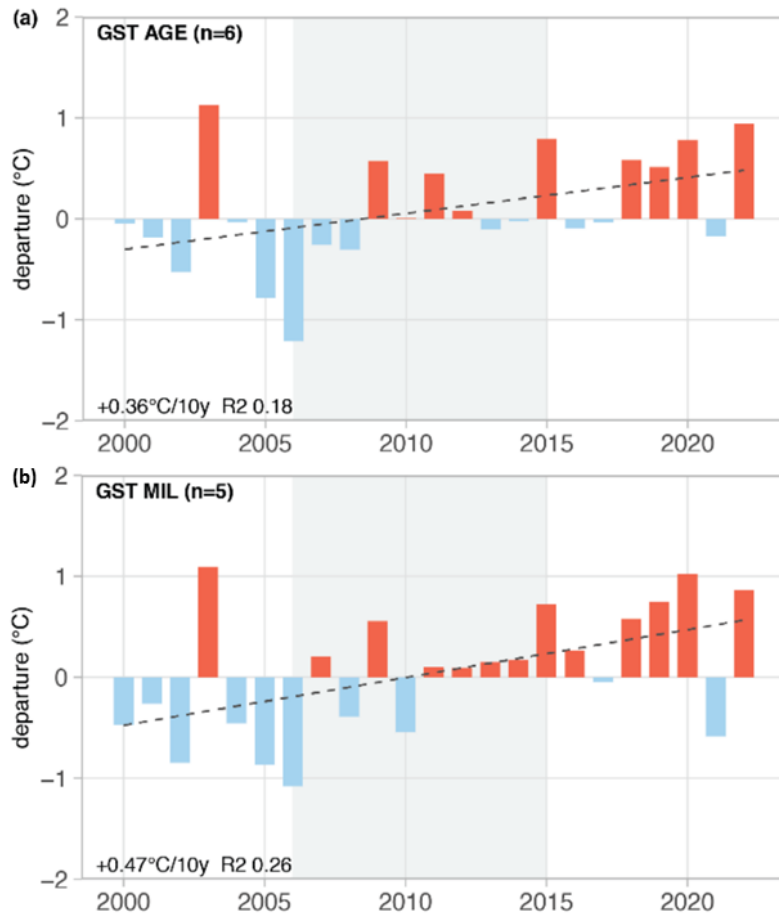


Figure 6.8: Deviation of the MAGST from the decadal average 2006 – 2015 for two rockglacier sites in the Lower Valais, (a) Aget and (b) Alpage de Mille. The number within brackets denotes the quantity of individual loggers utilised to compute the average for the sites. The dashed line represents the linear trend observed in the time series since the year 2000 (from PERMOS (2023)).

6.3.2 Mean Annual Ground Surface Temperature dependent on Rockglacier

As seen in section 5.3, the MAGST differ between the rockglaciers, especially between the actives and the inactive (Figure 5.6). The inactive rockglacier has lower MAGST in every hydrological year, besides 2012, than the active rockglaciers. Assuming less amount of ice in the ground, due to the inactive state of the rockglacier, would lead to a decreased ground cooling and thus, to higher MAGST (Kenner et al. 2024). However, this is not observed in this study. Other factors lead to a decreased MAGST.

The exposition slightly differs between the rockglaciers. Huhh2 is orientated west to northwest whereat the other two are north to northwest orientated. Thus, this could lead to slightly increased incoming solar radiation which would increase the MAGST (Gubler et al. 2011, 2013). The GST is mainly dependent on the geographical redistribution of solar radiation on the ground surface (Luo, Jin, & Bense 2019). Additionally, with an exposition towards the north, gently inclined slopes receive more solar radiation than steeper ones (Gubler et al. 2011). Though, the MAGST of Huhh2 is lower even though the topographic characteristics lead to the opposite behaviour.

As a result of the different inclinations, especially between Huhh2 and the active rockglaciers, wind driven snow distribution may accumulate at the flatter rockglacier site (Gubler et al. 2011). This would lead to a significant insulation of the ground from the atmosphere. However, the timing of an insulating snow cover is of great importance as well. Since the snow index does only show an early insulation of the ground for few years (e.g. 2004, 2019), the GST could cool down in almost every year, leading to low MAGST. The ZC phases are generally well developed, indicating a lot of snow. Thus, the ground in spring is still insulated from the increasing air temperatures, reinforcing a low MAGST at the site of Huhh2.

Likewise, the surface characteristics influence the MAGST (Haeberli et al. 2006; Nyenhuis 2005; Roer 2005). Even though the prevailing surface characteristic for all three rockglaciers generally is large boulders, the small-scale variations of the grain size and internal air circulation may result in different temperature regimes. An internal air circulation can be formed at inactive rockglaciers, depending on the ice content (Delaloye & Lambiel 2005). The logger b0Sp is placed between large boulders. Large voids between the boulders and the well shaded place creates a cool environment, maybe forcing a chimney effect. However, as only up to maximum three loggers per hydrological year were distributed on Huhh2, this assumption is

difficult to proof.

Nevertheless, the placement (representative for grain size and exposition), the timing, duration and thickness of snow can explain the low MAGST (Gubler et al. 2011). The combination of a late $\text{HTI}_{\text{start}}$ with a long lasting snow cover at well ventilated sites intensifies low MAGST (Delaloye & Lambiel 2005; Haeberli et al. 2006, 2010; Mittaz, Hoelzle, & Haeberli 2000). Rugged topography and heterogeneous surface characteristics result in a spatial differentiation of GST (Luo, Jin, & Bense 2019). Since the number of different observation sites at Huhh2 are considerably lower, the MAGST is not an average for many different sites. However, even within a small-spatial extent, the MAGST differs (Gubler et al. 2011) and can be representative for the inactive rockglacier.

By integrating the individual MAGST for each rockglacier in context of outstanding weather conditions, Huhh2 represents the rockglacier which is the least effected by the weather conditions. No matter if the hydrological year was outstanding warm (2022) or cold (2010), the MAGST remained low. However, in summer 2003, which marks the warmest summer on record, the MAGST was slightly positive (Figure 5.6). A positive MAGST only occurred in 2003, 2012 and 2019 for Huhh2. Thus, the air temperature did only have a secondary influence at the inactive rockglacier Huhh2.

In the period of the warmest summer (2003) Huhh3 represents the rockglacier with the highest MAGST. Likewise, in 2022, Huhh3 has the highest MAGST. Upon closer analysis of the timing of an insulating snow cover, Huhh3 generally has a late $\text{HTI}_{\text{start}}$ (e.g. 2022). Thus, the ground was directly coupled with the air temperature for a longer period which would result in lower GST during the cold season. However, the MAGST is higher than on Huhh1. In 2003, the $\text{HTI}_{\text{start}}$ was unusually early on Huhh3 which prevented the ground from cooling down and resulted in a high MAGST. Since Huhh3 consists of fine-grained material more often compared to Huhh1, the GST cannot achieve the same effectiveness of ground cooling (Haeberli et al. 2010). In addition, due to the slightly different expositions between Huhh1 and Huhh3 and the possible shading of the Hungerhorli on Huhh1, the MAGST on Huhh3 tends towards higher values. Thus, the main observed difference is the grain size, the exposition and the shading effect.

However, in 2010, which is within the calendar year with the lowest MAAT, Huhh3 has a lower MAGST than Huhh1. This implies that Huhh3 is more strongly affected by the variation of air temperature than Huhh1.

6.3.3 Spatial Variability of Mean Annual Ground Surface Temperature

Haeberli (1992) stated that permanently frozen ground is prevailing if the MAGST is $< 0^{\circ}\text{C}$. Since rockglaciers are a landform of permafrost (Barsch 1996), their MAGST should theoretically follow this assumptions. Figure 5.8 points out that the MAGST transformed at almost every measurement location towards higher temperatures, at many sites exceeding 0°C (e.g. b102, b210, b045). Considering the presence or absence of permafrost, the BTS is needed. For further discussion, see section 6.4.

Rockglacier Huhh3 has the highest long-term MAGST (Table 5.1). Comparing each hydrological year with the other rockglaciers implies that Huhh3 has the highest MAGST for the majority of the years (Figure 5.6). Only in the first decade, its MAGST was below 0°C (see section 5.3, Table 5.1).

Huhh3 has several lobes at the lower part which forms steep slopes. Steep slopes are more sensitive to the cooling effect of wind since less snow can accumulate (Gubler et al. 2011). However, they expose fine-grained material (Figure 5.8). Fine-grained material buried under a snow layer have a GST close to 0°C and are generally not exposed to intense ground cooling (Staub et al. 2017). Additionally, fine-grained material during snow-free period has a greater warming than coarse-grained substrate (Harris & Pedersen 1998).

In contrast, flat slopes are exposed to high snow accumulation which expands the duration of snow coverage. Hence, the MAGST can be reduced since it is for a shorter time period directly coupled with the atmospheric temperatures.

Comparing the MAGST average 2014 – 2023 for Huhh3 with the surface ruggedness does not confirm the above mentioned relations (Figure 5.8). Logger b2Lo, b213 and b218 have the lowest MAGST in the second decade but they lie on fine-grained material. All other loggers have a higher MAGST but are located at sites with a higher ruggedness. The loggers b2Lo, b213 and b218 are all located at flatter areas in comparison to the remaining loggers. Hence, the slope may have a greater impact than the surface ruggedness on Huhh3, for example due to an increased amount of snow accumulation.

The surface ruggedness is only discussed for the last decade since the used digital terrain model for the calculation of the surface ruggedness is from 2017.

Rockglacier Huhh1 has a lower long-term MAGST than Huhh3. Also the MAGST average for the intermediate (2006 – 2015) and last (2014 – 2023) decade is lower

than the ones from Huhh3. Only in the first decade, their MAGST average are the same. However, Huhh2 always has lower MAGST average values (Table 5.1).

The surface ruggedness depicts that some parts of Huhh1 are covered with fine-grained substrate, mainly at the upper part of the tongue, at the orographical right side and at the root zone. As mentioned in the above paragraph, fine-grained substrate is permafrost unfavourable. The MAGST average for the last decade confirms this statement. All loggers which have a MAGST average $> 0^{\circ}\text{C}$ lie on sites with the smallest observed surface ruggedness (Figure 5.8). Logger b1Wu is an exception. However, this logger is prone to large snow accumulations since it is located at the highest measurement site and at a depression which favours snow accumulation (personal communication).

6.4 Bottom Temperature of the Winter Snow Cover

The BTS from the first decade (2002 – 2011) shifted towards increased BTS in the second decade (2014 – 2023) at many measurement sites (Figure 5.9). However, the long-term trend of the BTS (Figure 5.3) indicate a minimal increase over the entire study period ($+0.014^{\circ}\text{C}/\text{year}$, total $+0.29^{\circ}\text{C}/21$ years).

The BTS is primarily dependent on the heat flow from the upper permafrost layers (Haeberli & Patzelt 1982; Hoelzle 1994; Keller 1994). Thus, the micro-relief and the presence or absence of permafrost are more important than the MAAT (Hoelzle 1992). This can be validated by comparing the BTS between individual logger sites on the rockglacier and the moraine in the first decade. Since the rockglaciers are permafrost bodies and consists of coarse blocks, their BTS has temperatures below -3°C on almost all study sites in the first decade. In contrast, the loggers located at the moraine have BTSs larger than -2°C indicating that there is probably no permafrost. This implies that the BTS does not depend on MAAT since all loggers are located very close to each other.

The loggers distributed on the moraine lie on fine-grained material (Nyenhuis 2005). On the rockglaciers, the prevailing grain size is mostly large boulders (Figure 5.9). Roer (2005) found that fine-grained material are permafrost unfavourable although they lie directly beside a rockglacier. Coarse debris favours the penetration of deep temperatures into the ground (Nyenhuis 2005; Roer 2005).

The ratio of voids filled with air, water or ice are different between the ground properties of rockglacier and the moraine and thus their thermal conductivity (Haeberli 1973; R. Li et al. 2019). Fine-grained materials have larger capillary forces which

increases the amount of water in the upper soil layers. During autumn, the freezing of water needs a lot of energy which prevents the ground from cooling down (Gubler et al. 2011). Meanwhile, coarse-material can cool down since no latent heat is needed due to less water in the upper soil layers (Haeberli et al. 2010; Keller 1994).

The BTS is also dependent of the thermal flux from the lower ground layers. If permafrost is present, the upper ground layers are cooled down from the lower ground layers (Haeberli 1973, 1985; Schoeneich 2011). This implies a lower BTS. All those factors result in a permafrost unfavourable condition on the moraine which can be validated by the BTS.

On the orographical right side of Huhh1 are BTSs which indicate a low probability for permafrost. A subsurface meltwater channel flows down along this rockglacier side from the small but still existing Hungerligletscher. Likewise, a mudflow occurred in the first years of observation (personal communication). Hence, the extent of permafrost at the orographical right side is reduced.

At the root zone of Huhh3, the BTS probably increased due to a thinning in this area resulting from the movement at the tongue (personal communication). Additionally, too few accumulation of rock at the root zone decreases the amount of material on the rockglacier at the top.

By comparing the surface ruggedness with the BTS average of the last decade (Figure 5.9), no obvious correlations are detected. High and low mean BTS occurred on fine-grained but also on coarse-grained substrate. Hence, the surface ruggedness does not have a major influence on the mean BTS in the second decade.

The minimal increase of the regional BTS (Figure 5.3) can attributed to the decrease of snow in winter, although the MAAT is rising. The presence or absence of snow can change the quantity of the BTS. With no or late snow fall, as it occurs more frequently with climate change in the Swiss Alps (NCCS 2018), the BTS can adopt to lower temperatures. Hence, a later arrival or the absence of the HTI_{start} can compensate the increasing air temperatures.

By reason for the requirement of an insulating snow layer, the future utility of the BTS may be reduced. Increasing temperatures in winter, resulting in a rise of the zero degree level, decrease the snow amount and thickness in the Alps in future climate, especially in lower altitudes (NCCS 2018). Although the precipitation

amount is increasing in winter in future climates, it falls less frequently as snow. Hence, a thick enough snow layer may not be reached anymore at every study site. If there is no insulating snow layer on top of the ground surface, the BTS can no longer be calculated and used for permafrost mapping.

Hence, the MAGST, an alternative parameter to the BTS, was evaluated if it is suitable to replace the BTS. By comparing the BTS with the MAGST, similar patterns can be seen (Figure 5.8 and 5.9). For both decades, low values of BTS correlate with low values of MAGST. At locations, where the MAGST is $> 0^{\circ}\text{C}$, the BTS has values between -2 to -3°C for most of the loggers in the first decade (e.g. b102, b211, b045). However three loggers (b105, b210 and b215) have a BTS of $< -3^{\circ}\text{C}$ and logger b103 has a BTS of $> -2^{\circ}\text{C}$. The different conclusions between the MAGST and BTS may occur due to the influence of direct solar radiation and thus, the placement of the loggers. Since the BTS is not depending on direct solar radiation and the MAGST is dependent, the resulting temperatures may differ. If the logger is placed unfavourable, or in contrast, at a well ventilated void between boulders, the MAGST can have different values although the loggers are located very close to each other.

In the second decade, the majority of the loggers with a MAGST $> 0^{\circ}\text{C}$ have a BTS of $> -2^{\circ}\text{C}$ (e.g. b113, b148, b151). Hence, a weak correlation exist between the BTS and the MAGST by shifting the categories for permafrost probability towards higher temperatures when analysing the MAGST. However, since the MAGST experiences an increasing trend whereas the BTS has only a minimal increase, a robust definition with the MAGST seems to be difficult to assess.

Many temperature extremes occurred in the second decade (MeteoSchweiz 2024), which has the ability to increase the MAGST since it is directly coupled with the air temperature (Gubler et al. 2011). Many studies observed an increase of permafrost temperatures during the past decades as well, and found that it is mainly a consequence of rising air temperatures (Biskaborn et al. 2019; IPCC 2019). Hence, as long as the air temperature does not stabilise, an assessment with the MAGST, regarding the probability of permafrost distribution, cannot serve as a robust parameter.

To conclude, a positive MAGST does not directly refer to the absence of permafrost, but in most cases it indicates that permafrost is only possible or that there is probably no permafrost. This trend is intensified in the second decade by comparing it to the first decade. Hence, a replacement of the BTS with the MAGST needs further research to asses categories of the probability of permafrost. Although the

MAGST is directly coupled with the atmosphere during snow-free periods, it may be usable for future detection of permafrost if the loggers are placed favourable at comparable sites.

6.5 Ground Freezing and Thawing Index

The GFI and GTI both show a trend towards more negative and positive values, respectively (Figure 5.10). The greater temperature gap between the two indices gives evidence for an increased occurrence of extreme temperatures. The greater the GTI, the warmer the year. At the same time, a greater GFI implies a colder year (PERMOS 2019).

The hydrological year 2022 had the highest GTI, which is also reported by PERMOS (2023) at all their measurement sites. The summer conditions in 2022 were extraordinarily warm. However, the GFI for the hydrological year 2022 reached the lowest value. This correlation can occur if no or only little snow fall covers the ground in autumn and winter followed by a warm summer. A late timing of an insulating snow cover enables a strong cooling of the ground, which implies more negative values of the GFI. Moreover, an early melt out increases the GTI (PERMOS 2019) but also the GFI. However, the latter is not found in this study which is in contrast to the findings of PERMOS (2023). Thus, the GST tends towards more negative temperatures during winter and towards more positive values during summer, reflecting the increased occurrence of extreme events and less snow.

The study of Frauenfeld, Zhang, and McCreight (2007) researched the freezing and thawing index variation over the twentieth century in the northern hemisphere. They found similar results that the GFI is decreasing while the GTI significantly increased in warm season. Although this study was done in high-latitude cold regions, the results show the same trend as in high altitude regions in the Swiss Alps. Likewise, research in the northern Northeast China found that the GTI is increasing whereas the GFI is decreasing from 1970 to 2010 (Luo et al. 2014). They stated that the ground freezing and thawing indices may provide implications of spatio-temporal changes in the thermal regimes of active layer and permafrost soils. A recent study analysed the dynamics of the ground freezing and thawing indices from 1961 to 2010 on the Qinghai-Tibet Plateau (Fang et al. 2023). They reported a large decrease and increase in GFI and GTI, respectively. The transformation

towards a greater gap between the two indices were reported as a consequence of the direct influence of air temperature but also precipitation.

To sum up, both indices are not only dependent on air temperature but also on the timing, duration and thickness of the snow cover. Extraordinary temperatures enhance the effect of a greater gap between very high and very low values.

Splitting the ground freezing and thawing index to the level of rockglacier enables the detection of different reactions depending on the rockglacier (Figure 5.11). The magnitudes of the indices of rockglacier Huhh1 are almost the same as they are at the aggregated level. However, the GTI shows slightly larger values. In contrast, Huhh3 has remarkable high GTI during the entire period. Thus, small-scale variations like snow accumulation, exposition and ground properties lead to the different results. Different soils cool at other rates depending upon heat conductivity and moisture content. Thus, the freezing and melting occur at different rates (French 2017). Since rockglacier Huhh3 is generally steeper than Huhh1, the slope can retrieve more direct solar radiation, especially in summer (Gubler et al. 2011). This results in an increased GTI.

The indices of rockglacier Huhh2 differ from the active rockglaciers. The GTI is almost stable between 1 – 2°C with some years showing larger values (2006, 2013). The GTI does not show an increasing trend, thus not following the air temperature trend. The GFI has a strongly decreasing trend towards the lowest measured GFI. More negative GFIs in combination with smaller GTIs depicts more days in a year with negative GST. Thus, rockglacier Huhh2 implies a site with permafrost favourable conditions. However, due to the small amount of measurement locations on the inactive rockglacier, the loggers may not be representative for the entire rockglacier.

Conspicuous are the variations of the maximum and minimum GTI and GFI depending on the hydrological year. In 2022, rockglacier Huhh1 has both the highest and lowest values, whereas rockglacier Huhh3 has its highest GTI in 2006, its lowest GFI in 2021. Huhh2 has the largest GTI also in 2006, the lowest GFI is in 2022. To distinguish the variations between the rockglaciers, a small-scale analysis of the exposition, timing, duration and thickness of the snow cover on logger level is needed.

6.6 Limitations

Since only the GST is measured, a connection with the air temperature, precipitation and snow thickness is difficult. Small-scale variations of the non-measured parameters cannot be distinguished. Although Staub and Delaloye (2017) presented indices to derive snow insulation and melt indices, they do not always correlate with the prevailing GST. A weather station close to the study site (e.g. in the Hungerlitali) would enable to calculate the surface offset and an interpolation of the snow height. Additionally, a regular recording of the snow height (e.g. with a fix installed camera) can help to interpret the small-scale distribution of snow during winter and spring. However, the interpretation of the GST on a regional and rockglacier scale does not need further parameters since MeteoSchweiz (2024) and HADES (2023) provide interpolated weather data for the entirety of Switzerland.

At the beginning of the measurement period, the loggers were removed from their site and replaced with another temperature logger. Since the UTL-1 loggers have only an accuracy of $\pm 0.25^\circ\text{C}$ and are sensitive to drift, a temperature drift may have occurred only due to the logger replacement. Hence, in the worst case, a non-detectable temperature drift of 0.5°C may have happened. However, since the GST is analysed at daily means, this possible temperature drift is negligibly small.

A detailed documentation about the logger placement and the prevailing ground properties would enable an analysis of the logger position and the grain size. The provided digital elevation model has a spatial resolution of 0.5 m, the ruggedness on the rockglaciers mainly differ if it is smaller or larger than 0.5 m. Since the grain size can differ within small distances (< 0.5 m), the spatial resolution is on the scarce side of adequate resolution. However, to gain an overview about the regional distribution of the ruggedness, the digital elevation model has a sufficient resolution.

7. Conclusion and Outlook

A long-term analysis of the GST enables a detection of the most influencing factors on GST in a seasonal, inter-annual and multi-decadal time scale. Additionally, the dependency of the GST on snow and surface properties, air temperature and the correlation between the MAGST and BTS was evaluated.

The seasonal GST depends mostly on the variation of air temperature in snow free periods. The timing, thickness and duration of the snow cover was of major importance from autumn to spring until the snow cover is completely depleted. During periods with snow, the direct influence of air temperature is reduced. Hence, a high variability was detected between the sites in summer, whereas only a low variability was measured during winter. The high variability in snow-free periods is mainly a consequence of small-scale variations of the ground substrate (e.g. fine-grained vs. coarse-grained) and the exposition. The low variability in winter can be reduced to the timing, thickness and duration of snow. Snow cover from a thickness of 0.8 m upwards has an insulating effect on the ground. Hence, the timing of the $\text{HTI}_{\text{start}}$ affected the GST in winter. In most cases an early $\text{HTI}_{\text{start}}$ resulted in high GSTs whereas a late $\text{HTI}_{\text{start}}$ enables a decrease of GSTs towards lower temperatures. Hence, a late $\text{HTI}_{\text{start}}$ resulted in low BTS and vice versa. The length of the time gap between the SOD and the $\text{HTI}_{\text{start}}$ cannot confirm if it influences the size of the winter GST.

Inter-annual variations originated from the timing, thickness and duration of the snow cover and from the intensity of the direct incoming solar radiation in snow-free periods. Additionally, the air temperature during summer and winter are important as well, especially during winter with no or only little snow.

The multi-decadal GST measurements depict an increasing trend, following the air temperature course. More extreme events of high temperatures forced higher MAGST. Although, the GST does not always follow the air temperature since the ground properties and snow coverage have a major influence as well.

Since the BTS is dependent on a snow cover with at least a thickness of 0.8 m, the future use may be reduced due to decreased snow fall in the Siwss Alps. Hence, the MAGST was tested if it can replace the BTS for detection of permafrost proba-

bility. Since the MAGST depends on air temperature during snow-free season, the quantity between the BTS and MAGST differed in several years, leading to different conclusions of permafrost occurrence. Hence, to be able to use the MAGST as a permafrost indicator would need a new assessment for the quantity of the MAGST. Since the MAGST experience a rising trend and the BTS only a weak increasing trend, the MAGST would need repeated adjustments due to increasing temperatures.

Comparing the BTS of the rockglaciers with the moraine confirmed that the BTS is not dependent on air temperature since all analysed landforms are located very close to each other. The grain size seemed to be the most influencing parameter besides the timing of the snow cover. Fine-grained material is permafrost unfavourable whereas coarse grained substrate is permafrost favourable.

The analysis of the ground freezing and thawing index visualised a rising temperature difference between the two indices with ongoing time. This highlights an increased occurrence of extreme temperatures during summer and the reduced amount of snow during winter which lead to decreased GSTs.

By continuing the proceedings enables a prolonged time series for documentation and comparing the state of permafrost with climate change. Further research with this data set can be used to compare the GST with the kinematics of rockglaciers, to find further parameters for permafrost detection or to enhance the importance of climate change in high mountain environment.

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A. Appendix

Table A.1: Count of UTL loggers per hydrological year for Huhh1, Huhh2, Huhh3 and moraine.

Hydroyear	Landform	Count of Logger	Landform	Count of Logger	Landform	Count of Logger	Landform	Count of Logger
2001/02	Huhh1	8	Huhh2	0	Huhh3	4	Moraine	0
2002/03	Huhh1	12	Huhh2	3	Huhh3	5	Moraine	2
2003/04	Huhh1	15	Huhh2	3	Huhh3	10	Moraine	12
2004/05	Huhh1	8	Huhh2	0	Huhh3	6	Moraine	3
2005/06	Huhh1	1	Huhh2	0	Huhh3	0	Moraine	0
2006/07	Huhh1	9	Huhh2	3	Huhh3	2	Moraine	0
2007/08	Huhh1	9	Huhh2	2	Huhh3	3	Moraine	5
2008/09	Huhh1	0	Huhh2	0	Huhh3	0	Moraine	0
2009/10	Huhh1	8	Huhh2	2	Huhh3	8	Moraine	0
2010/11	Huhh1	9	Huhh2	2	Huhh3	9	Moraine	0
2011/12	Huhh1	8	Huhh2	3	Huhh3	9	Moraine	0
2012/13	Huhh1	7	Huhh2	3	Huhh3	2	Moraine	0
2013/14	Huhh1	9	Huhh2	2	Huhh3	9	Moraine	0
2014/15	Huhh1	2	Huhh2	0	Huhh3	3	Moraine	0
2015/16	Huhh1	2	Huhh2	0	Huhh3	3	Moraine	0
2016/17	Huhh1	10	Huhh2	1	Huhh3	7	Moraine	0
2017/18	Huhh1	7	Huhh2	1	Huhh3	6	Moraine	0
2018/19	Huhh1	7	Huhh2	1	Huhh3	6	Moraine	0
2019/20	Huhh1	7	Huhh2	1	Huhh3	6	Moraine	0
2020/21	Huhh1	7	Huhh2	1	Huhh3	6	Moraine	0
2021/22	Huhh1	7	Huhh2	1	Huhh3	6	Moraine	0
2022/23	Huhh1	6	Huhh2	1	Huhh3	6	Moraine	0
2023/24	Huhh1	6	Huhh2	1	Huhh3	6	Moraine	0

Table A.2: Count of measurement days and number of observations for regional aggregation, Huhh1, Huhh2, Huhh3 and the moraine per hydrological year (part 1).

Hydroyear	Landform	Count of measurement days	Number of observations	Measurement days (%)
2001/02	Huhh	326	4000	89.3
2002/03	Huhh	365	7308	100.0
2003/04	Huhh	366	8033	100.3
2004/05	Huhh	365	5045	100.0
2005/06	Huhh	365	661	100.0
2006/07	Huhh	365	4949	100.0
2007/08	Huhh	333	4683	91.2
2008/09	Huhh	0	0	0.0
2009/10	Huhh	336	6272	92.1
2010/11	Huhh	365	6937	100.0
2011/12	Huhh	366	6728	100.3
2012/13	Huhh	365	1239	100.0
2013/14	Huhh	365	7248	100.0
2014/15	Huhh	365	1825	100.0
2015/16	Huhh	363	1931	99.5
2016/17	Huhh	365	6570	100.0
2017/18	Huhh	365	5138	100.0
2018/19	Huhh	365	5110	100.0
2019/20	Huhh	366	4784	100.3
2020/21	Huhh	365	4745	100.0
2021/22	Huhh	365	4745	100.0
2022/23	Huhh	365	4525	100.0
2001/02	Huhh1	326	2676	89.3
2002/03	Huhh1	365	4362	100.0
2003/04	Huhh1	357	4206	97.8
2004/05	Huhh1	365	2891	100.0
2005/06	Huhh1	365	601	100.0
2006/07	Huhh1	365	3059	100.0
2007/08	Huhh1	333	2997	91.2
2008/09	Huhh1	0	0	0.0
2009/10	Huhh1	336	2697	92.1
2010/11	Huhh1	365	3285	100.0
2011/12	Huhh1	366	2811	100.3
2012/13	Huhh1	365	931	100.0
2013/14	Huhh1	365	3253	100.0
2014/15	Huhh1	365	365	100.0
2015/16	Huhh1	362	768	99.2
2016/17	Huhh1	365	3650	100.0
2017/18	Huhh1	365	2576	100.0
2018/19	Huhh1	365	2555	100.0
2019/20	Huhh1	366	2222	100.3
2020/21	Huhh1	365	2190	100.0
2021/22	Huhh1	365	2190	100.0
2022/23	Huhh1	365	1970	100.0
2001/02	Huhh2	13	38	3.6
2002/03	Huhh2	362	1086	99.2
2003/04	Huhh2	339	915	92.9
2004/05	Huhh2	0	0	0.0

Table A.3: Count of measurement days and number of observations for regional aggregation, Huhh1, Huhh2, Huhh3 and the moraine per hydrological year (part 2).

Hydroyear	Landform	Count of measurement days	Number of observations	Measurement days (%)
2005/06	Huhh2	12	36	3.3
2006/07	Huhh2	365	1095	100.0
2007/08	Huhh2	333	687	91.2
2008/09	Huhh2	0	0	0.0
2009/10	Huhh2	335	670	91.8
2010/11	Huhh2	365	730	100.0
2011/12	Huhh2	366	721	100.3
2012/13	Huhh2	14	19	3.8
2013/14	Huhh2	361	722	98.9
2014/15	Huhh2	0	0	0.0
2015/16	Huhh2	9	9	2.5
2016/17	Huhh2	365	365	100.0
2017/18	Huhh2	365	365	100.0
2018/19	Huhh2	365	365	100.0
2019/20	Huhh2	366	366	100.3
2020/21	Huhh2	365	365	100.0
2021/22	Huhh2	365	365	100.0
2022/23	Huhh2	365	365	100.0
2001/02	Huhh3	319	1286	87.4
2002/03	Huhh3	362	1860	99.2
2003/04	Huhh3	357	2912	97.8
2004/05	Huhh3	359	2154	98.4
2005/06	Huhh3	12	24	3.3
2006/07	Huhh3	365	795	100.0
2007/08	Huhh3	333	999	91.2
2008/09	Huhh3	0	0	0.0
2009/10	Huhh3	323	2905	88.5
2010/11	Huhh3	365	2922	100.0
2011/12	Huhh3	366	3196	100.3
2012/13	Huhh3	164	289	44.9
2013/14	Huhh3	365	3273	100.0
2014/15	Huhh3	365	1460	100.0
2015/16	Huhh3	363	1154	99.5
2016/17	Huhh3	365	2555	100.0
2017/18	Huhh3	365	2197	100.0
2018/19	Huhh3	365	2190	100.0
2019/20	Huhh3	366	2196	100.3
2020/21	Huhh3	365	2190	100.0
2021/22	Huhh3	365	2190	100.0
2022/23	Huhh3	365	2190	100.0
2002/03	Moraine	365	1363	100.0
2003/04	Moraine	357	3281	97.8
2004/05	Moraine	365	724	100.0
2005/06	Moraine	0	0	0.0
2006/07	Moraine	0	0	0.0
2007/08	Moraine	333	1332	91.2

Table A.4: Metadata part 1 for Huhh1, Huhh2, Huhh3 and the moraine for the hydrological years 2002 – 2007.

Coordinates and Altitude		Year of coordinates		Altitude (m a.s.l.)		Characteristics				Logger Name						
E (LV95)	N (LV95)					Mean MAGST (°C) 2002-23	Mean MAGST (°C) 2002-11	Mean MAGST (°C) 2006-15	Mean MAGST (°C) 2014-23	Mean BTS (°C) 2002 - 2023	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07
Huhh2	b008	2621995	1115395	2003	2620.8	-1.75	-1.75	-1.75	-1.96	-2.62			TU08			
Huhh2	b042	2621819.663	1115456.174	2011	2587.2	-1.41	-1.50	-1.96	-1.96	-4.63		TU14	TU02			TU42
Huhh2	b045	2621792.861	1115394.936	2013	2578.6	-0.27	-0.74	-0.19	-3.69	0.41		TU11	TU05			TU45
Huhh2	b05p	2621865.494	1115405.658	2016	2600.5	-1.22	-1.46	-1.52	-1.52	-3.96		TU06				TU44
Huhh1	b102	2622021.745	1115296.313	2016	2659.4	0.61	-1.30	-1.30	-1.31	-3.10	TU10	TU22	TU30			
Huhh1	b103	2622056.82	1115245.804	2016	2675.0	1.11	0.98	1.82	1.14	-1.22		TU32	TU55			
Huhh1	b105	2621956.749	1115270.419	2016	2655.6	-0.26	-0.71	-0.42	-4.04	-0.22	TU13	TU24	TU53	TU13		
Huhh1	b109	2621995.317	1115275.236	2013	2655.6	-1.58	-1.67	-1.12	-1.58	-5.02	TU11	TU23	TU54			
Huhh1	b110	2622006.727	1115181.857	2016	2697.5	-0.73	-1.22	-0.75	-0.38	-5.15		TU28	TU50	TU09		
Huhh1	b112	2622038.266	1115180.517	2016	2705.3	-1.44	-2.14	-1.75	-0.84	-6.11		TU27	TU49	TU21		TU21
Huhh1	b113	2622178	1115010	2003	2811.8	0.42	0.42			-1.78			TU12	TU12		
Huhh1	b114	2622023.89	1115144.82	2001	2716.0	-3.84	-3.84			-6.64	TU14					
Huhh1	b115	2622060.26	1115081.07	2001	2754.4	-4.42	-4.42			-7.45	TU15					
Huhh1	b116	2622081.38	1115228.9	2001	2683.9	0.44	0.44	0.51		-1.72	TU16			TU16		
Huhh1	b118	2622082.508	1115108.163	2016	2741.2	-0.91	-0.76	-0.50	-1.02	-3.55		TU30	TU29			TU29
Huhh1	b119	2622135	1115042	2003	2785.4	-2.11	-2.11			-4.25			TU19			
Huhh1	b121	2622043	1115285	2003	2658.7	-1.52	-1.52			-3.83	TU09	TU21				
Huhh1	b125	2621983.864	1115239.992	2013	2663.6	-0.50	-0.55	0.09	-0.19	-2.95	TU12	TU25	TU52	TU28		
Huhh1	b128	2622122	1115099	2003	2750.8	-0.75	-0.75			-1.99			TU28			
Huhh1	b147	2622042	1115051	2003	2767.7	-2.95	-2.95			-5.60		TU31	TU47			
Huhh1	b148	2622053	1115117	2003	2734.9	0.48	0.48	1.33		-1.87		TU29	TU48	TU48		TU48
Huhh1	b151	2622042	1115208	2007	2690.8	0.28	0.28	0.35	-1.01	-1.01		TU26	TU51			TU40
Huhh1	b198	NA	NA	NA	NA	0.96	0.89	1.05	1.29	-2.75			TU39			TU39
Huhh1	b199	NA	NA	NA	NA	0.53	0.56	0.45	0.83	-2.17			TU04			
Huhh1	b199u	2622097.496	1114991.642	2016	2786.7	-0.30	-0.62	-0.54	-0.12	-3.62			TU27			TU27
Huhh3	b206	NA	NA	NA	NA	1.14	1.14			-2.73						
Huhh3	b210	2621374.135	1115110.714	2016	2546.4	0.51	-0.46	0.02	-3.32	0.98		TU08	TU38			TU20
Huhh3	b211	2621373.006	1115134.056	2013	2537.2	0.18	0.14	0.44	0.51	-3.87		TU13	TU11	TU19		
Huhh3	b213	2621462.864	1115083.931	2016	2567.1	-0.38	-1.33	-0.49	-0.05	-3.65			TU37			
Huhh3	b214	2621465.702	1115121.413	2013	2559.7	-0.84	-1.33	-0.25	-0.43	-3.90		TU02	TU01	TU15		
Huhh3	b215	2621430.773	1115056.696	2016	2570.8	0.18	-0.55	0.00	0.50	-4.47			TU09	TU41		
Huhh3	b217	2621418.59	1115218.62	2001	2512.7	-3.63	-3.63			-5.31	TU17					
Huhh3	b218	2621381.662	1115234.136	2013	2510.8	-0.55	-0.86	-0.52	-0.20	-5.04	TU18	TU09	TU07	TU18		
Huhh3	b219	2621363.97	1115185.24	2001	2507.9	-3.79	-3.79			-6.99	TU19					
Huhh3	b220	2621481.015	1115029.258	2016	2594.9	0.54	-0.24	0.40	0.88	-3.41		TU13	TU22	TU22		
Huhh3	b222	2621531.934	1115006.533	2016	2621.9	0.72	0.19	0.54	1.03	-2.87		TU14	TU14	TU14		TU14
Huhh3	b226	NA	NA	NA	NA	0.34	-1.23	1.63	1.49	-2.97			TU26			
Huhh3	b210	2621423.493	1115196.656	2016	2514.7	-1.16	-1.37	-0.81	-1.07	-5.99	TU20	TU01	TU21			
Moraine	m311	2622150	1114906	2007	2839.4	-1.22	-1.22	-1.22		-3.87						
Moraine	m316	2622118	1115290	2003	2671.4	-0.15	-0.15			-1.08			TU16	TU16		
Moraine	m320	2622249	1115327	2003	2694.4	-1.00	-1.00			-1.44			TU20			
Moraine	m322	2622135	1115235	2003	2699.7	1.13	1.13			-1.13			TU22	TU10		
Moraine	m323	2622289	1115095	2003	2777.1	0.40	0.40			-1.64			TU23			
Moraine	m324	2622183	1115317	2003	2694.6	2.01	2.01	1.39		-0.79			TU24	TU34		
Moraine	m325	2622265	1115157	2003	2755.6	1.18	1.18			-0.46			TU25			
Moraine	m331	2622235	1114960	2003	2830.4	0.37	0.37			-0.95			TU31			
Moraine	m332	2622215	1115227	2003	2732.9	0.66	0.66	0.03	0.03	-0.45			TU32			
Moraine	m333	2622233	1115144	2002	2767.2	1.30	1.30			-0.12			TU33	TU46		
Moraine	m334	2622213	1115395	2002	2689.8	1.04	1.04			-0.49			TU34	TU45		
Moraine	m335	2622384	1114970	2003	2852.2	-0.33	-0.33	-1.01	-1.01	-1.48			TU35			
Moraine	m336	2622258	1115214	2003	2731.9	0.83	0.83			-0.67			TU36			

Table A.5: Metadata part 2 for Huhh1, Huhh2, Huhh3 and the moraine for the hydrological years 2008 – 2024.

Logger Name																			
Rockglacier	Logger-ID	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22	2022/23	2023/24	
Huhh2	b008																		
Huhh2	b042					TU42	TU42												
Huhh2	b045			TU45	TU45	TU45	TU45												
Huhh2	b0Sp			TU44	TU44	TU44	TU44												
Huhh1	b102																		
Huhh1	b103																		
Huhh1	b105			TU23	TU23	TU23	TU23		TU39	2550	TU48	3508	3508	3508	3508	3508	3508	3508	
Huhh1	b109			TU09	TU09	TU09	TU09			2549	TU23	2549	2549	2549	2549	2549	2549	2549	
Huhh1	b110			TU29	TU29	TU29	TU29		TU29		TU09	3509	3509	3509	3509	3509	3509	3509	
Huhh1	b112			TU16	TU16	TU16	TU16		TU29	2552	TU29	3510	3510	3510	3510	3510	3510	3510	
Huhh1	b113										TU16	3511	3511	3511	3511	3511	3511	3511	
Huhh1	b114																		
Huhh1	b115																		
Huhh1	b116																		
Huhh1	b118			TU40	TU40	TU40	TU40				TU40	3512	3512	3512	3512	3512			
Huhh1	b119																		
Huhh1	b121																		
Huhh1	b125			TU21	TU21		TU21				TU21								
Huhh1	b128																		
Huhh1	b147																		
Huhh1	b148																		
Huhh1	b151																		
Huhh1	b198			TU48	TU48	TU48	TU48												
Huhh1	b199			TU39	TU39	TU39	TU39				TU39								
Huhh1	b1Wu			TU27	TU27	TU27	TU27				TU27	3513	3513	3513	3513	3513	3513	3513	
Huhh3	b206								2062										
Huhh3	b210			TU20	TU20	TU20	TU20		TU20	2548	TU20	3524	3524	3524	3524	3524	3524	3524	
Huhh3	b211			TU19	TU19	TU19	TU19												
Huhh3	b213			TU38	TU38	TU38	TU38				TU38	3507	3507	3507	3507	3507	3507	3507	
Huhh3	b214			TU14	TU14	TU14	TU14												
Huhh3	b215			TU41	TU41	TU41	TU41				TU41	3504	3504	3504	3504	3504	3504	3504	
Huhh3	b217																		
Huhh3	b218			TU18	TU18	TU18	TU18				TU18								
Huhh3	b219																		
Huhh3	b220			TU26	TU26	TU26	TU26				TU26	3506	3506	3506	3506	3506	3506	3506	
Huhh3	b222			TU49	TU49	TU49	TU49		TU19	2106	TU19	3505	3505	3505	3505	3505	3505	3505	
Huhh3	b226								TU49										
Huhh3	b2Lo			TU36	TU36	TU36	TU36				TU36	3523	3523	3523	3523	3523	3523	3523	
Moraine	m311																		
Moraine	m316																		
Moraine	m320																		
Moraine	m322																		
Moraine	m323																		
Moraine	m324																		
Moraine	m325																		
Moraine	m331																		
Moraine	m332																		
Moraine	m333																		
Moraine	m334																		
Moraine	m335																		
Moraine	m336																		

Table A.6: GST value for each logger at its individual ZC if the difference is larger than $0 \pm 0.25^\circ\text{C}$. There were no GST drift since the hydrological year 2017/18.

Landform	Logger-ID	Value at zero curtain ($^\circ\text{C}$)															2016/17
		2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	
Huhh1	b102		0.8	0.8												0.75	0.31
Huhh1	b103			0.31													0.31
Huhh1	b105		0.8	0.31	-0.31					-0.31	-0.31	-0.31		-0.31			0.31
Huhh1	b109		0.8	0.8													0.8
Huhh1	b110														0.8		0.8
Huhh1	b112			0.8													
Huhh1	b113																
Huhh1	b114	0.31															
Huhh1	b115		0.8														
Huhh1	b116		0.8														
Huhh1	b118			0.31													0.8
Huhh1	b119																
Huhh1	b121		0.8	0.8													
Huhh1	b125		0.8	0.31													0.8
Huhh1	b128																
Huhh1	b147																
Huhh1	b148			-0.31		-0.31	-0.31	-0.31									
Huhh1	b151		0.8	0.8													
Huhh1	b1Wu																
Huhh1	b198									-0.31	-0.31	-0.31		-0.31			
Huhh1	b199																
Huhh2	b0Sp			0.31													0.8
Huhh2	b008			-0.31													
Huhh2	b042		0.8				0.8										
Huhh2	b045			-0.31		-0.31	-0.31	-0.31		-0.31		-0.31		-0.31			
Huhh3	b2Lo	0.8	0.31														
Huhh3	b206																
Huhh3	b210		0.31														
Huhh3	b211																
Huhh3	b213																
Huhh3	b214			-0.31													
Huhh3	b215		0.5							-0.31	-0.31	-0.31		-0.31			-0.31
Huhh3	b217	0.8															
Huhh3	b218	0.8															0.8
Huhh3	b219	0.8															
Huhh3	b220																0.8
Huhh3	b222																0.8
Huhh3	b226																
Moraine	m311																
Moraine	m316																
Moraine	m320																
Moraine	m322																
Moraine	m323			-0.31													
Moraine	m324							-0.31									
Moraine	m325			-0.31													
Moraine	m331																
Moraine	m332			-0.31													
Moraine	m333			-0.31													
Moraine	m334																
Moraine	m335																
Moraine	m336																

Table A.7: Mean BTS for each logger for four different time periods.

Landform	Logger-ID	E (LV95)	N (LV95)	Mean BTS (°C) 2002-23	Mean BTS (°C) 2002-11	Mean BTS (°C) 2006-15	Mean BTS (°C) 2014-23
Huhh1	b102	2622021.75	1115296.31	-3.10	-4.02	NA	-2.71
Huhh1	b103	2622056.82	1115245.80	-1.22	-0.48	-1.08	-1.40
Huhh1	b105	2621956.75	1115270.42	-4.04	-4.34	-4.13	-3.77
Huhh1	b109	2621995.32	1115275.24	-5.02	-5.23	-4.40	-4.90
Huhh1	b110	2622006.73	1115181.86	-5.15	-5.18	-4.65	-5.11
Huhh1	b112	2622038.27	1115180.52	-6.11	-6.71	-6.26	-5.51
Huhh1	b113	2622178.00	1115010.00	-1.78	-1.78	NA	NA
Huhh1	b114	2622023.89	1115144.82	-6.64	-6.64	NA	NA
Huhh1	b115	2622060.26	1115081.07	-7.45	-7.45	NA	NA
Huhh1	b116	2622081.38	1115228.90	-1.72	-1.72	-1.57	NA
Huhh1	b118	2622082.51	1115108.16	-3.55	-3.62	-3.38	-3.45
Huhh1	b119	2622135.00	1115042.00	-4.25	-4.25	NA	NA
Huhh1	b121	2622043.00	1115285.00	-3.83	-3.83	NA	NA
Huhh1	b125	2621983.86	1115239.99	-2.95	-3.25	-1.92	-2.59
Huhh1	b128	2622122.00	1115099.00	-1.99	-1.99	NA	NA
Huhh1	b147	2622042.00	1115051.00	-5.60	-5.60	NA	NA
Huhh1	b148	2622053.00	1115117.00	-1.87	-1.87	-0.80	NA
Huhh1	b151	2622042.00	1115208.00	-1.01	-1.01	-1.36	NA
Huhh1	b198	NA	NA	-2.75	-3.17	-2.36	-0.86
Huhh1	b199	NA	NA	-2.17	-2.41	-1.67	-2.48
Huhh1	b1Wu	2622097.50	1114991.64	-2.62	-3.08	-2.83	-2.42
Huhh2	b008	2621995.00	1115395.00	-2.62	-2.62	NA	NA
Huhh2	b042	2621819.66	1115456.17	-4.63	-4.63	-5.72	NA
Huhh2	b045	2621792.86	1115394.94	-3.69	-3.89	-3.30	-2.64
Huhh2	b0Sp	2621865.49	1115405.66	-3.96	-4.45	-4.07	-3.81
Huhh3	b206	NA	NA	-2.73	NA	NA	-2.73
Huhh3	b210	2621374.14	1115110.71	-3.32	-3.64	-3.37	-3.19
Huhh3	b211	2621373.01	1115134.06	-3.87	-4.22	-3.76	-2.97
Huhh3	b213	2621462.86	1115083.93	-3.65	-4.58	-3.88	-3.36
Huhh3	b214	2621465.70	1115121.41	-3.90	-4.43	-3.49	-2.09
Huhh3	b215	2621430.77	1115056.70	-4.47	-5.18	-4.26	-4.18
Huhh3	b217	2621418.59	1115218.62	-5.31	-5.31	NA	NA
Huhh3	b218	2621381.66	1115234.14	-5.04	-5.68	-5.08	-3.79
Huhh3	b219	2621363.97	1115185.24	-6.99	-6.99	NA	NA
Huhh3	b220	2621481.02	1115029.26	-3.41	-4.50	-3.36	-2.93
Huhh3	b222	2621531.93	1115006.53	-2.87	-2.76	-2.80	-2.90
Huhh3	b226	NA	NA	-2.97	-2.90	-3.04	-3.04
Huhh3	b2Lo	2621423.49	1115196.66	-5.99	-6.53	-6.31	-5.63
Moraine	m311	2622150.00	1114906.00	-3.87	NA	NA	NA
Moraine	m316	2622118.00	1115290.00	-1.08	NA	NA	NA
Moraine	m320	2622249.00	1115327.00	-1.44	NA	NA	NA
Moraine	m322	2622135.00	1115235.00	-1.13	NA	NA	NA
Moraine	m323	2622289.00	1115095.00	-1.64	NA	NA	NA
Moraine	m324	2622183.00	1115317.00	-0.79	NA	NA	NA
Moraine	m325	2622265.00	1115157.00	-0.46	NA	NA	NA
Moraine	m331	2622235.00	1114960.00	-0.95	NA	NA	NA
Moraine	m332	2622215.00	1115227.00	-0.45	NA	NA	NA
Moraine	m333	2622233.00	1115144.00	-0.12	NA	NA	NA
Moraine	m334	2622213.00	1115335.00	-0.49	NA	NA	NA
Moraine	m335	2622384.00	1114970.00	-1.48	NA	NA	NA
Moraine	m336	2622258.00	1115214.00	-0.67	NA	NA	NA

Table A.8: Mean BTS for each logger per hydrological year (part 1).

Logger-ID	Hydroyear	Mean BTS (°C)	Logger-ID	Hydroyear	Mean BTS (°C)	Logger-ID	Hydroyear	Mean BTS (°C)
b008	2004	-2.62	b105	2021	-3.87	b118	2017	-5.94
b042	2003	-4.06	b105	2022	-4.65	b118	2018	-2.81
b042	2004	-4.09	b105	2023	-4.45	b118	2019	-2.70
b042	2007	-5.72	b109	2002	-6.42	b119	2004	-4.25
b045	2003	-5.26	b109	2003	-5.47	b121	2002	-4.38
b045	2004	-4.84	b109	2004	-4.05	b121	2003	-3.27
b045	2007	-1.36	b109	2011	-5.08	b125	2002	-5.34
b045	2008	-1.49	b109	2012	-4.84	b125	2003	-2.70
b045	2010	-6.35	b109	2013	-3.96	b125	2004	-2.19
b045	2011	-4.86	b109	2014	-3.43	b125	2005	-4.45
b045	2012	-3.58	b109	2017	-6.43	b125	2010	-2.64
b045	2014	-2.64	b110	2003	-5.00	b125	2011	-2.29
b0Sp	2003	-3.22	b110	2004	-4.47	b125	2013	-1.49
b0Sp	2007	-4.49	b110	2005	-7.11	b125	2014	-1.16
b0Sp	2008	-4.04	b110	2007	-5.01	b125	2017	-4.05
b0Sp	2010	-5.70	b110	2008	-5.16	b128	2004	-1.99
b0Sp	2011	-4.77	b110	2010	-4.78	b147	2003	-5.60
b0Sp	2012	-2.86	b110	2011	-4.69	b148	2003	-3.88
b0Sp	2014	-2.76	b110	2012	-5.41	b148	2004	-3.14
b0Sp	2017	-5.23	b110	2014	-2.91	b148	2006	-1.32
b0Sp	2018	-2.60	b110	2015	-4.60	b148	2007	-0.50
b0Sp	2019	-1.90	b110	2016	-4.58	b148	2008	-0.57
b0Sp	2020	-1.84	b110	2017	-6.66	b151	2003	0.13
b0Sp	2021	-4.36	b110	2018	-4.94	b151	2004	-1.78
b0Sp	2022	-6.07	b110	2019	-5.46	b151	2008	-1.36
b0Sp	2023	-6.00	b110	2020	-4.59	b198	2005	-4.72
b102	2002	-6.07	b110	2021	-5.22	b198	2008	-4.21
b102	2003	-2.71	b110	2022	-6.60	b198	2010	-2.15
b102	2004	-3.27	b110	2023	-5.71	b198	2011	-1.62
b102	2017	-5.67	b112	2003	-6.68	b198	2012	-2.94
b102	2018	-1.01	b112	2004	-6.05	b198	2014	-0.86
b102	2019	-1.37	b112	2005	-7.70	b199	2005	-2.95
b102	2020	-1.58	b112	2007	-6.34	b199	2007	-4.05
b102	2021	-3.03	b112	2008	-5.96	b199	2010	-1.20
b102	2022	-4.74	b112	2010	-6.96	b199	2011	-1.50
b102	2023	-1.83	b112	2011	-7.37	b199	2012	-0.67
b103	2003	0.51	b112	2012	-6.34	b199	2014	-1.00
b103	2004	-1.46	b112	2013	-6.41	b199	2017	-4.13
b103	2015	-1.08	b112	2014	-4.60	b1Wu	2004	-2.01
b103	2016	-1.78	b112	2017	-6.49	b1Wu	2007	-3.30
b103	2017	-2.58	b112	2018	-4.68	b1Wu	2008	-3.80
b103	2018	-0.43	b112	2019	-5.20	b1Wu	2010	-3.25
b103	2019	-0.57	b112	2020	-4.46	b1Wu	2011	-3.04
b103	2020	-0.81	b112	2021	-6.06	b1Wu	2012	-1.96
b103	2021	-1.64	b112	2022	-6.23	b1Wu	2014	-1.62
b103	2022	-2.32	b112	2023	-6.63	b1Wu	2017	-4.15
b103	2023	-1.34	b113	2004	-2.60	b1Wu	2018	-1.90
b105	2002	-5.70	b113	2005	-0.97	b1Wu	2019	-1.68
b105	2003	-3.08	b114	2002	-6.64	b1Wu	2020	-1.34
b105	2004	-3.34	b115	2002	-7.45	b1Wu	2021	-2.20
b105	2005	-5.13	b116	2002	-1.35	b1Wu	2022	-3.94
b105	2007	-4.13	b116	2005	-2.39	b1Wu	2023	-2.58
b105	2008	-4.56	b116	2007	-1.66	b206	2016	-2.73
b105	2010	-4.32	b116	2008	-1.49	b210	2003	-4.08
b105	2011	-4.43	b118	2003	-3.50	b210	2004	-3.57
b105	2012	-4.03	b118	2004	-3.85	b210	2007	-2.55
b105	2013	-2.58	b118	2007	-2.11	b210	2008	-2.69
b105	2014	-3.45	b118	2008	-2.75	b210	2010	-5.29
b105	2017	-5.91	b118	2010	-4.64	b210	2011	-4.54
b105	2018	-2.73	b118	2011	-4.89	b210	2012	-2.74
b105	2019	-2.58	b118	2012	-3.51	b210	2014	-3.25
b105	2020	-2.61	b118	2014	-2.40	b210	2015	-3.54

Table A.9: Mean BTS for each logger per hydrological year (part 2).

Logger-ID	Hydroyear	Mean BTS (°C)	Logger-ID	Hydroyear	Mean BTS (°C)
b210	2016	-2.34	b220	2014	-2.21
b210	2017	-4.04	b220	2017	-3.20
b210	2018	-2.07	b220	2018	-2.08
b210	2019	-1.99	b220	2019	-2.26
b210	2020	-2.79	b220	2020	-2.27
b210	2021	-5.30	b220	2021	-3.70
b210	2022	-3.86	b220	2022	-3.88
b210	2023	-4.35	b220	2023	-4.03
b211	2003	-3.13	b222	2004	-2.93
b211	2004	-3.79	b222	2005	-2.92
b211	2005	-5.21	b222	2007	-2.03
b211	2010	-4.82	b222	2008	-3.52
b211	2011	-4.23	b222	2010	-2.44
b211	2012	-3.20	b222	2011	-2.67
b211	2013	-3.50	b222	2012	-3.33
b211	2014	-2.97	b222	2014	-1.92
b213	2004	-3.07	b222	2015	-3.72
b213	2010	-4.30	b222	2016	-2.65
b213	2011	-6.38	b222	2017	-3.96
b213	2012	-3.10	b222	2018	-2.65
b213	2014	-1.73	b222	2019	-2.35
b213	2017	-5.26	b222	2020	-2.11
b213	2018	-2.83	b222	2021	-3.59
b213	2019	-2.41	b222	2022	-2.96
b213	2020	-2.32	b222	2023	-3.23
b213	2021	-4.76	b226	2004	-2.90
b213	2022	-4.05	b226	2015	-3.04
b213	2023	-3.66	b2Lo	2002	-7.10
b214	2003	-3.58	b2Lo	2003	-6.53
b214	2004	-3.48	b2Lo	2004	-5.72
b214	2005	-5.82	b2Lo	2008	-2.92
b214	2010	-4.83	b2Lo	2010	-9.91
b214	2012	-3.63	b2Lo	2011	-7.67
b214	2014	-2.09	b2Lo	2012	-5.69
b215	2004	-4.03	b2Lo	2014	-6.06
b215	2005	-6.81	b2Lo	2017	-6.32
b215	2010	-5.54	b2Lo	2018	-5.07
b215	2011	-4.22	b2Lo	2019	-4.93
b215	2012	-4.00	b2Lo	2020	-3.62
b215	2014	-3.27	b2Lo	2021	-6.60
b215	2017	-5.10	b2Lo	2022	-5.89
b215	2018	-3.62	b2Lo	2023	-6.75
b215	2019	-2.95			
b215	2020	-2.69			
b215	2021	-5.75			
b215	2022	-5.14			
b215	2023	-5.02			
b217	2002	-5.31			
b218	2002	-6.16			
b218	2003	-4.45			
b218	2005	-4.74			
b218	2010	-7.44			
b218	2011	-5.53			
b218	2012	-4.44			
b218	2014	-3.07			
b218	2017	-4.53			
b219	2002	-6.99			
b220	2004	-4.02			
b220	2005	-5.55			
b220	2010	-4.24			
b220	2011	-4.19			
b220	2012	-2.83			

Table A.10: Mean SOD and $\text{HTI}_{\text{start}}$ for each hydrological year, all loggers aggregated.

Hydroyear	Mean Duration (days)	Mean SOD	Mean HTIstart
2002	46	14.11.2001	30.12.2001
2003	27	11.11.2002	23.11.2002
2004	29	17.10.2003	15.11.2003
2005	42	27.10.2004	08.12.2004
2006	15	05.10.2005	21.10.2005
2007	54	29.10.2006	22.12.2006
2008	43	24.10.2007	07.12.2007
2009	NA	NA	NA
2010	39	29.10.2009	07.12.2009
2011	53	27.10.2010	19.12.2010
2012	38	30.10.2011	07.12.2011
2013	43	27.10.2012	08.12.2012
2014	15	25.10.2013	09.11.2013
2015	43	12.11.2014	25.12.2014
2016	52	27.10.2015	18.12.2015
2017	50	14.11.2016	02.01.2017
2018	35	31.10.2017	05.12.2017
2019	16	16.10.2018	01.11.2018
2020	21	04.11.2019	25.11.2019
2021	68	14.10.2020	21.12.2020
2022	64	25.10.2021	28.12.2021
2023	66	14.10.2022	19.12.2022

Personal Declaration

I hereby declare that the submitted Thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the Thesis.

A handwritten signature in black ink, reading 'E. Dällenbach' in a cursive script.

Esther Dällenbach
Winterthur, 26.04.2024