# The Evolution of Glacier Mass Balance Gradients under the Current Climate Change

*A Statistical Analysis of the WGMS Dataset*

---

**Master Thesis**

**Alyssa Ghirlanda**

Dep. of Geosciences, University of Fribourg, Switzerland

*Supervised by*

**Prof. Martin Hoelzle**

Dep. of Geosciences, University of Fribourg, Switzerland

*Co-supervised by*

**PD Dr. Michael Zemp**

Dep. of Geography, University of Zürich, Switzerland

**Dr. Horst Machguth**

Dep. of Geosciences, University of Fribourg, Switzerland

*December 2018*

UNI FR
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

wgms

*"The sad thing is that*

*science gathers knowledge faster*

*than society gathers wisdom."*

*Isaac Asimov*

# Acknowledgements

First and foremost I owe my deepest gratitude to my supervisor Martin Hoelzle for its precious knowledge, advices, remarks and whole-hearted support through the entire realisation of this master thesis, and above all, for sharing his catchy passion for glaciology with me. The realisation of this thesis would not have been possible without its trust and endless motivation.

Furthermore, I would like to thank my co-supervisors Michael Zemp for his availability on discussing WGMS datasets and Horst Machguth for sharing its valuable working experience on mass balance gradients. I am very grateful to Cécile Pellet for her help with the statistical computing. I would also like to thank Martina Barandun, Marlene Kronenberg, Julie Wee and the other members of the Geography Unit in Fribourg as well as Florian Denzinger for their availability, advices and encouragement. I am grateful to Guy Ramdsen for his proofreading.

In a general way, I would like to thank the teaching staff of the Geography unit in Fribourg for waking up in me a deep interest for studying our planet Earth and its changes through their captivating lectures and contagious motivation since the beginning of my academic studies five years ago. I am also grateful to Ólafur Ingólfsson and the other lecturers at the University Centre in Svalbard for their extremely interesting lectures about arctic environment changes.

Finally, it is a pleasure to thank my fellow students and loved ones who supported me and never stopped believing in me throughout the entire process of this master thesis and generally, since always.

# Abstract

Glaciers variations are a unique observable expression of climate change. In several mountain ranges, rapid environmental changes are happening and cause an accelerating glacier mass loss since approximatively the 1990s. The mass balance gradient of glaciers is both a good measure of glacier-climate interactions and an important representative of the climatic environment of glaciers. In the present study, the hypothesis that mass balance gradients are steepening during the last decades as a consequence of higher ablation rates and of an induced increase in accumulation rates that a warmer atmosphere could trigger is tested. 49 glaciers are selected from the WGMS database and their annual mass balance data series with elevation is downloaded for the period 1954-2017. Their ablation, glacier-wide and accumulation gradients are calculated by the slope of the linear regression line passing through the mass balance points. The detailed evolution curves and the linear evolution trends of these mass balance gradients are analyzed for glaciers individually, for the 49 selected glaciers together and for glaciers classified according to climatic and geometric parameters. As a result, a general steepening trend over the period is observed. The total linear increase in gradients is quantified to +10% for ablation gradients, +14% for glacier-wide gradients and +25% for accumulation gradients over a period of 50 years. The evolution is marked by a clear and rapid shift from smaller to steeper gradients between the mid-1980s and the mid-1990s for maritime and transitional glaciers and seems to have been triggered by the simultaneous increase in solar radiation known as "global brightening". Continental glaciers have an earlier and longer steepening in glacier-wide and accumulation gradients probably triggered by warming air temperature. This increase is potentially related to a long-term warming induced increase in accumulation rates and would mark a climate regime shift in continental environments towards more maritime conditions. The observed important evolution differences between continental and maritime glaciers showed that the evolution of mass balance gradients is dependent on the climatic environment of glaciers. In addition, glaciers with different geometric parameters, particularly glaciers with different hypsometry and slope showed contrasted evolutions of their mass balance gradients. The observed high sensitivity of mass balance gradients to climatic changes points out that a better understanding of this complex relationship is necessary. It is particularly important in the current context of climate change and given the key role of mass balance gradients for glacier dynamics and glacier response time to climatic perturbations.

**Key Words**

Glaciers, Mass Balance Gradients, Climate Change, Climatic Environments, Climate Sensitivity

# Table of Contents

Acknowledgements IV

Abstract V

1 Introduction 10

**1.1 Motivation 10**

1.1.1 Relevance of studying Glaciers 10

1.1.2 Interest of Mass Balance Gradients 12

**1.2 Objectives and Research Questions 14**

**1.3 Structure 17**

2 Background 18

**2.1 Glaciers 18**

2.1.1 Basics 18

*2.1.1.1 Cryosphere, Glaciers, Ice Caps and Ice Sheets 18*

*2.1.1.2 Glaciers Genesis and Survival 18*

2.1.2 Mass Balance 19

*2.1.2.1 Accumulation and Ablation 19*

*2.1.2.2 Mass Balance Definition 20*

*2.1.2.3 Accumulation Area, Ablation Area and Equilibrium Line 21*

2.1.3 Distribution, Monitoring and Recent Changes of World-wide Glaciers 22

*2.1.3.1 Present Global Glacier Distribution 22*

*2.1.3.2 The World Glacier Monitoring Service and its Dataset 23*

*2.1.3.3 Observed Global Mass Balance Changes 24*

*2.1.3.4 Observed Regional Mass Balance Changes 25*

**2.2 Mass Balance Gradients 26**

2.2.1 Definition 26

2.2.2 Governing Factors 28

*2.2.2.1 Ablation Gradient 28*

*2.2.2.2 Accumulation Gradient 31*

2.2.3 Climatic Environments 33

*2.2.3.1 Maritime-type Glaciers 33*

*2.2.3.2 Continental-type Glaciers 34*

*2.2.3.3 Climate Sensitivity of Maritime and Continental Glaciers 35*

3 Methodology 37

**3.1 Data Collection** **37**

3.1.1 WGMS Database 37

3.1.2 Glacier Selection 38

3.1.3 Data Organization 39

**3.2 Mass Balance Data Processing** **41**

3.2.1 General Processing 41

3.2.2 Units 42

3.2.3 Elevation Reference 42

3.2.4 Error Check 42

3.2.5 Removal of Decreasing Accumulation Values 42

**3.3 Gradient Extraction** **43**

3.3.1 Definition of the $ELA_0$ 43

3.3.2 Absolute Gradients 44

*3.3.2.1 Gradient Equation* *44*

*3.3.2.2 Elevation Coverage* *45*

*3.3.2.3 Calculation and Calibration* *46*

3.3.3 Relative Gradients 47

**3.4 Data Analysis** **48**

3.4.1 Evolution of Absolute Gradients 48

*3.4.1.1 Individual Glaciers* *48*

*3.4.1.2 Overview* *50*

3.4.2 Evolution of Relative Gradients 51

*3.4.2.1 General Procedure* *51*

*3.4.2.2 Classification according to Climatic Parameters* *51*

*3.4.2.3 Classification according to Geometric Parameters* *54*

*3.4.2.4 Classification according to Gradient-related Parameters* *58*

4 Results 59

**4.1 Evolution of Absolute Mass Balance Gradients** **59**

4.1.1 Individual Glaciers 59

*4.1.1.1 Hintereisferner* *59*

*4.1.1.2 Kesselwandferner* *60*

*4.1.1.3 Zongo* *60*

*4.1.1.4 Devon Ice Cap NW* *61*

*4.1.1.5 White* 62
*4.1.1.6 Schwarzberg* 63
*4.1.1.7 Silvretta* 63
*4.1.1.8 Abramov* 64
*4.1.1.9 Hellstugubreen* 65
*4.1.1.10 Nigardsbreen* 65
*4.1.1.11 Storglaciaeren* 66
4.1.2 Overview 67
*4.1.2.1 Mean Gradient* 67
*4.1.2.2 Standard Deviation* 68
*4.1.2.3 Annual Rate of Change* 69
*4.1.2.4 Correlation between Gradients* 72
*4.1.2.5 Summary* 73
**4.2 Evolution of Relative Mass Balance Gradients** **75**
4.2.1 All Glaciers 75
4.2.2 Classified Glaciers according to Climatic Parameters 77
*4.2.2.1 Continentality* 77
*4.2.2.2 Region* 78
*4.2.2.3 Latitude* 79
*4.2.2.4 Minimal Elevation* 80
4.2.3 Classified Glaciers according to Geometric Parameters 82
*4.2.3.1 Length* 82
*4.2.3.2 Area* 83
*4.2.3.3 Length/Area Ratio* 84
*4.2.3.4 Slope* 85
*4.2.3.5 Elevation Coverage of Upper Half Area* 86
4.2.4 Classified Glaciers according to Gradient-related Parameters 87
*4.2.4.1 Mean Glacier-wide Gradient* 87
*4.2.4.2 Standard Deviation of Accumulation Gradients* 88

**5 Discussion** 89
**5.1 Uncertainties of the Results** **89**
5.1.1 Mass Balance Gradient 89
*5.1.1.1 Glacier Selection* 89
*5.1.1.2 Mass Balance Data* 90
*5.1.1.3 Linear Regression Model* 90

*5.1.1.4 $ELA_0$ versus ELA* 91
*5.1.1.5 Relative gradients* 92
5.1.2 Evolution Results 93
*5.1.2.1 Linear Evolution Trend and Annual Rate of Change* 93
*5.1.2.2 Evolution Curves* 94
*5.1.2.3 Classification Process* 95
**5.2 Interpretation of the Results** **95**
5.2.1 Causes of the Inter-Annual Gradient Changes 95
*5.2.1.1 Hypothesis on the Possible Climatic Causes* 95
*5.2.1.2 Hypothesis Test* 97
5.2.2 Causes of the Long-term Gradient Evolution 99
*5.2.2.1 Climatic Data* 99
*5.2.2.2 Period 1 (1954-1967)* 102
*5.2.2.3 Period 2 (1968-1978)* 103
*5.2.2.4 Period 3 (1979-1985)* 104
*5.2.2.5 Period 4 (1986-1994)* 105
*5.2.2.6 Period 5 (1995-2011)* 106
*5.2.2.7 Period 6 (2012-2017)* 107
*5.2.2.8 Summary* 107
5.2.3 Evolution Differences of Classified Glaciers over the Period 109
*5.2.3.1 Influence of Climatic Parameters* 109
*5.2.3.2 Influence of Geometric Parameters* 111
5.2.4 Comparison with B, AAR and ELA Evolution 113

6 Conclusion 116
**6.1 Summary and Perspectives** **116**
**6.2 Key Findings** **119**

7 References 120

Annexes 126

# 1 Introduction

## 1.1 Motivation

### 1.1.1 Relevance of studying Glaciers

Studying glaciers in a changing climate context is highly relevant as they are:

**1) A unique climate indicator witnessing climate changes**

As stated by the International Panel on Climate Change (IPCC), the climate system is unequivocally warming since 1850 and this trend is projected to continue over the 21st century (*IPCC, 2014a*). The ongoing climate change is mainly caused by anthropogenic greenhouse gas emissions resulting from economic and population growth (*IPCC, 2014a*), even if population growth does not necessarily have to imply higher greenhouse gas emissions if renewable energy resources are used. Since the mid-20th century, anthropogenic forcings are playing a dominant role in the surface temperature increase, affecting the global water cycle, contributing to ocean temperature warming and causing global mean sea level rise (*IPCC, 2014a*). Since the 1960s, the ongoing climate change is also inducing the melt of glaciers (*IPCC, 2014a*), being particularly sensitive to global warming (*UNEP, 2007*). The current glacier decline is accelerating (*Dyurgerov and Meier, 2005*) and characterized by a historically unprecedented ice loss since the turn of the century (*WGMS, 2017; Zemp et al., 2015*). Today, glaciers are continuing to lose mass in many mountain ranges around the world (*WGMS, 2017; Vaughan et al., 2013*), witnessing that higher air temperature is associated with higher glacier shrinkage (*Braithwaite, 2011*). Interestingly, some glaciers have also advanced in a few regions (e.g. in New Zealand, Norway, Southern Patagonia or in the Karakoram range in Asia), sometimes as a result of increased snow accumulation (*Vaughan et al., 2013*). These observations show that glaciers can be considered as a "natural climate-meter" as they sensitively respond to temperature but also other climate variables such as precipitation (*Vaughan et al., 2013*). Glaciers are thus an observable physical expression of climate change, providing some of its clearest evidences (*WGMS, 2008*), this is why they are recognized as an important climate indicator (*Bojinski et al., 2014*). They are consequently defined in the Global Climate Observing System (GCOS) as

one of the Essential Climate Variables (ECVs) for which their observation is "crucial for monitoring, understanding and predicting the variations and changes of the climate system" (*WMO, 2016*).

### 2) A major component of the climate system

The earth's climate system consists of five major subsystems interacting between each other: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere (*IPCC, 2014a*). Glaciers, ice caps and ice sheets, which are part of the cryosphere, are covering approximatively 10% of the earth's continental surface at the present time (*WGMS, 2008*) and are constantly exchanging mass and energy with the atmosphere and other parts of the earth system (*Benn and Evans, 2010*). These snow- and ice-covered surfaces have high reflectance properties (high albedo) and so reduce the net solar radiation available to warm the Earth. As a consequence, the local, regional and global atmosphere temperature and circulation are impacted (*Vaughan et al., 2013*). This phenomenon is characterized by a positive feedback effect leading to an increasing destabilized system: the ice-albedo feedback (*Grenfell, 2011*). With the ongoing climate change, glacierized regions are shrinking and so lowering the continental albedo. It induces higher solar radiation absorption, hence warmer regional temperatures and an accelerated glacier melt (*Vaughan et al., 2013*). In the climate system, changes in one subsystem may give rise to a change elsewhere as each of them is coupled with the others (*Vaughan et al., 2013*). Consequently, glaciers are not only a climate indicator but glacier changes can actively impact all the components of the climate system at different level (i.e., global, regional or local) depending on their size. It is even more worrying considering that this system has an ability to change very fast or abruptly - even irreversibly if some tipping points are reached (*IPCC, 2014a*).

### 3) An important entity interacting with society in both essential and life-threatening ways

Mountain glaciers are the source of water supply, or life, for over half of the world's population (*Zemp et al., 2007*). Due to glacier melt, glaciers will reach a maximum meltwater discharge followed by a decreased glacier runoff, impacting regional water supplies, often crucial for multiple societal needs (e.g. agriculture, hydropower generation, drinking water supplies, recreation and industry) (*Huss et al., 2017*). In their study, *Huss and Hock* (*2018*) show that this tipping point has already been attained by half of 56 large-scale glacierized drainage basins worldwide and the peak water is projected to be reached by all of them by the end of the century. In addition, regional water cycles are impacted (*WGMS, 2017*): the runoff regime of glacial-fed rivers is shifting towards a nival-pluvial regime being characterized with a more variable flow (*Braun and Hagg, 2009; Huss et al., 2017*). For example, this problematic is of great importance in Central Asia, a particularly arid region, where

glacial water runoff is essential for water allocation during the dry summer months (*Dyurgerov and Meier, 2005*; *Sorg et al., 2012*). As a result, water shortage due to glacier melt in the Tien Shan and the Pamir Mountains can lead to political instabilities, drastic ecological changes and food insecurity in the whole Central Asian area (*Hoelzle et al., 2017*). The Himalaya-Hindu Kush, the South American Andes and the European Alps are also critical regions (*Barnett et al., 2005*; *Beniston, 2005*).

With glacier recession, mountain areas also face an increasing risk of local natural hazards such as Glacial Lake Outburst Floods (GLOFs) (*Bolch et al., 2011*; *WGMS, 2017*). These flooding events following the breach of a natural dam in front of a glacial lake may become more frequent because of new lakes formation and growth of existing ones (*Huss et al., 2017*). The outburst of glacial lakes can cause extremely high water discharge and large mudflow events (*Bolch et al., 2011*). For this reason, they are a serious threat for infrastructures and the population located downstream (*Clague and Evans, 2000*).

Ice loss from glaciers and ice sheets exert a major control on global sea level as glacial meltwater end up in the oceans (*Vaughan et al., 2013*). As global glacier volume will continue to shrink during the 21st century and beyond, global mean sea level will rise up to 0.82m by 2100 with the most pessimistic emission scenario (RCP8.5) (*IPCC, 2014a*). As a consequence, "coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion" (*IPCC, 2014b*).

### 1.1.2 Interest of Mass Balance Gradients

As stated by *Cogley* (*2012*), there are four principal ways for measuring glacier changes implying the following parameters' investigation: glacier length, glacier area, glacier volume - all three related to glacier dynamics - and glacier mass balance.

On a glacier, the mass balance reflects the energy balance (i.e. the sum of the individual energy components), in which shortwave radiation generally plays the most important role, especially on melting glaciers located in continental areas (*e.g. Braithwaite, 1981*). Precipitation and temperature also greatly influence the energy budget of the glacier (e.g. *Hooke, 2005*). These atmospheric conditions considered on the long term reflect the climatic environment in which the glacier sits (*Kuhn, 1981*). Through the measure of annual accumulation and ablation, the mass balance reveals annual atmospheric conditions in a more direct and undelayed response comparing to glacier dynamics, which is a delayed reaction to mass balance changes (*Kuhn, 1981*; *Haeberli, 1998*; *Zemp et al., 2009*) (Figure 1). It must be mentioned that a change in glacier area, slope or thickness has a

feedback effect on accumulation and ablation and therefore on mass balance. Therefore, glacier mass balance is the preferred measure of glacier changes in the context of glacier-climate interaction as it can be used to infer current climatic change with greater certainty (*Cogley, 2012*; *Dyurgerov and Meier, 2005*), though it does not address the whole complexity of the relationship between glaciers and climate (*Cogley, 2012*).

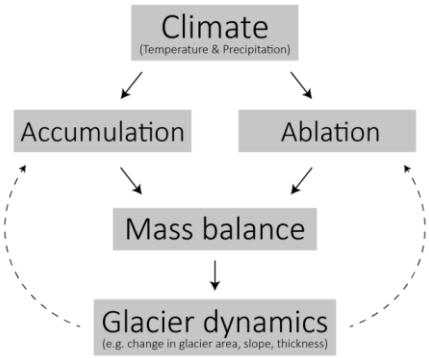



**Figure 1 :** chain of processes linking climate, glacier accumulation and ablation, mass balance and glacier dynamics. The dotted line is the feedback effect of change in glacier area, slope or thickness on accumulation and ablation. Modified from *Meier* (*1965*) and *Kuhn* (*1981*).

Knowing that precipitation is a key input parameter to mass balance models (*Machguth, 2008*), the observation of glacier mass balance in high-mountain and high-latitude areas is also particularly important because precipitation measurements are often sparse and biased in these environments where direct climate observations are lacking (*Dyurgerov and Meier, 2005*).

The surface mass balance gradient, or *db/dz*, is a measure of mass balance that is specifically looking at how fast the mass balance varies with altitude on a glacier (*Cogley et al., 2011*). Since long, mass balance gradients, first called the energy of glaciation by *Shumskii* in 1947, are regarded as a substantial measure of glacier-climate interactions because they are important representatives for the climate regime in which the glacier is located (*Kuhn, 1981*; *Oerlemans, 2001*; *Dyurgerov and Meier, 2005*). It is crucial to know that the glacier sensitivity to climate change is strongly related to its climatic environment (*WGMS, 2017*), even if the local topography or geometric parameters like the glacier hypsometry[1] also play a role in the glacier response to climatic changes (*Kuhn et al., 1985*). More maritime environments host glaciers with higher mass balance gradients and higher mass balance sensitivity[2] (*Oerlemans, 2001*): they have shorter mass turnover[3] time, faster flowing dynamics and quicker response time (*Oerlemans, 2001*). The intensity of the hydrological cycle is

[1] The distribution of the glacier area with elevation (*WGMS, 2008*)
[2] The change in mass balance due to a change in a climatic variable such as air temperature or precipitation (*Cogley et al., 2011*)
[3] The renewal of the mass of a glacier by mass balance processes (*Cogley et al., 2011*)

also higher (*Meier et al., 2003*). Due to its role on glacier velocity, the mass balance gradient at the equilibrium line altitude is also called the activity index (*Meier, 1965; Cogley et al., 2011*).

Therefore, mass balance gradients are useful to reconstruct the past, present and future climatic environments of glaciers (e.g. *Machguth and Cohen, 2016*). In addition, their crucial role on the mass balance sensitivity of glaciers is particularly important in the ongoing climate change context where future scenarios of glacier response, meltwater runoff and glacier contribution to sea-level rise have to be made as accurately as possible (*Oerlemans and Fortuin, 1992*). Nevertheless, the increase in mass balance sensitivity to warmer air temperature is not predicted by glacier-climate models and thus deserves more attention (*Dyurgerov and Meier, 2005*) - and the analysis of mass balance gradients is a way to study this sensitivity.

## 1.2 Objectives and Research Questions

The principal objective of the present work is to analyze the evolution of mass balance gradients of different glaciers worldwide during the last six decades approximatively. In this study, mass balance gradients are studied for their role as climate change indicators, based on the premise that mass-balance gradients should change if environmental parameters change (*Oerlemans and Hoogendoorn, 1989*) – and it is known that with the ongoing climatic change, in several mountain ranges, precipitation and temperatures are changing (*Dyurgerov and Meier, 2005*).

Thus, the main interest of the thesis is to test this assumption and to see if a change in the mass balance gradient of selected glaciers over the period of analysis is observable, describe it and potentially detect a similarity in the evolution trends between glaciers which could be ultimately linked to the current climate change. The hypothesis is that a general steepening of the mass balance gradients is expected, witnessing an increasing trend in ablation and/or accumulation of glaciers worldwide. Indeed, it is well known that the global atmosphere is warming and that most of the glaciers are losing mass as a consequence of the increased energy content in the climate system (*WGMS, 2008*), but the precipitation regimes are also changing, even if this phenomenon is recognized to be more complex and local. However, based on the Clausius-Clapeyron physical law, a warmer atmosphere is able to contain more moisture content (*Cuffey and Paterson, 2010*). As a consequence to global temperature rise, glaciers could thus undergo a warming induced increase in accumulation rates if precipitation falls as snow, creating steeper gradients (*Dyurgerov and Meier, 2005*). In their study, *Dyurgerov and Meier* (*2005*) detected a trend in increasing winter snow accumulation starting in the mid-1990s for twenty-one Northern Hemisphere glaciers. If this trend

continues through the 21st century, it implies that the climatic environment of glaciers is potentially becoming more maritime, causing an increase of glacier's sensitivity to climate change (*Oerlemans, 2001*) as well as other consequences related to glacier mass turnover and glacier dynamics mentioned above.

The World Glacier Monitoring Service (WGMS), responsible for internationally coordinated glacier monitoring, collects precious long-term observations of annual mass balance changes from numerous glaciers worldwide (*WGMS, 2017*). From the WGMS database, 49 glaciers are selected and their annual mass balance at different elevations form the raw data of this study. The ablation gradient $db/dz_{abl}$, the glacier-wide gradient $db/dz_{gw}$ and the accumulation gradient $db/dz_{acc}$ are then calculated. The first specific objective of the study is to analyze the evolution, i.e. the temporal variability, of the absolute value (in m w.e. $(100m)^{-1}$) of these three gradients[4]. The period of analysis (1954-2017) results from the availability of the data (i.e. 1954 is the first year with data from at least 2 selected glaciers). The first main research question and the implied more detailed questions related to it are:

1) **What is the individual evolution of the annual absolute mass balance gradients for each of the 49 selected glaciers over the period 1954-2017?**

   *a.) For each glacier, what is the mean, the standard deviation, the minimal and the maximal values [of the annual mass balance gradients evolution]?*

   *b.) For each glacier, what is the detailed evolution curve?*

   *c.) For each glacier, what is the linear evolution trend?*

   *d.) What is the overview of the mean and the standard deviation of all glaciers?*

   *e.) What is the overview of the correlation between the three gradients of all glaciers?*

   *f.) What is the overview of the annual rate of change of all glaciers? – or are mass balance gradients steepening?*

The results from question *a.)* describe statistically the annual mass balance gradient dataset for each glacier, the question *b.)* and *c.)* target specifically the main objective which is to describe the evolution of the mass balance gradients over the entire observation period[5], the question *d.)*

[4] From now on in this work, when the term *mass balance gradient*, *gradient* or $db/dz$ is used, it implicitly refers to the ablation mass balance gradient $db/dz_{abl}$, the glacier-wide mass balance gradient $db/dz_{gw}$ and the accumulation mass balance gradient $db/dz_{acc}$, unless it is specified otherwise.

[5] The detailed evolution curve (c) describes visually the evolution of the annual gradients through a graphical representation of the running mean. The linear evolution trend (d) both graphically represents the linear evolution trend and allows a quantification of the $db/dz$ change over the total period expressed in % relative to the mean $db/dz$ over the period for each glacier.

summarizes the central tendency and the variability of the mass balance gradients for all glaciers by giving an overview of these parameter values and their distribution (allowing a quantitative comparison between glaciers), the question *e.)* aims to analyze the strength of relationship between the evolution of $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$ and the question *f.)* asks if mass balance gradients are steepening and is answered by analyzing the annual rate of change of all glaciers calculated from the linear evolution trend of their annual mass balance gradients with time.

In the first research question, $db/dz$ are expressed in absolute values, giving accurate results. As annual $db/dz$ can display very different values between glaciers, they have to be expressed in a relative way to allow mean (or synthetic) evolution results for the 49 glaciers as well as the evolution comparison between classified glaciers. For these objectives, the annual mass balance gradients are calculated as a function of the standard deviation of the mean annual absolute $db/dz$ for each glacier. The second main research question and its more detailed questions are:

2) **What is the mean evolution curve of the annual relative mass balance gradients for the 49 selected glaciers and for classified glaciers over the period 1954-2017?**

   a.) *What are the detailed mean evolution curves of all 49 selected glaciers together?*

   b.) *How do the mean evolution curves of glaciers classified according to climatic parameters differ between the classes?*

   c.) *How do the mean evolution curves of glaciers classified according to geometric parameters differ between the classes?*

   d.) *How do the mean evolution curves of glaciers classified according to gradient-related parameters differ between the classes?*

The results from question *a.)* are three synthetic detailed $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$ evolution curves from the 49 glaciers while the questions *b.)*, *c.)* and *d.)* test if glaciers displaying different climatic, geometric and gradient-related[6] parameters show different detailed $db/dz$ evolution curves.

[6] Gradient-related parameters account for the descriptive statistics (here the mean and standard deviation) of the calculated absolute gradient datasets.

# 1.3 Structure

The present thesis is structured in five main remaining chapters:

In chapter 2, the theoretical *Background* on which the master thesis relies on exposes relevant information about glaciers, mass balance and worldwide glacier changes (chapter 2.1) as well as about mass balance gradients (chapter 2.2) in the context of glacier-climate interaction and the current climate change. The chapter defines the important concepts, explains important knowledge and exposes the state of the art which will be referred to in the discussion of the results.

In chapter 3, the *Methodology and Data* is presented, i.e. the different methodological steps from the data collection to the data analysis. It explains in detail how the raw mass balance data are acquired (chapter 3.1), which processing is applied to them (chapter 3.2), how the absolute and relative gradients are calculated (chapter 3.3) and how the research questions are tackled (chapter 3.4).

In chapter 4, the *Results* linked to the first research question (chapter 4.1) and the second research question (chapter 4.2) are presented[7].

In chapter 5, a *Discussion* about the obtained results is conducted. The uncertainties of the calculated mass balance gradients and the evolution results (chapter 5.1) are first discussed. Then, the observed results are interpreted (chapter 5.2). First, the causes of inter-annual (5.2.1) and long-term (5.2.2) gradients changes are investigated. Then, the evolution differences of classified glaciers are discussed (5.2.3). At the end, a comparison between the observed mass balance gradients evolution and selected mass balance parameters is shown (5.2.4).

In chapter 6, the *Conclusion* summarizes the work and gives future perspectives (chapter 6.1) as well as highlights key findings (chapter 6.2).

At the end of the work, chapter 7 lists the *References* and the *Annexes* are shown.

[7] For simplification purpose, the content of chapters 4.1 and 4.2 is not mentioned here as it is presented in detail in chapter 3.4, when the methodology of the data analysis is explained.

# 2 Background

## 2.1 Glaciers

### 2.1.1 Basics

#### 2.1.1.1 Cryosphere, Glaciers, Ice Caps and Ice Sheets

The cryosphere (derived from the Greek *kryos*, meaning *cold*) regroups all parts of the Earth's surface where water is dominantly in a frozen state (*Harris and Murton, 2005*). Glaciers are one of its components with snow cover, sea ice, river and lake ice, ice shelves and permafrost (*Cuffey and Paterson, 2010; WGMS, 2008)*. Broadly defined, glaciers refer to all ice bodies created by snowfall accumulation (*Cuffey and Paterson, 2010)*. Therefore, the term includes ice sheets and ice caps, which are dome-shaped firn/ice features with a radial flow and generally cover the subsurface topography. Their size is >50'000 $km^2$ for ice sheets and <50'000 $km^2$ for ice caps (*Cogley et al., 2011*). On the opposite, glaciers *in stricto sensus* are smaller, have a unidirectional downhill flow and are constrained by the subsurface topography, inducing internal stress and friction at the base and sides (*Zemp and Haeberli, 2007*). Due to their large volumes and areas, the two continental ice sheets (i.e. the Greenland Ice Sheet and the Antarctic Ice Sheet) are fundamentally different from glaciers and ice caps as they can greatly influence the global climate (*WGMS, 2008*). On the other hand, they react to climate forcing at greater time scales (century to millennium or more), whereas glaciers and ice caps react relatively quickly to climatic effects (months to century) (*WGMS, 2008; Zemp and Haeberli, 2007*). From now on in the present work, glaciers and ice caps only are encompassed when the term *glacier* is used as the two ice sheets are not analyzed.

#### 2.1.1.2 Glaciers Genesis and Survival

A glacier is a perennial mass of ice (and likely firn[8] and snow) on land, originating from the recrystallization of snow or other forms of solid precipitation (*Cogley et al., 2011*). A glacier forms when the snowpack accumulated in the cold or humid season does not melt entirely in the warm

[8] Structurally, the metamorphic stage intermediate between snow and ice, in which the pore space is at least partially interconnected, allowing air and water to circulate (*Cogley et al., 2011*). By convention, snow becomes firn at the end of the balance year (*Cogley, 2012*).

or dry season (*Oerlemans, 2001*). Over the years, solid precipitations are buried, compacted and transformed to ice (*Marshall, 2012*), until the interconnecting air- or water-filled passages between the grains are closed off (*Cuffey and Paterson, 2010*). Glacier ice behaves as a thick viscous fluid, deforming itself slowly and continuously under its own weight (creeping process) (*Cuffey and Paterson, 2010; Marshall, 2012*). When the ice at the glacier bed is at its pressure-melting point[9], the glacier also undergoes a rigid displacement over the bed (sliding process) (*Cogley et al., 2011*). As gravity is the leading motion factor, glaciers continuously flow downslope (*Dobhal, 2011*). They typically display a vertical extend of hundreds of metres (sometimes thousands) until they meet warmer air temperature, triggering the melt or sublimation of the ice body and ultimately its disappearance (*Cogley, 2012*). Therefore, cold temperatures and a certain amount of solid precipitation are prerequisite for glaciers' existence.

### 2.1.2 Mass Balance

#### 2.1.2.1 Accumulation and Ablation

On a glacier, two fundamental antagonist mass exchange processes, transferring mass between the glacier and its surroundings, are taking place (*Cuffey and Paterson, 2010*):

- Mass gain or *accumulation*, including all processes by which snow, firn and ice are added to the glacier and
- Mass loss or *ablation*, including all processes by which snow, firn and ice are removed from the glacier (*Cuffey and Paterson, 2010*).

As stated in *Cogley et al.* (*2011*), accumulation is mainly controlled by snowfall but other forms of solid precipitation, gain of windborne snow[10], avalanching, hoar deposition and freezing rain can also add mass to the glacier. The main processes of ablation is melt, and sometimes sublimation, loss of windborne snow and avalanching. For tidewater glaciers, calving[11] is very significant.

Different glacier types in reference to the seasonal distribution of accumulation and ablation can be differentiated (*Benn and Evans, 2010*):

1) *Winter accumulation type*, where most of the accumulation occurs during winter and most of the ablation during summer due to the pronounced seasonal variations in temperature. This repartition is characteristic of mid- and high-latitude glaciers such as those in the

[9] The temperature at which ice and water are in thermodynamic equilibrium at a given pressure (*Cogley et al., 2011*)
[10] Snow entrained, suspended and transported by the wind enabling the redistribution of snow inward or outward the glacier (*Cogley et al., 2011*)
[11] Breaking off of discrete pieces of ice from a glacier margin into lake or sea water, producing icebergs (*Cogley et al., 2011*)

European Alps, Scandinavia, North America, Patagonia, the western Himalaya and New Zealand.

2) *Summer accumulation type*, where both the accumulation and ablation maxima take place during summer because the winter season is too cold and too dry for important snow precipitation. This glacier type is found in high-altitude areas in the outer tropics such as in the monsoon-dominated parts of the Himalaya, the Pamir and the Tien Shan as well as the high Andes in Peru and Bolivia.

3) *Year-round ablation type*, where much of the accumulation is either distributed throughout the year or coincides with the wet season and ablation is also season independent because seasonal variations in temperature are not significant. It is typical for glaciers in the inner tropics like in east-central Africa, New Guinea and the Ecuadorian/Colombian Andes.

#### 2.1.2.2 Mass Balance Definition

The *mass balance* (also called *balance* or *mass budget*) refers to the change in the mass of the glacier, or a part of it, over a defined time period (*Cogley et al., 2011*). Therefore, it is the sum of accumulation (positive contribution to the mass balance) and ablation (negative contribution) (*Cuffey and Paterson, 2010*). The point mass balance[12] $b$, or $\Delta m$ is given by the following equation:

$$b = c + a = \int_{t1}^{t} (c + a)\, dt$$

Where $c$ is accumulation, $a$ is ablation and $t$ is the time interval. The glacier-wide mass balance, noted $B$ *or* $\Delta M$, corresponds to the mass change of the whole glacier[13]. The mass balance is often expressed in metres [of] water equivalent (m w.e.), accounting for the thickness of an equal mass having the density of water (*Cogley et al., 2011*). The sum of annual accumulation $C_a$ or $c_a$ and annual ablation $A_a$ *or* $a_a$ constitute the annual mass balance $B_a$ or $b_a$. It must be noted that the beginning and end dates of the spanned time $t$ depend on the chosen time system (i.e. stratigraphic, fixed-date, floating-date or combined system) as described in *Cogley et al.* (*2011*).

The seasonal mass balance can also be calculated and thus refers to the sum of accumulation and ablation during the winter season or summer season only. The addition of the winter balance $B_w$ or $b_w$ and summer balance $B_s$ or $b_s$ also gives the annual mass balance $B_a$ or $b_a$. Theoretically on a winter

[12] Mass balance at a particular location on the glacier, for example at an ablation stake or a snow pit (*Cogley et al., 2011*)
[13] Point mass balances are indicated by lower-case letters while glacier-wide balances are denoted by upper-case letters (*Cogley et al., 2011*)

accumulation type glacier, the winter balance $B_w$ approximates the annual accumulation $C_a$ whereas it is not the case on a summer accumulation type glacier.

#### 2.1.2.3 Accumulation Area, Ablation Area and Equilibrium Line

Altitude is the most important factor influencing the mass balance on a glacier (*Oerlemans, 2001*) as temperature and precipitation are directly dependent to it. Accumulation is greater in the upper parts of the glacier where much of the snowfall occurs and ablation in the lower parts where much of the ice melts. It is possible to delimitate spatially two zones on the glacier surface according to the dominant process, as represented in Figure 2. The glacier area where the cumulative mass balance relative to the start of the mass-balance year is positive ($b_n > 0$) is referred to as the accumulation area whereas the ablation area encompasses the glacier area where mass-balance is negative ($b_n < 0$) at the end of the mass balance year (*Cuffey and Paterson, 2010*; *Cogley et al, 2011*). The theoretical line separating these two zones is called the equilibrium line and corresponds to all the points on the glacier surface with a balanced-budget ($b_n = 0$). Thus, the altitude of the equilibrium line, or *ELA*, at the end of a balance year depends on the annual temperature and precipitation conditions: in warm and low-precipitations years, the *ELA* is high (*Cuffey and Paterson, 2010*). At the end of the ablation period, the equilibrium line is visible on a temperate glacier as it coincides to the lower limit of the remaining snow-covered area, i.e. the snowline (*Benn and Evans, 2010*; *Cogley et al., 2011*). Especially in colder regions, the presence of superimposed ice[14] complicates this relationship as it can create a zone below the snowline and above the equilibrium line of exposed ice (*Cogley et al., 2011*).

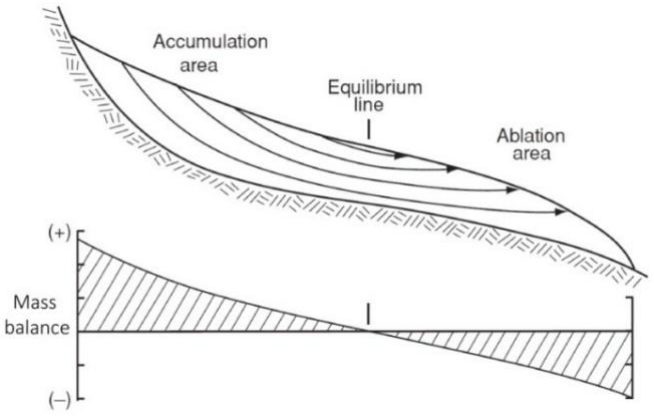



**Figure 2** : Cross section of a typical glacier showing the equilibrium line separating the accumulation area from the ablation area (up) and their corresponding mass balance (down). The arrows represent the flow direction. Modified from *Hooke* (*2005*).

[14] Ice accumulated on the current summer surface and mass balance year by refreezing rain or meltwater (*Cogley et al., 2011*)

### 2.1.3 Distribution, Monitoring and Recent Changes of World-wide Glaciers

#### 2.1.3.1 Present Global Glacier Distribution

On a local scale, the terrain (e.g. aspect, slope or relief) determines where ice and snow can accumulate and how much solar radiation the glacier can receive (*Zemp and Haeberli, 2007*). On a global scale, glacier distribution is a function of annual precipitation sum and mean annual air temperature (*WGMS, 2008*), with glaciers' favorite location being wet and cold places (*Oerlemans, 2001*). *Wet* implies a region near a moisture source (e.g. the ocean) and located in upwind direction so that the moisturized air is brought to the glacier (*Oerlemans, 2001*). *Cold* implies a region either at high latitude (colder air due to less solar energy available) or high altitude (colder air due to air expansion caused by lower air density and dry adiabatic lapse rate) (*Oerlemans, 2001*). As a result, glaciers are distributed widely across the earth's surface, with a concentration near the poles (*Cogley, 2012*) and on the windward side of the mountain ranges under the influence of westerly winds (e.g. in Norway, Alaska, Patagonia or New Zealand) (*Oerlemans, 2001*).

As stated in the last IPCC report, many uncertainties are linked to the determination of the total number and covering area of glaciers (*Vaughan et al., 2013*). For example, separating the peripheral glaciers from the ice sheets of Greenland and Antarctica, or more generally the subdivision of contiguous ice masses, is challenging. The current best estimate of the total number of glaciers world-wide is around 170,000, covering a total area of about 730,000 km$^2$. Figure 3 displays a recent global distribution of glaciers worldwide (including tidewater[15] glaciers), regrouped by proximity in 19 different glacier regions for which the covered area is weighted.

[15] The geographical setting in which a glacier terminates in the sea with its lowest end either floating or grounded below sea level (*Cogley et al., 2011*)

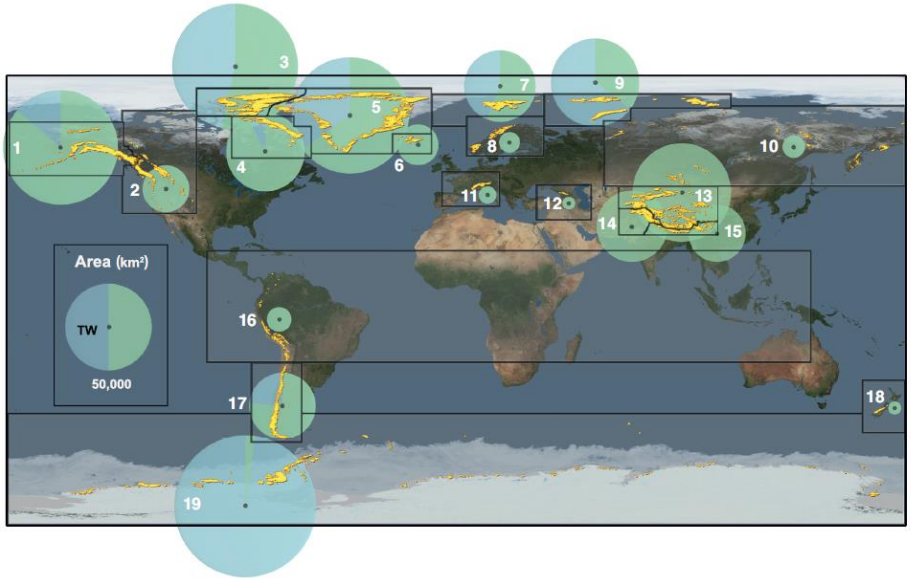



**Figure 3** : Global distribution of glaciers (yellow) with increased area for visibility, covered area (diameter of the circle) and area percentage of tidewater (TW) glaciers (blue circle part). Data are from *Arendt et al.* (*2012*) and *Gardner et al.* (*2013*). The Figure is from *Vaughan et al.* (*2013*). In order from the most glacierized region to the least, these 19 regions are: Antarctic and sub-Antarctic N°19, Asia Central N°13, Asia South West N°14, Asia South East N°15, Arctic Canada north N°3, Greenland N°5, Alaska N°1, Russian Arctic N°9, Arctic Canada south N°4, Svalbard N°7, Southern Andes N°17, Western North America N°2, Iceland N°6, Low latitudes N°16, North Asia N°10, Scandinavia N°8, Central Europe N°11, New Zealand N°18 and Caucasus and Middle East N°12 (*Gardner et al., 2013*).

#### 2.1.3.2 The World Glacier Monitoring Service and its Dataset

Glacier change observations are collected worldwide since 1894, resulting from the foundation of the International Glacier Commission at the 6th International Geological Congress in Zurich, Switzerland (*Zemp et al., 2007*). One year later, the periodic publication of compiled information on glacier fluctuations began (*Forel, 1985*). After decades of length change measurements, the focus went to mass balance observations since the late 1940s (*Haeberli, 1998*). In 1986 the World Glacier Monitoring Service (WGMS) started to maintain and continue the collection of information on glacier changes, when the two former ICSI services PSFG (Permanent Service on Fluctuations of Glaciers) and TTS/WGI (Temporal Technical Secretariat/World Glacier Inventory) were combined. The WGMS is based in Zurich and collects data about glacier distribution and changes at the global scale thanks to annual calls-for-data through its scientific collaboration network, which is active in more than 30 countries (*WGMS, 2017*). They analyze and publish glacier changes data through different reports: the Fluctuations of Glaciers series (1967-2012), the Glacier Mass Balance Bulletin series (1991-2013) and the new biennial Global Glacier Change Bulletin (since 2015) (*WGMS, 2017*). The full dataset is also available on the WGMS and GTN-G websites (www.wgms.ch and www.gtn-g-org) where it can be map-based browsed, on the wgms Glacier App and is obtainable digitally on request and free of charge (*Zemp et al., 2009*; *Zemp et al., 2015*). Thus, reliable long-term observations on glacier changes are today gathered and available for the scientific community as

well as for policymakers, the media and the public (*WGMS, 2017*). These glacier observations are part of the Global Climate Observing System (GCOS) (*Haeberli et al., 2000*) as they are essential for the understanding of climate-glacier processes (*WGMS, 2017*).

Overall, the database of the WGMS regroups approximately 99,000 observations from 9,500 glaciers worldwide (*WGMS, 2017*) with the oldest data coming from the 16th century (*Zemp et al., 2015*). A large proportion of the dataset is made up of glacier front variations (46,550 observations) (*Zemp et al., 2015; WGMS, 2017*). Glacier mass balance time series are obtained with two different survey methods:

- The glaciological method, regrouping 6,562 annual glacier-wide observations overs the past seven decades from 450 glaciers (and 37,560 annual point mass balance from 125 glaciers). They often include seasonal balances, mass-balance distribution with elevation, the *ELA*, the accumulation-area ratio[16] (*AAR*) and the corresponding point measurement location.
- The geodetic method, with 5,325 multi-year resolution data from 4,281 glaciers and extending back to the mid-19th century (*Zemp et al., 2015*).

The observations are regrouped by proximity, i.e. in the 19 different regions previously presented. In its Global Glacier Change Bulletin, the WGMS not only provides global mass balances but also regional data. At the end of the report, detailed information on selected glaciers with ongoing direct glaciological mass balance measurements in different mountain ranges are presented.

Currently, 41 glaciers have the status of a *reference glacier*, meaning that they have been measured continuously for more than 30 uninterrupted observation years with the glaciological method (*WGMS, 2017*). The reference glaciers are particularly important because climate change-related trend analysis is preferably based on long-term measurement series (*WGMS, 2017*).

#### 2.1.3.3 Observed Global Mass Balance Changes

In its most recent report, the WGMS (*2017*) compiles the global mass balance changes observed annually from 1930 to 2015. In Figure 4, the annual glaciological mass balance is displayed for all observed glaciers (mean of the 19 regions) and for the reference glaciers (mean of the 19 regions and arithmetic mean). The annual rate of geodetic mass balance is shown for all glaciers (mean of the 19 regions). The number of observation series witnesses that the observation series coming from the glaciological method is growing, reflecting the successful efforts of in-situ monitoring programmes. The most important global result is that the percentage of positive annual mass

[16] The ratio (between 0 and 1) of the glacier area occupied by the accumulation zone to the area of the entire glacier at the end of the mass-balance year (*Cogley et al., 2011*)

balances displays a long-term decreasing trend (from 33% in the 1980s to below 20% in the last years) and that there is not a single positive mass balance year since four decades. It is important to mention that the extreme balance values before the 1960s are due to the very small sample size. More in detail, the results indicate a strong mass loss in the beginning of the measurements slowing down the next decade (1956-1965), followed by a moderate ice loss until 1985 and a subsequent acceleration until the present. The average mass balance was approximately -0.26 m w.e. since 1930 until 1990 and dropped to approx. -0.43 m w.e. for the period 1991-2000 and to approx. -0.76 m w.e. for the next period (2001-2010). Thus, the results point out that there is a clear shift towards acceleration in mass loss since approx. the 1990s (*Dyurgerov and Meier, 2005*) followed by a particularly unprecedented ice loss at the turn of the 21st century (*Zemp et al., 2015*). Rapid environmental changes are thus happening (*WGMS, 2008*).

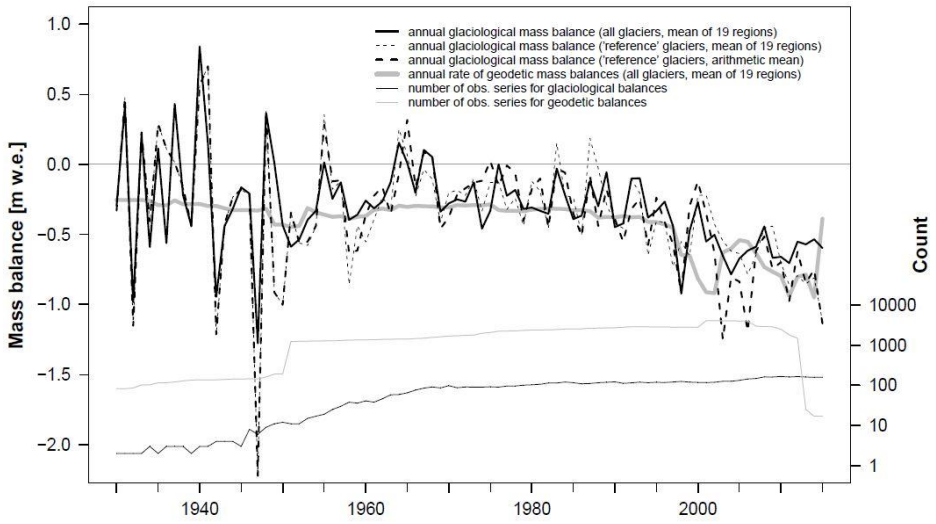



**Figure 4 :** Evolution of global averages of observed mass balances from 1930 to 2015. Annual mass balances from the glaciological and the geodetic method are shown. The results are display either for all glaciers or for the "reference" glaciers with both the arithmetic mean and the mean of the 19 glacier regions to account for the dataset bias towards the important number of glaciers in Scandinavia, Europe or Svalbard (WGMS, 2017).

### 2.1.3.4 Observed Regional Mass Balance Changes

The 19 regional mass balance averages from 1930 to 2015 are shown in Figure 5 (*WGMS, 2017*). Most of the regions display a higher proportion of negative mass balance years comparing to positive mass balance years. According to the glaciological survey, highly negative mass balance years (< -0.5 m w.e.) are generally condensed in the most recent years, especially since the 1990s. For many regions (i.e. Alaska, Western North America, Scandinavia, Iceland, Southern Andes and New Zealand) these years are interspersed by marked positive (> 0.5 m w.e.) mass balance years, indicating an important variability in the mass balance. Other regions display a less variable trend, oriented towards negative mass balance years only (i.e. Svalbard and Jan Mayen, Central Europe, Central

Asia, Asia South East and Low Latitudes). Antarctic and Sub-Antarctic Islands is the only region without any highly negative mass balance years (<0.5 m w.e.) during the full period. Even if the tendency show that mass balance are predominately negative, it is important to point out that much spatial and temporal variability exists (*Meier et al., 2003*).

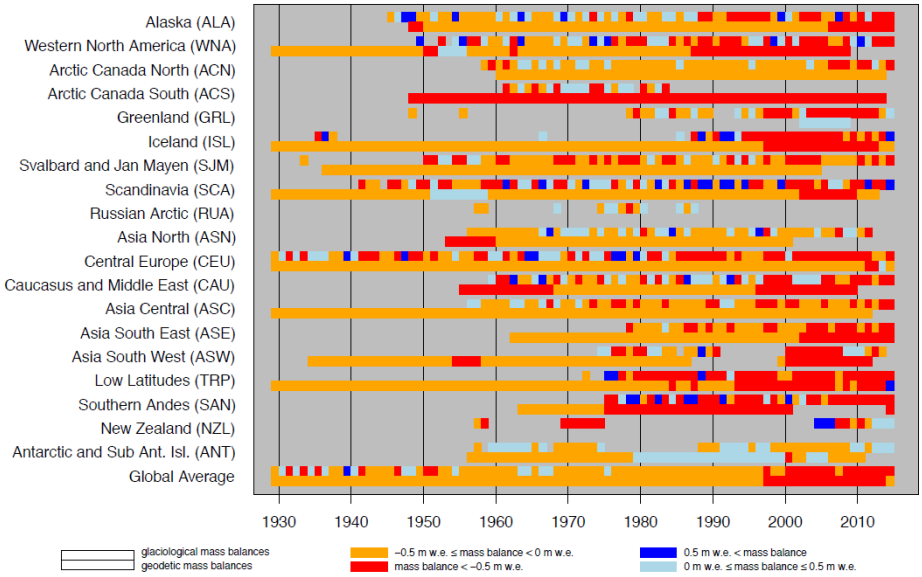



**Figure 5 :** Regional and global mass balance averages of the 19 glacier regions coming from glaciological (m w.e.) and geodetic (m w.e. a$^{-1}$) surveys from 1930 to 2015 (*WGMS, 2017*).

# 2.2 Mass Balance Gradients

## 2.2.1 Definition

The mass balance gradient $db/dz$, or $\beta$, is defined as "the rate of change of mass balance with altitude" that is, the derivative of the mass balance profile[17] (*Cogley et al., 2011*). Its mathematical expression is:

$$\beta = \frac{db}{dz}$$

With $b$ being the mass balance, $z$ the altitude (or elevation) of the glacier surface (*Oerlemans, 2010*) and $d$ (or $\Delta$) the difference. Figure 6 illustrates the mass balance gradient on a graph displaying the annual mass balance $b$ on the x-axis and the elevation $z$ on the y-axis. The theoretical mass balance profile $b(z)$ is made by the mass balance values on the glacier surface at every elevation. As no such observation exist, it is the curve linking the observed mass balance at the corresponding elevation

[17] The variation of mass balance with altitude $b(z)$ (*Cogley et al., 2011*).

points. It can also be derived from energy balance models (*Benn and Evans, 2010*). The altitude where *b(z)* crosses the 0 m w.e. corresponds to the *ELA* and thus separates the accumulation zone above from the ablation zone below. Per definition, the mass balance gradient is the slope of the tangent line (i.e. the derivative) to this balance profile at a certain point. Generally, the mass balance gradient is expressed in m w.e. $(100m)^{-1}$, witnessing for the slope of the balance profile for the concerned 100 m elevation interval, i.e. the difference of mass balance divided by $dz$ = 100 m. If the value is high, it means that there is an important mass balance change $db$ for $dz$, namely a large, high or "steep"[18] mass balance gradient (*Hooke, 2005*). On the opposite, if the value is low, there is is a small, or low, mass balance gradient (*Hooke, 2005*).

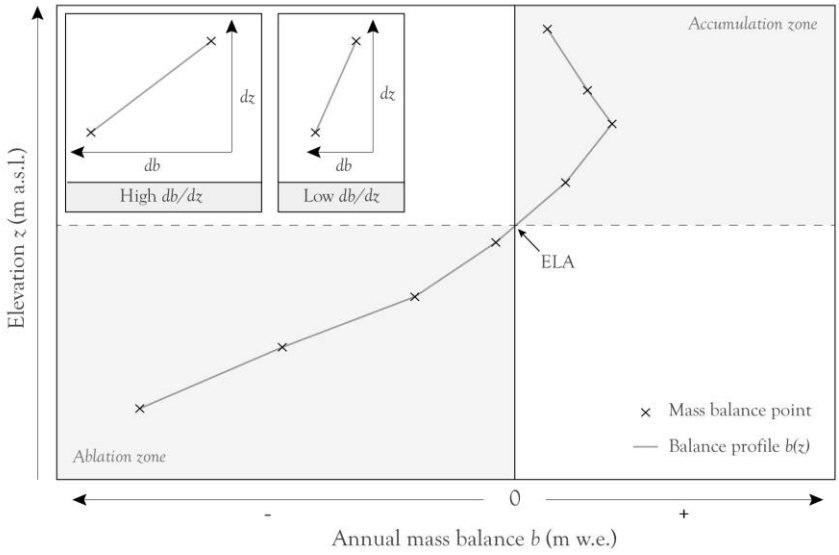



**Figure 6 :** mass balance points *b* distributed with elevation *z* and the resulting balance profile *b(z)*. On the top left corner, the schematical difference between a theoretical high *db/dz* and a low *db/dz* is represented for the same elevation difference and showing that the gradient depends on the annual mass balance difference only.

*db/dz* is generally larger and more constant in the ablation area whereas it is smaller and more variable in the accumulation area, the inflection point often being close to the *ELA* (*Nesje and Dahl, 2000*). Due to their differences, detailed studies distinguish the ablation gradient, noted here $db/dz_{abl}$ from the accumulation gradient $db/dz_{acc}$. The two gradients are influenced by different climatic variables (*Nesje and Dahl, 2000*) and other processes explained in chapter 2.2.2. In the literature, the term mass balance gradient usually refers to the glacier-wide gradient $db/dz_{gw}$, encompassing both the ablation and the accumulation gradient. Therefore, it is strongly linked to the absolute values of ablation and accumulation (*Kuhn, 1981*). Chapter 2.2.3 explains why mass

[18] The term « steep » is often used in the literature because the mass balance gradient is noted *db/dz*. As a consequence, the slope looks flat when the mass balance is displayed on the *x* axis and the altitude on the *y* axis but it would look steep in inverse axis configuration.

balance gradients of glaciers located in maritime or in continental environments are different and how it influences their sensitivity to climate change.

## 2.2.2 Governing Factors

### 2.2.2.1 Ablation Gradient

As a summary, the ablation gradient typically displays a linear trend due to its dependence on the atmospheric temperature lapse rate. Its steepness is due to the mean annual air temperature, the length of the ablation period and the amount of solar radiation that the glacier receives. These factors determine the maximal value of ablation, influencing the gradient. According to the energy balance on the glacier surface, the melt is driven by downward shortwave radiation, downward longwave radiation and sensible heat transfer (*Braithwaite, 1981*; *Cuffey and Paterson, 2010*). Temperature is a very important parameter as it is directly influencing the two latter ones. In addition, temperature determines the heat loss from to the glacier to the atmosphere through its role in the emitted longwave radiation (*Cuffey and Paterson, 2010*). Albedo determines the upward shortwave radiation and thus also plays an important role on glacier melt amount (e.g. *Oerlemans and Hoogendoorn, 1989*). Other non-climatically controlled factors such as shading effects, glacier geometry, or debris cover can cause a local non-linearity in the ablation gradient.

#### Atmospheric Temperature Lapse Rate

Air temperature decreases with altitude due to reduced air pressure and density with height (*Barry, 2008*). Lower air temperatures mean that a smaller turbulent heat flux and less incoming longwave radiation from the atmosphere add energy to the glacier surface (*Oerlemans, 2001*). Therefore, ablation rates are proportional to elevation and strongly decrease with altitude (*Cogley, 2012*; *Hooke, 2005*). The ablation gradient is often constant (or linear) because the atmospheric temperature lapse rate (i.e. the altitudinal temperature change) approximates a linear function (approx. 6 to 7°C per kilometer) (*Oerlemans and Hoogendoorn, 1989*; *Oerlemans, 2010*).

#### Mean Annual Air Temperature

Mean annual air temperature, in particular summer temperatures, determines the amount of melt that the glacier undergoes (*Cuffey and Paterson, 2010*). With a warming of the overlying atmosphere above the melting point, the net energy flux into the surface is positive (the downward longwave radiation and the sensible heat transfer increase) and the melt rates tend to strongly increase (*Oerlemans and Hoogendoorn, 1989*; *Cuffey and Paterson, 2010*).

In addition, higher mean annual air temperature cause the ice surface to spend more time at the melting point so the ablation period is longer (*Cuffey and Paterson, 2010*) (see next paragraph). It has been proven that the temperature at the *ELA* is a good predictor for the mass balance gradient (e.g. *Machguth and Cohen, 2016*). Glaciers located in mid-latitudes and/or at low elevation where the mean air temperature is higher and the air temperature frequently rises above 0°C during the summer typically show higher ablation rates, resulting in steeper ablation gradients. For these glaciers, temperature is a very important factor that indirectly controls the melt.

### Length of the Ablation Period

An obvious process is that the mass balance gradient gets steeper with time, following the amount of melt increase. Therefore, the longer the ablation period, the larger the ablation gradient is (*Kuhn, 1981*). The length of the ablation period can change from year to year but it mainly varies among climatic regions. It is much longer in a tropical climate than at high latitude or altitude regions (*Kuhn, 1981*). The length of the ablation period is thus determined by the mean annual air temperature (see previous paragraph) and the annual course of air temperature. Climatic regions with a lower temperature amplitude through the year (often maritime areas) have a longer ablation period due to the flatter shape of the temperature evolution sine curve covering more positive degree days (*Machguth and Cohen, 2016*). The correlation between air temperature and ice melt is the basis for the well known degree-day model (*Krenke and Khodakov, 1966*; *Braithwaite and Olesen, 1989*), relating melt to the sum of positive temperatures over the year. Glaciers undergoing more positive degree days also display higher mean annual temperatures, the relationship being non-linear (*Oerlemans and Hoogendoorn, 1989*). These glaciers generally show steeper ablation gradients because the sensible heat flux contribute directly to melt only when the air temperature is above 0°C (*Cuffey and Paterson, 2010*).

### Solar Radiation

Solar radiation provides a particular amount of the energy for melt and makes a large contribution to the glacier surface energy flux when melting occurs (*Oerlemans, 2001*). The amount of received shortwave radiation depends on latitude (*Kuhn, 1981*) - higher latitudes receive less net solar insolation than lower latitudes due to the wider angle of sun rays with the Earth's surface (*Barry, 2008*). In addition, the downward shortwave radiation on a glacier surface increases with altitude because the atmosphere is thinner (*Cuffey and Paterson, 2010*). For glaciers located at very-high altitude (e.g. Zongo in Bolivia), net shortwave radiation controls the variations of the energy available for melt (*Sicart et al., 2008*). Therefore, temperature and melt are poorly correlated over daily time scales (*Sicart et al., 2008*). Because temperatures are lower at higher elevation, the ablation

of high-altitude glaciers are more influenced by shortwave radiation rather than longwave radiation positively correlated with temperature (*Cuffey and Paterson, 2010*).

Albedo, local geometric factors like slope and aspect as well as shading effects influence the absorbed solar radiation (*Oerlemans, 2001*). Albedo generally increases with altitude on the glacier so less solar radiation is absorbed (*Oerlemans, 2001*). According to their slope and aspects, glacier surfaces that receive more direct solar radiation undergo more ablation (*Cuffey and Paterson, 2010*). As a consequence, in the northern hemisphere, north facing slopes generally display lower ablation rates (*Cufey and Patterson, 2010*). Shadow from the surrounding rock walls can cause a local inversion of the mass balance gradient because the ice melt is reduced at the concerned elevation (*Machguth et al., 2016*).

Decadal global solar radiation, known as global dimming and brightening, can occur depending on the greenhouse effect or aerosol changes, as it was observed during the 20$^{th}$ century, and can have profound effect on global glacier melt (*Ohmura et al., 2007, Wild et al., 2017*).

### Surface Albedo

The surface of glaciers is never homogeneous: it displays a mosaic of different materials and structures which have different capacity to reflect the solar radiation (i.e. different albedo) (*Oerlemans, 2001*). The surface albedo (value between 0 and 1) has a significant influence on the total net shortwave radiation absorbed by the glacier, which is generally the most important energy source for melt (*Klok and Oerlemans, 2004*; *Cuffey and Paterson, 2010*). The temporal and spatial variability in the surface energy budget of glaciers are determined to a large extend by the surface albedo (*Oerlemans, 2001*).

A surface with high albedo (e.g. fresh snow, approx. 0.85) will melt less than a surface with a lower albedo (e.g. clean ice, approx. 0.35) (*Cuffey and Paterson, 2010*). Albedo can vary along the surface profile of a glacier depending on the different surface characteristics: the aspect, the slope, the roughness, the topography, the presence of liquid water, impurities (e.g. mineral dust, soot or black carbon) or debris at the surface, the crystal structure of ice or the exposition to wind (*Oerlemans, 2010; Naegeli, 2017*). A locally higher surface albedo than at the surrounding elevations on a glacier will be seen with smaller ablation gradient than normal at the concerned elevation interval, the opposite for a lower albedo. This factor predominantly depends on the individual characteristics of each glacier (*Machguth and Cohen, 2016*). Albedo can be altitude independent, but marked vertical albedo changes often happen near the *ELA* as it is a transition zone where the glacier surface grades from snow, to snow patches, to bare ice (*Cuffey and Paterson, 2010*). With increasing air temperature, melt removes snow to expose ice, so the snow line altitude increases and the duration of the snow-

cover decreases. As a consequence, bare-ice is longer exposed over the season and surface melt is significantly increased as more shortwave radiation are absorbed, creating an ice-albedo feedback (*Oerlemans and Hoogendoorn, 1989*).

After a fresh snowfall and over the melt season, the albedo of ice and snow decreases over time (*Cuffey and Paterson, 2010*). Thus, the peak of shortwave radiation absorption is generally happening a few months after the summer solstice (*Cuffey and Paterson, 2010*).

**Debris Cover**

The presence of debris on the lowest part of the glacier is the most common cause of non-linear gradients (*Nesje and Dahl, 2000*; *Benn and Evans, 2010*). In the ablation area, debris are exposed at the surface as glacier ice is melting. Over the melt seasons, the debris cumulates to reach their maximum generally in the lower ablation zone (*Cuffey and Paterson, 2010*). Debris cover is a special case of marked albedo changes over a glacier surface as it can both increase and decrease the surface reflectance properties of the glacier surface depending on its thickness (*Cuffey and Paterson, 2010*). A thick debris coverage locally reduces ice melt as it forms an insulating cold air layer for the underlying ice or snow (*Naegeli, 2017*). A thin debris cover triggers stronger ice melt due to the lower albedo of debris cover (e.g. debris-rich ice, approx. 0.2) comparing to a bare surface (e.g. clean firn, approx. 0.55) and to the heat conduction through the rocks, melting the underlying snow and ice (*Naegeli, 2017*; *Cuffey and Paterson, 2010*). The strongest values of ice melt are found at around 2 cm thickness of debris cover (*Benn and Evans, 2010*). This factor is also glacier-specific (*Østrem, 1959*).

#### 2.2.2.2 Accumulation Gradient

In summary, the accumulation gradient is often non-linear. Just above the *ELA*, the gradient is usually similar to the linear ablation gradient (i.e. it is still witnessing the atmospheric temperature lapse rate) or slightly decreases. Higher up, there can be a stronger decrease which can lead for some glaciers up to an inversion of the gradient (i.e. mass balance with elevation have decreasing values), creating a bending of the balance profile. These processes are mainly linked to the influence of the amount of snowfall which is physically controlled but can also be due to snow redistribution by wind and avalanches, linked to topographic effects (*Benn and Evans, 2010*).

**Amount of Snowfall**

The amount of snowfall is generally the most important governing process in the accumulation area. As stated by *Cuffey and Paterson* (*2010*), snowfall rates are controlled by three main factors:

- (1) The water content of the overlying atmosphere: a higher water content triggers more snowfall. The Clausius-Clapeyron formula relates that the vapor pressure at saturation increases exponentially with the air temperature.
- (2) A subfreezing air (<0°C) in the lower atmosphere, so that precipitation reach the ground as snow instead as rain.
- (3) A rapid cooling of moisture-bearing air masses when it lifts.

These three factors highlight that temperatures strongly influence the amount of snowfall as it controls (1) and (2) and can affect (3). Therefore, high accumulation rates, and thus high accumulation gradients, are found where the atmosphere is cold enough to allow solid precipitation but warm enough so that the water content of the atmosphere triggers high amount of precipitation.

In addition, the amount of snowfall generally increases with altitude because the fraction of precipitation that falls as snow increases due to air temperature cooling (*Oerlemans and Hoogendoorn, 1989*). As air cools down while gaining altitude because it expands due to lesser atmospheric pressure, the relative water content of the air mass increases (the absolute moisture holding capacity of the air decreases with decreasing temperature). When it saturates (i.e. when the relative water content reaches 100%), precipitation is triggered. From a certain elevation threshold, typically 3500 m, it is possible that snowfall stops increasing with elevation because they have been triggered at lower elevation (*Oerlemans, 2010*). As a consequence, the accumulation gradient becomes smaller or even starts to be negative due to the fact that precipitation have already been triggered, resulting in a bending in the upper part of the balance profile (*Hooke, 2005*). This phenomenon, known as the elevation-desert effect, is magnified in high and extremely cold environments (*Cuffey and Paterson, 2010*).

### Snow Redistribution by Wind and Avalanches

Wind and avalanche processes can remobilize the snow from or to the glacier surface. These processes are often linked to the topography from the glacier and the adjacent terrain and can strongly influence the accumulation gradient (*Benn and Evans, 2010*). For example, avalanching of snow from adjacent steep valley slopes or headwalls can locally be an important source of accumulation for some mountain glaciers (*Cuffey and Paterson, 2010*), particularly in the Himalaya (*Benn and Evans, 2010*). As a consequence, the mass balance gradient steepens at the concerned altitude. On the other hand, at the uppermost parts on a glacier, the accumulation gradient can start decreasing because snow cannot accumulate properly due the mountain slopes steepness. As this process is altitude dependant, it can be found on the accumulation gradient of many glaciers

and corresponds to the elevation threshold since which accumulation rates are decreasing. Snow drift can therefore influence the shape of the uppermost part of the balance profile (*Kuhn, 1981*).

### 2.2.3 Climatic Environments

The ablation and the accumulation gradients are governed by the temperature and precipitation regime in which the glacier is located, making of the mass balance gradient "an important quantity characterizing the climate setting of a glacier" (*Oerlemans, 2010*). Thus, studying mass balance gradients means to study the climatic environments of glaciers. Meier and Post (*1962*) clearly stated that the mass balance gradient at the equilibrium line altitude reflects the continentality of the climate in which a glacier is located (*Kuhn, 1981*). Therefore, two main different climatic environments with opposite precipitation and temperature regimes sustaining glaciers are usually referred to: the maritime and the continental environment. Glaciers located in the two different climate regimes consequently show contrasting mass balance gradients: lower (or smaller) for continental-type glaciers and higher (or steeper) for maritime-type glaciers (*Hooke, 2005*) (Figure 7).

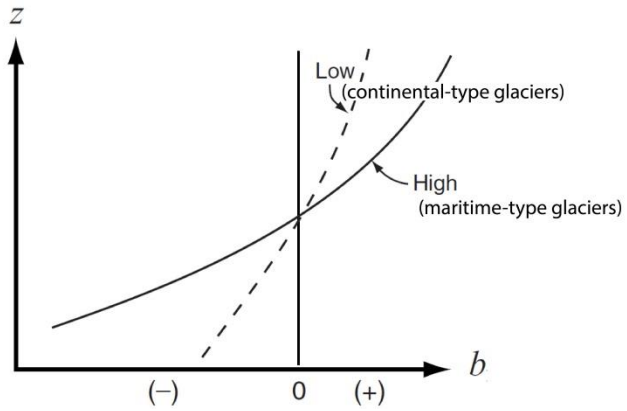



**Figure 7 :** simplified typical mass balance gradients for continental-type glaciers (low gradient) (dotted line) and maritime-type glaciers (high gradient) (continuous line). Modified from *Hooke* (2005).

#### 2.2.3.1 Maritime-type Glaciers

Maritime environments are characterized by a climate with a large amount of precipitation (1500 to 5000 mm $yr^{-1}$), a small seasonal temperature range and a high humidity leading to a large mean fractional cloudiness (0.6 to 0.9) (*Oerlemans, 2010*). Maritime-type glaciers will consequently receive large snowfall and rely on it for their existence (*Hooke, 2005*). They are subject to warmer air temperature triggering ice melt as they can extend into warmer areas than continental-type glaciers (*Cuffey and Paterson, 2010*). As a consequence, their *ELA* stands near the 0°C free air isotherm. There is indeed a strong dependence of the *ELA* on the annual amount of precipitation: the higher the amount of precipitation, the lower is the *ELA* (*Oerlemans, 2010*). As maritime-type glaciers are

highly dependent on a moisture source, they are found either *i)* near a large waterbody or *ii)* on a main atmospheric flow direction, with no/few mountain ranges laying in-between (*Stumm, 2011*; *Hooke, 2005*). In a warmer climate setting, more moisture is also initially available for precipitation[19], highlighting that temperature and precipitation are not entirely independent factors (*Oerlemans, 2001*).

Due to the warmer and wetter climate regime in which maritime glaciers sit as well as their longer ablation period, they display relatively high ablation and accumulation rates (*Kuhn, 1981*). Therefore, their mass balance gradient is considerably higher, i.e. their mass balance quickly increases with altitude. Typical examples of maritime glaciers are Franz Josef in New Zealand and Nigardsbreen in Norway (*Oerlemans, 2001*).

#### 2.2.3.2 Continental-type Glaciers

Continental environments host glaciers in a climate with a small amount of precipitation (300 to 1000 mm $yr^{-1}$), a large seasonal temperature range and a low humidity leading to a generally smaller fractional cloudiness (0.3 to 0.7) (*Oerlemans, 2010*). The large annual temperature amplitude is due to the fact that continental-type glaciers are located far from a moisture source, where there is no water body evening out temperature extremes (*Stumm, 2011; Cuffey and Paterson, 2010*). As a consequence, these glaciers owe their existence to cold temperature because they cannot rely on a high amount of snowfall (*Hooke, 2005*). These two processes are interdependent as in colder regions, the air moisture holding capacity decreases, which in turn limits the precipitation available for accumulation (*Stumm, 2011*). Thus, their *ELA* lies significantly higher than the 0°C free air isotherm so that they are subject to less melt causing ablation. Consequently, they are found at higher latitude or altitude than maritime-type glaciers (*Oerlemans, 2001*). It must be noted that it is not the high altitude of the equilibrium line which is central for continentality but rather the elevation of the equilibrium line above the 0°C level of the free atmosphere (*Meier and Post, 1962*). In other words, the temperature at the *ELA* is a good indicator of continentality (*Huss and Farinotti, 2012*; *Machguth and Cohen, 2016*).

Due to their colder and drier climate setting as well as their shorter ablation period[20], continental glaciers display smaller ablation and accumulation rates than maritime glaciers (*Kuhn, 1981*). The mass balance does not display an important change with altitude so their mass balance gradient is relatively low (or small). White in the Canadian Arctic or Tuyuksuyskiy in Kazakhstan are typical examples of continental glaciers (*Oerlemans, 2001*).

[19] A 10°C warming doubles the vapor content of saturated air (*Cuffey and Patterson, 2010*).
[20] Glaciers in high arctic can have an ablation period two or three times shorter than those in the Alps (*Hooke, 2005*).

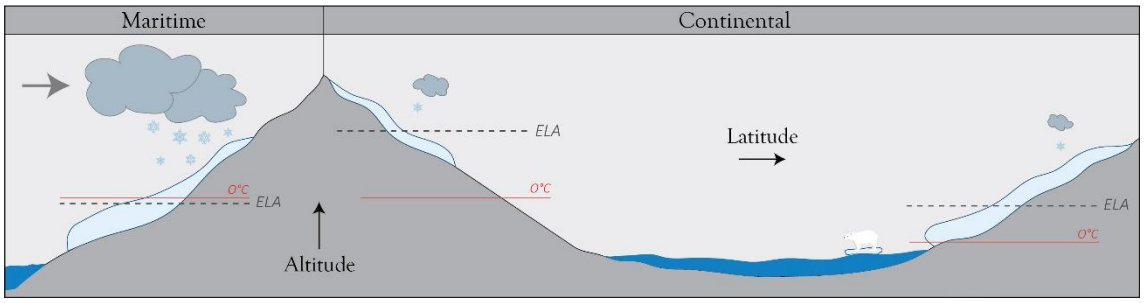



**Figure 8 :** Schematical illustration of the main climatic differences between for a maritime-type glacier (left), a high altitude continental-type glacier (middle) and a high latitude continental-type glacier

Figure 8 illustrates the main climatic environment differences between continental- and maritime-type glaciers. It is important to mention that there often is an asymmetry in the precipitation regime in most of the mountain ranges: the side exposed to the moisture source (e.g. the western side of glaciers located in the westerlies) is very wet whereas the eastern side is dry (*Oerlemans, 2001*). As a consequence, a mountain range can host both maritime- and continental- type glaciers according to if they are located on the windward side or not. A typical example is the Southern Alps of New Zealand, where mass balance gradients of glaciers located west of the Main Divide are considerably higher than the eastern glaciers. It is because they are directly exposed to the prevailing westerly circulation and receive much more precipitation (*Anderson et al., 2010; Cullen et al., 2016*).

It must also be noted that many glaciers are neither completely maritime nor continental but are located in a transitional climate, displaying intermediate climatic environmental characteristics and mass balance gradients (*Oerlemans, 2010*). Most of the glaciers located in the Alps, the central Rocky Mountains or in northern Scandinavia are examples of transitional-type glaciers (*Oerlemans, 2010*).

#### 2.2.3.3 Climate Sensitivity of Maritime and Continental Glaciers

A change in the mass balance component of a glacier will impact its mass balance. For example, an increase in snowfall and/or a decrease in air temperature will lead to increased mass balance with a resulting expansion of the accumulation zone and a lowering of the *ELA* (*Benn and Evans, 2010*). The opposite effect will happen in case of reduced snowfall and/or higher air temperatures. The change in mass balance of a glacier in response to a given change in climate refers to its climate sensitivity (*Oerlemans, 2001*). It has been found that the climate sensitivity of maritime glaciers is larger than the one of continental glaciers (*Oerlemans, 2001*). It means that for a given change in temperature or precipitation, the resulting change in mass balance will be greater for maritime-type glaciers. It is due to the fact that first, annual precipitation sum is higher in maritime area so the modification in the partitioning of precipitation between snow and rain has a larger absolute effect (*Benn and Evans, 2010*). Secondly, the albedo feedback is more effective in a maritime area because

the amount of snowfall is larger (*Oerlemans and Hoogendoorn, 1989*). Thirdly, the ablation area is located in a warmer climatic zone as they extend further down (*Oerlemans, 2001*). Therefore, the increased temperature will have greater impact on melt rates as the relationship between temperature and ablation is non-linear (*Oerlemans and Hoogendoorn, 1989*). Thus, glaciers with a steeper mass balance gradient, implying that they are located in a maritime climatic environment characterized by relatively high air temperature and high precipitation, have a higher climate sensitivity (*Oerlemans, 2001*; *Meier et al., 2003*).

Another important point is that the mechanism and timing of the transformation from snow to glacier ice depends on temperature; it is faster in maritime environments than in colder and drier regions because wet snow refreezing speed up the process (*Cuffey and Paterson, 2010*). Maritime glaciers also receive more snowfall and thus, more weight is added on the upper part on the glacier. Therefore, they have a higher rate of ice supply (*Abermann et al., 2011*). As a consequence, glaciers in a maritime environment flow faster in order to maintain a steady state profile (*Kuhn, 1981*). With this so-called high mass turnover, they are consequently showing smaller response time to climate change than continental-type glaciers, for a given geometry (*Meier, 1984*; *Oerlemans, 2010*; *Cuffey and Paterson, 2010*).

It is known that the climatic sensitivity of a glacier does not only depend on its climatic environment but also on local topographic effects and geometric factors like its hypsometry[21]. As a consequence, two adjacent glaciers can show different mass balance responses to an identical climate forcing (e.g. *Kuhn et al., 1985*). *Oerlemans* (*2008*) also suggests that maritime glaciers have a higher climate sensitivity because they are also generally longer and flatter, causing a stronger mass balance response to climate change.

[21] The distribution of the glacier area with elevation

# 3 Methodology

## 3.1 Data Collection

### 3.1.1 WGMS Database

The raw data serving as input data for the mass balance gradients obtained in the present study are mass balance data coming from the *Fluctuation of Glaciers database* created and published by the WGMS (*2017*). These raw data exist either as *i)* area weighted mean annual mass balance values for elevation bands of 20m, 50m or 100m or as *ii)* mass balance point values from direct glaciological measurements. Descriptive information about the selected glaciers has the same source. All these data are accessible from the WGMS website (https://wgms.ch), under the *Data* tab and the *Database versions* section. There, the current version (from 2018) is downloaded as a zip file. The database is made of 11 different csv-files containing information on glaciers from various nature. The files containing information of interest for the present study are: *General information*, *State*, *Mass balance* and *Mass balance point*. First, these files are converted from *csv* to *xlsx* format where they appear as tables, enabling a better visualization. Each of these files contains tens of different data categories (e.g. glacier name, maximal elevation, winter balance, annual balance, etc.) organized by columns and yearly information from thousands of glaciers listed by row, except for the *General Information* file which contains one raw of information for each glacier. Figure 9 lists which data categories from the mentioned files have been extracted after a process of glacier selection (see chapter 3.1.2) and then organized in 2 different files called *Glaciers characteristics* and *Mass balance data* containing the raw data for the present study (see chapter 3.1.3). The information from the file *Mass balance data* was processed first.

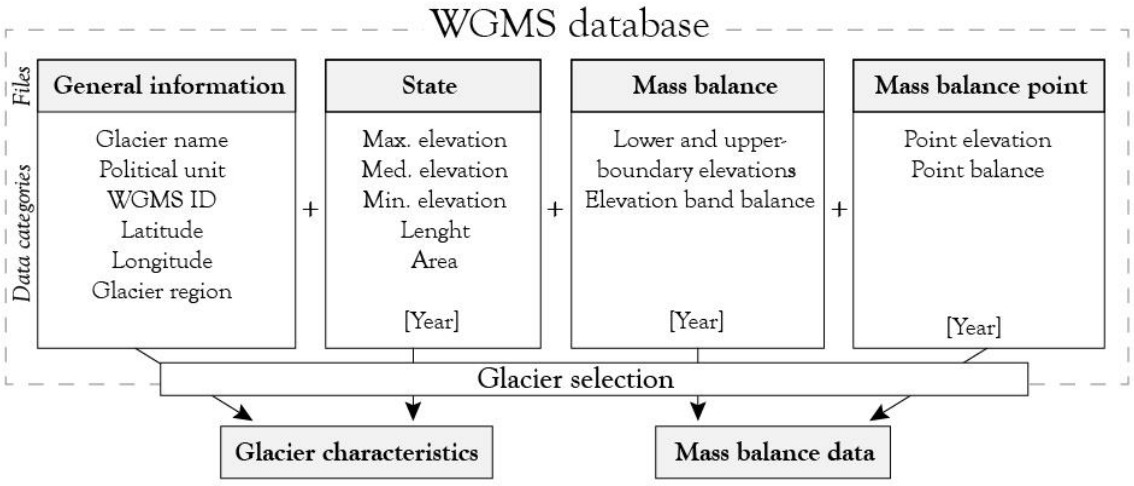



**Figure 9** : The four files from the WGMS database in which information from the different mentioned categories were collected for the present analysis after a process of glacier selection. These data will be later organized in two different files containing either glacier characteristics or mass balance data.

### 3.1.2 Glacier Selection

Only data from specific glaciers serving the aim of the present study (i.e. the analysis of mass balance gradients evolution in a context of glacier-climate interactions) are extracted from the WGMS database. Therefore, glaciers must be selected beforehand. Glaciers for which all or most of the following criteria are available are selected. Criteria concerning the dataset are:

- Annual mass balance with elevation bands or point data (at least at three different elevation references)
- Long time series (at least approx. 10 years of total coverage)
- Time series covering also the present

Criteria concerning the glacier itself are:

- Not affected by surge instabilities
- Not calving in lake or ocean
- Not heavily debris covered
- Not too small[22]

Glaciers displaying these criteria are known to be more suited for climate analysis (*WGMS, 2008*). After a database exploration according to the mentioned criteria and selection advices related to the quality of the datasets and the suitability of glaciers for glacier-climate interactions analysis from

[22] The smallest selected glacier has a minimal area of 0.6 km$^2$ (Urumqui Glacier W).

*Martin Hoelzle* and *Michael Zemp*, 49 glaciers could be selected. Their assigned number for this study, WGMS ID, name and political unit are presented in Table 1.

| Nr. | Political unit | WGMS ID | Glacier name | Nr. | Political unit | WGMS ID | Glacier name |
|---|---|---|---|---|---|---|---|
| **1** | AT | 491 | Hintereisferner* | **26** | NO | 321 | Austdalsbreen |
| **2** | AT | 480 | Jamtalferner | **27** | NO | 298 | Engabreen* |
| **3** | AT | 507 | Kesselwandferner* | **28** | NO | 299 | Graasubreen* |
| **4** | AT | 489 | Vernagtferner* | **29** | NO | 322 | Hansebreen |
| **5** | BO | 1503 | Zongo | **30** | NO | 300 | Hellstugubreen* |
| **6** | CA | 39 | Devon Ice Cap NW* | **31** | NO | 323 | Langfordjoekelen |
| **7** | CA | 45 | Helm* | **32** | NO | 290 | Nigardsbreen* |
| **8** | CA | 57 | Peyto* | **33** | NO | 2296 | Rembesdalskaaka* |
| **9** | CA | 41 | Place* | **34** | NO | 302 | Storbreen* |
| **10** | CA | 0 | White* | **35** | RU | 726 | Djankuat* |
| **11** | CH | 394 | Allalin* | **36** | RU | 761 | Garabashi |
| **12** | CH | 463 | Basodino | **37** | RU | 795 | Maliy Aktru* |
| **13** | CH | 367 | Gietro* | **38** | RU | 780 | Vodopadniy |
| **14** | CH | 359 | Gries* | **39** | SE | 1461 | Marmaglaciaeren |
| **15** | CH | 360 | Grosser Aletsch | **40** | SE | 334 | Rabots Glaciaer |
| **16** | CH | 473 | Rhone | **41** | SE | 342 | Riukojietna |
| **17** | CH | 395 | Schwarzberg | **42** | SE | 332 | Storglaciaeren* |
| **18** | CH | 408 | Silvretta* | **43** | SJ | 292 | Austre Broeggerbreen* |
| **19** | CN | 1511 | Urumqi Glacier E | **44** | SJ | 291 | Midtre Lovenbreen* |
| **20** | CN | 1512 | Urumqi Glacier W | **45** | SJ | 2307 | Waldemarbreen |
| **21** | KG | 732 | Abramov | **46** | US | 90 | Gulkana* |
| **22** | KG | 753 | Golubin | **47** | US | 3334 | Lemon Creek* |
| **23** | KZ | 797 | Shumskiy | **48** | US | 205 | South Cascade* |
| **24** | KZ | 817 | Tuyuksuyskiy* | **49** | US | 94 | Wolverine* |
| **25** | NO | 317 | Aalfotbreen* | | | | |

**Table 1 :** list of the 49 selected glaciers from the WGMS (*2017*) database. Their assigner number (Nr.) for the present analysis, their political unit and WGMS ID are mentioned. Glaciers with an * correspond to the current reference glaciers of the WGMS.

### 3.1.3 Data Organization

The data from the selected glaciers are organized in two different file categories according to the nature of the downloaded data as represented in Figure 9. The data are used for two different aims: *1)* glacier identification and glacier classification (*Glacier characteristics* file) and *2)* mass balance gradients calculation (*Mass balance data* file).

The file *Glaciers characteristics* contains one single *xlsx* file displaying information on the listed data categories in Figure 9, for all 49 selected glaciers. It must be mentioned that only the most recent available values of maximal, median and minimal elevation, length and area values are stored. For some glaciers, these data had to be taken from the WGMS App, as there were not available in the database from the WGMS website. The information from the file *Glaciers characteristics* is stored in Annex 1.

| Nr. | Glacier name | Total time coverage |
|---|---|---|
| 1 | Hintereisferner | 1964-2017 |
| 2 | Jamtalferner | 1989-2016 |
| 3 | Kesselwandferner | 1967-2017 |
| 4 | Vergtferner | 1965-2015 |
| 5 | Zongo | 1992-2015 |
| 6 | Devon Ice Cap NW | 1961-2000 |
| 7 | Helm | 1982-2005 |
| 8 | Peyto | 1966-2005 |
| 9 | Place | 1965-2005 |
| 10 | White | 1960-2016 |
| 11 | Allalin | 1956-2016 |
| 12 | Basodino | 1993-2016 |
| 13 | Gietro | 1967-2016 |
| 14 | Gries | 1962-2016 |
| 15 | Grosser Aletsch | 1954-1985 |
| 16 | Rhone | 1980-2015 |
| 17 | Schwarzberg | 1956-2016 |
| 18 | Silvretta | 1954-2016 |
| 19 | Urumqi Glacier E | 1989-2016 |
| 20 | Urumqi Glacier W | 1989-2016 |
| 21 | Abramov | 1968-2016 |
| 22 | Golubin | 1981-2016 |
| 23 | Shumskiy | 1968-1984 |
| 24 | Tuyuksuyskiy | 1965-2016 |
| 25 | Aalfotbreen | 1963-2015 |
| 26 | Austdalsbreen | 1988-2016 |
| 27 | Engabreen | 1970-2016 |
| 28 | Graasubreen | 1963-2016 |
| 29 | Hansebreen | 1986-2016 |
| 30 | Hellstugubreen | 1962-2016 |
| 31 | Langfordjoekelen | 1989-2016 |
| 32 | Nigardsbreen | 1962-2016 |
| 33 | Rembesdalskaaka | 1963-2016 |
| 34 | Storbreen | 1990-2016 |
| 35 | Djankuat | 1968-2009 |
| 36 | Garabashi | 1984-2014 |
| 37 | Maliy Aktru | 1970-2012 |
| 38 | Vodopadniy | 1988-2000 |
| 39 | Marmaglaciaeren | 1995-2016 |
| 40 | Rabots Glaciaer | 1986-2015 |
| 41 | Riukojietna | 1996-2015 |
| 42 | Storglaciaeren | 1971-2016 |
| 43 | Austre Broeggerbreen | 1990-2009 |
| 44 | Midtre Lovenbreen | 1996-2009 |
| 45 | Waldemarbreen | 2000-2017 |
| 46 | Gulkana | 2008-2017 |
| 47 | Lemon Creek | 2008-2016 |
| 48 | South Cascade | 1965-2015 |
| 49 | Wolverine | 2008-2017 |

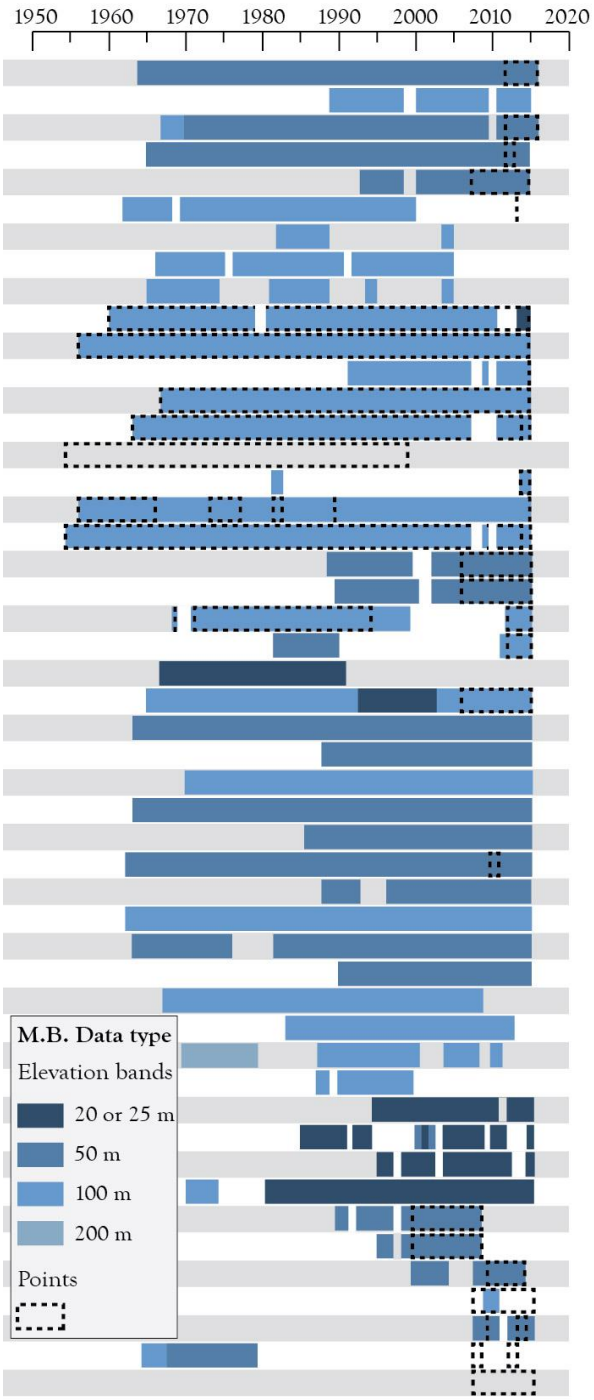



**Figure 10 :** total temporal coverage over the period of analysis of the available mass balance data, as elevation bands or points, from the WGMS database for the 49 selected glaciers

The file *Mass balance data* displays the mass balance values (either for elevation bands or points) and their corresponding elevation reference for each year when data are available. After data processing, this information will be the input for the mass balance gradients calculation explained in chapter 3.3. Figure 10 shows the temporal data coverage over the period of analysis for the two mass balance data type and each glacier as available in the WGMS database. Annex 2 lists the total time coverage,

missing years and total number of years with mass balance data for each glacier as well as the selected data type. The mean and median total time coverage[23] for an individual glacier are 37 and 36 years respectively, while the mean and median number of years with available data for an individual glacier are 33 and 30 years respectively. The glacier with the smallest number of years with available data is the Rhone glacier with 6 years but, as its total time coverage goes from 1980 to 2015, this glacier has been selected. Schwarzberg glacier has the longest period with available data with an uninterrupted mass balance data series of 61 years. Silvretta is the glacier with the longest total time coverage with 63 years (1954 to 2016) and Lemon Creek has the smallest time coverage with 9 years only.

## 3.2 Mass Balance Data Processing

The aim of the different steps of data processing is to make the downloaded mass balance data with elevation bands from the WGMS files ready for the gradients calculation and the data analysis. Annex 3 (i.e. *Mass balance data* file) contains all processed annual mass balance data of the 49 selected glaciers with elevation bands which will be used to calculate the mass balance gradients.

### 3.2.1 General Processing

For some years and some glaciers, no mass balance data are available and a *NA* value is entered in the corresponding blank cell. For some glaciers, it has been noticed that there are some years where both no data nor year entry exist (i.e. some years between the first and last year of data do not have a row in the WGMS file). To facilitate the subsequent data analysis, these years have to be identified, a new row is inserted in the file containing the missing year value and a *NA* value entered. The same procedure is done for all years outside the temporal coverage of each individual glacier but inside the total temporal coverage of the analysis (1954-2017). Then, the *Mass balance data* file is organized so that the years from the total period are displayed in ascending order from left to right as a top row. The left column will contain the elevation references (see chapter 3.2.3) of each given mass balance value. As the mass balance values are not always given for the same elevations each year, a *NA* value will be entered in the files in all remaining blank cells to fill the table.

[23] The total time coverage is the time difference between the last and the first year of available data without taking into account potential periods or years without data inside the period

### 3.2.2 Units

Concerning the units, the mass balance information from the WGMS database are given in mm w.e. These original values are multiplied by 1000 to be converted in m w.e., as the unit from the mass balance gradient will be given in m w.e. $(100m)^{-1}$.

### 3.2.3 Elevation Reference

Unlike point mass balance data for which the mass balance is already given for a discrete elevation, elevation band data from the original WGMS file *Mass Balance* have an upper and a lower elevation limit. Due to the chosen method of mass balance gradient extraction (see chapter 3.3) that requires a discrete elevation for each mass balance value, the data have to be processed. The mean altitude of the elevation band is calculated and is taken as the elevation reference point. As an example, for an elevation interval of 50 m length spanning the elevation 2400 m a.s.l. to 2450 m a.s.l., the new elevation reference is 2400 + 2450 / 2 = 2425 m a.s.l. If the elevation reference is not ending with 0 or 5, it is rounded to give the next elevation ending in 0 or 5 for clarity purpose in the files. For example, an elevation interval between 2400 m a.s.l. and 2425 m a.s.l. has a new elevation reference value of 2415 m a.s.l. instead of 2412.5 m a.s.l. The annual mass balance value corresponding to the original elevation interval is not modified. This procedure concerns 46 on 49 glaciers (i.e. all glaciers with mass balance given by elevation bands).

### 3.2.4 Error Check

The mass balance values of each glacier are first checked in order to avoid data inconsistency due to potential errors in the original dataset. It has been noticed that the mass balance data from Shumskiy glacier from 1985 to 1991 seem to had their elevation shifted: typical mass balance values from 1968 to 1984 are found in the period 1985 to 1991 with a positive elevation shift of +100 m a.s.l. Regarding this suspicious behavior, a *NA* value has been assigned to all years and all elevation from 1985 to 1991, as if no data were available for these years. No other apparent error of this type has been found in the rest of the dataset.

### 3.2.5 Removal of Decreasing Accumulation Values

On the highest elevation bands of glaciers, it is not rare that mass balance values start decreasing with elevation from a certain point (see chapter 2.2.2.2), due to snow redistribution by wind and avalanching or by the fact that precipitation have been triggered at lower elevations. Mass balance values which starts decreasing (at least two in a row) are deleted until the highest glacier elevation reference and replaced by *NA* values. The deleting of these values enables an easier mass balance

gradient extraction (see chapter 3.3.2.3) and do not prevent the aim of the study. For most of the glaciers, this task does not concern many values outer the highest elevation data and the accumulation area is only slightly shortened. The removal of decreasing accumulation values from 14 of the 49 glaciers prevents the accumulation gradient calculation for 1 to 5 years maximum. Exceptions in deleting decreasing accumulation values have been made for Storglaciaeren and Austre Broeggerbreen. For these glaciers, there is only a slight decrease concerning a restraint elevation range before the mass balance values start increasing again at higher elevations in a linear behavior.

# 3.3 Gradient Extraction

This chapter explains the methodology used to extract the targeted mass balance gradients (i.e. the absolute and relative $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$) for the analysis from the processed data.

## 3.3.1 Definition of the $ELA_0$

For the obtaining of $db/dz_{abl}$ and $db/dz_{acc}$, an elevation limit separating the mass balance data from the two areas has to be set for each individual glacier. Per definition, it is the *ELA* that separates the ablation area below from the accumulation area above (see chapter 2.1.2.3). The *ELA* is different for each glacier and vary from year to year (e.g. *Oerlemans, 2001*), causing a change of ablation and accumulation sizes between years. In some years, the *ELA* is as high as no accumulation gradient could be calculated because most of - or sometimes the whole - balance profile lies in the ablation area. For this reason, it has been decided in the present study to assign to each glacier a unique elevation delimiting the ablation from the accumulation area for the whole period of study, which is the $ELA_0$, or balanced-budget *ELA*. The $ELA_0$ corresponds to the altitude at which the linear regression line fitting the observed relationship between annual *ELA* and annual *B* crosses the vertical line of $x$ = 0 m w.e. $a^{-1}$ (Figure 11). Annex 4 contains the $ELA_0$ of each glacier as well as the $R^2$ between the ELA and the B values. The mean R2 of all glaciers is 0.80, confirming the relevant link between the annual ELA and the annual B of the glaciers. A discussion about the advantages and bias and the influence on the results of this method to delimitate the ablation from the accumulation zones as compared to the consideration of annual ELA are presented in chapter 5.1.1.4.

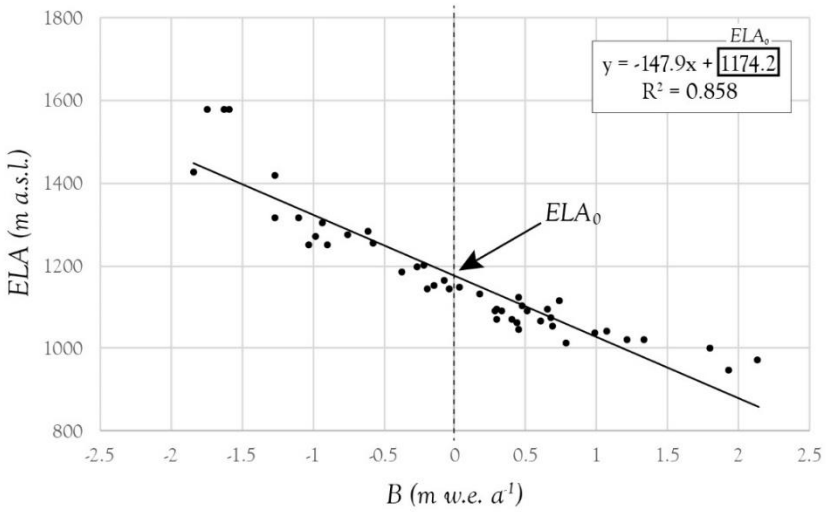



**Figure 11 :** Annual mass balance *B* versus annual *ELA* for Engabreen glacier for the years used to calculate the gradients. The $ELA_0$ is the elevation where the linear regression line crosses the 0 *B* and can be obtained by the linear regression equation intercept parameter.

## 3.3.2 Absolute Gradients

### 3.3.2.1 Gradient Equation

The gradients *db/dz* are obtained by linearly regressing the mass balance points given by their mass balance *b* (m w.e.) and their elevation reference *z* (m a.s.l.). The linear regression is the equation, or model, aiming to minimize the distance between the fitted line and the data points. The mass balance gradient *db/dz* (m w.e. (100 m)$^{-1}$) is given by the slope of the linear regression line going through the mass balance points situated in the corresponding elevation zone and multiplied by 100 to account for a 100 m elevation difference. The slope describes the rate of change between the two variables (i.e. *b* and *z*), which is called in glaciological terms the mass balance gradient (see chapter 2.2.1). The equation of the linear regression line is:

$$y = ax + b$$

where *y* is the mass balance (*b*), *a* is the slope, *b* is the intercept (i.e. y value when x = 0), and *x* is the elevation (*z*). This equation gives the mass balance gradient value *db/dz* as the slope *a*. Its visual representation implies that the elevation *z* (i.e. the independent variable) is displayed on the x-axis and the mass balance *b* (i.e. the dependant variable) on the y-axis (A in Figure 12). Nevertheless, the axis configuration commonly used to represent the distribution of mass balance points with altitude or the balance profile *b(z)* is the opposite (B in Figure 12), "wrongly" displaying the independent variable (i.e. elevation) on the y-axis, as it is more intuitive in terms of physical process (i.e. as the elevation represents a vertical process in reality, it is more logical to visualize it vertically rather than horizontally). This is also the reason why it is counter intuitive to speak about smaller balance

gradients for an apparent steeper balance profile slope. In fact, the slope appears steeper due to the axis configuration used for visual representation, which is not the one used to calculate the gradient. In order to avoid confusion, one should be aware of this fact.

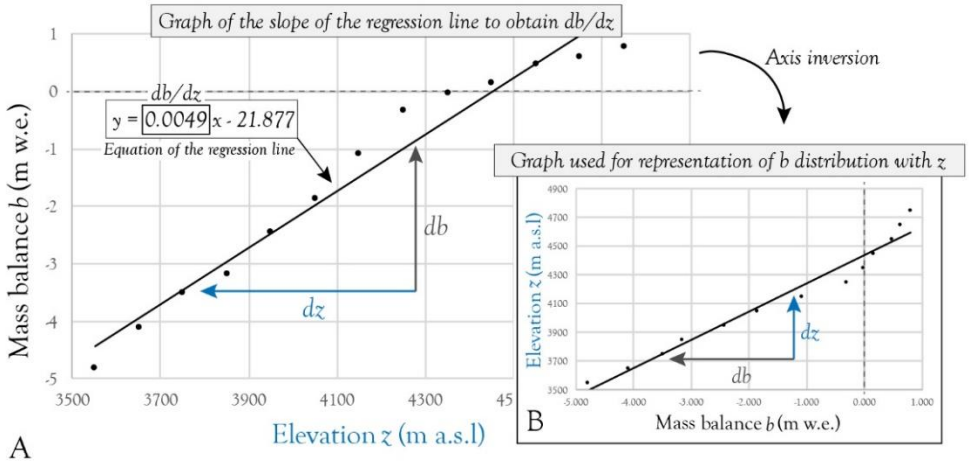



**Figure 12** : mass balance *b* versus elevation *z* for Abramov glacier (1973) with the axis configuration corresponding to the correct slope of the regression line (A) and to the more intuitive visual representation generally used (B).

### 3.3.2.2 Elevation Coverage

$db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$ are distinguished by their elevation coverage on the glacier. As mentioned in chapter 3.3.1, the $ELA_0$ is the chosen elevation limit between the ablation and the accumulation gradient[24]. The mass balances values *b* for which the elevation reference is smaller than the $ELA_0$ are used to calculate $db/dz_{abl}$. The values having a higher elevation reference than the $ELA_0$ are used to calculate $db/dz_{acc}$. $db/dz_{gw}$ is calculated from all mass balance values taken into account for the ablation and accumulation gradients. As an example, Figure 13 represents the mass balance values of Storbreen glacier for the year 2000, 2001 and 2002 organized by decreasing elevation and on a graph to show the elevation coverage of each gradient in reference to the $ELA_0$.

[24] The problems and the advantages of taking the $ELA_0$ reference to delimit the ablation from the accumulation zone instead of considering the annual ELA for the gradient calculation is discussed in chapter 5.1.1.3

| Elevation | Annual $b$ (m w.e.) | | |
|---|---|---|---|
| (m a.s.l.) | 2000 ○ | 2001 ● | 2002 ○ |
| 2075 | NA | 1.95 | 0.00 |
| 2070 | NA | NA | NA |
| 2025 | NA | 1.62 | -0.20 |
| 1975 | 2.98 | 1.25 | -0.40 |
| 1925 | 2.12 | 0.85 | -0.62 |
| 1875 | 1.45 | 0.33 | -0.85 |
| 1825 | 0.84 | -0.19 | -1.29 |
| 1775 | 0.76 | -0.35 | -1.78 |
| 1725 | 0.25 | -0.69 | -2.22 |
| 1675 | 0.15 | -0.71 | -2.46 |
| 1625 | -0.28 | -0.87 | -2.64 |
| 1575 | -1.01 | -1.04 | -2.90 |
| 1525 | -1.69 | -1.27 | -3.15 |
| 1475 | -2.37 | -1.55 | -3.41 |
| 1425 | NA | NA | NA |
| 1420 | -2.63 | -1.66 | -3.61 |

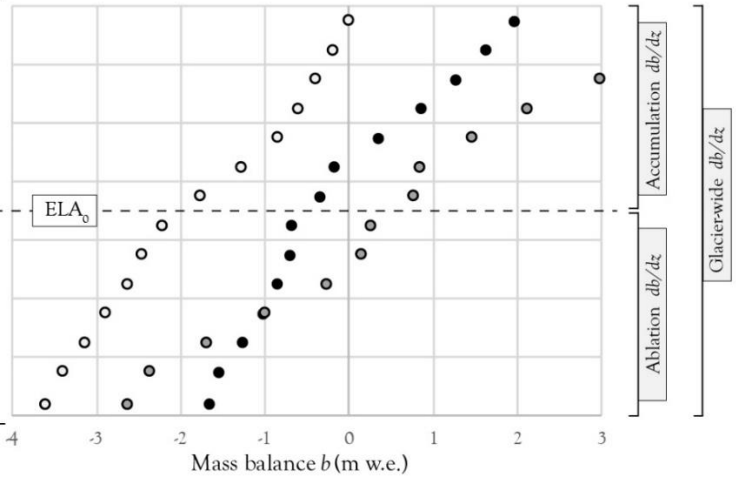



**Figure 13** : mass balance data distributed with elevation for the years 2000, 2001 and 2002 for Storbreen glacier and their graphical representation. The $ELA_0$ spatially delimits on the graph the mass balance points associated with the accumulation gradients (above), the ablation gradient (below) and the glacier-wide gradient (all points).

### 3.3.2.3 Calculation and Calibration

The mass balance gradients are first calculated from the processed data from the 49 selected glaciers. The output is one annual value of $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$ for each glacier for all years of available data when at least two mass balance values are available for each elevation zone. As the gradients are obtained through the slope of the linear regression line, the assumption made is that the behavior of the data is linear. The annual coefficient of determination $R^2$ is used to test the linear model fit of the $b$ data and calibrate the data when it is not the case[25]. When an annual $R^2$ value is below 0.7, mass balance data are checked and if one or two points jeopardize the linearity of the gradient (i.e., the mass balance value is either much lower of higher than its two adjacent values), they are deleted. If the $R^2$ increases above 0.7, the new resulting $db/dz$ is considered for the analysis. If the $R^2$ stays below 0.7, a *NA* value is entered for the corresponding year and gradient, meaning that the gradient is not calculated. This procedure did not concern many glaciers nor years. It must be specified that the $R^2$ of the gradients for which only two mass balance values are available returns a $R^2$ value of 1 because in this case the goodness of the linear regression line fit is perfect per definition. The gradients calculated from only two mass balance values are kept for the analysis, even if the relationship may not be significant, to prevent glacier loss[26].

In the ablation area, it has been noticed that for some glaciers and some years, the mass balance gradient is negative (i.e. the mass balance values are decreasing with elevation). Five glaciers are

[25] $R^2$ represents in this case the percentage of the mass balance variation with elevation that is explained by a linear model.
[26] It is clear that ideally more mass balance values (at least 6) should be used to calculate the gradients but such data are often not available, particularly in the accumulation area (*Hoelzle, 2018: personal communication*).

concerned with this behavior for one to two years maximum. For these cases, all their *b* values are replaced by *NA* and the $db/dz_{abl}$ is not calculated.

With the calibrated gradient, the mean of the mean annual $R^2$ of each glacier (all values are considered except when $R^2$ = 1) is 0.95 for $db/dz_{abl}$, 0.94 for the $db/dz_{gw}$ and 0.92 for $db/dz_{acc}$ witnessing a high goodness of the linear model fit to the data used for calculating the gradients and thus justify the chosen methodology to compute $db/dz$. For each glacier, the calculated absolute annual $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$ for the period of analysis can be found in Annex 5.1, 5.2 and 5.3 respectively.

### 3.3.3 Relative Gradients

The procedure explained hereafter is applied for each of the three gradients. For each glacier, the mean absolute gradient $db/dz$ over the total period of data coverage is taken as the center of gravity or the point "zero". The mean standard deviation $\sigma$ (which takes into account the spread of the annual gradients as compared to their mean, i.e. their variability) is used to create 8 different intervals – 4 below the mean gradient and 4 above – to account for the relative evolution of annual gradients. The 8 different intervals are identical for each glacier, but their boundary values are relative to the $\sigma$ of the gradients of each glacier. Once the mean gradient and the $\sigma$ of the gradients are calculated, every absolute annual gradient value previously calculated is then classified in one of the 8 intervals. Each interval has a different discrete value assigned (-4, -3, -2, -1, 1, 2, 3 or 4), allowing the quantitative analysis of the relative gradients, and a color for visual representation. Figure 14 shows the mathematical definition of the interval boundaries as well as the values and colors assigned to each of the 8 intervals. The $\sigma$, the mean, as well as the limit values of each interval for all glaciers can be found in Annex 6.1, 6.2 and 6.3 for $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$ respectively. Annex 7.1, 7.2 and 7.3 display the calculated annual relative $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$.

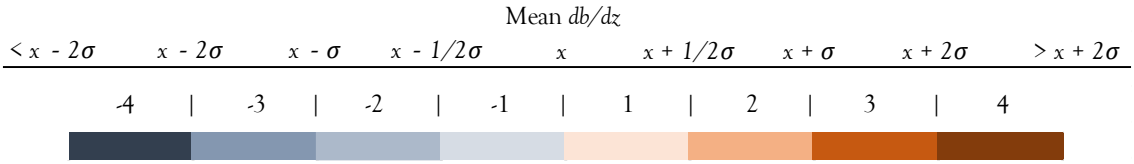



**Figure 14 :** the 8 different relative gradients intervals for the assignation of the annual absolute gradients. The mathematical expression of the interval limits as a function of the mean $db/dz$, or *x*, are presented. The value and color of the 8 intervals are identified.

If the dataset of each glacier would follow a perfect normal distribution, 68.2 % of the annual gradients would fall in the intervals -2, -1, 1 and 2 (i.e within one $\sigma$) and 95.4% when adding the -3 and 3 intervals (i.e. within two $\sigma$). The intervals -4 and 4 thus account for the smallest and greatest

values of annual *db/dz* (outside two $\sigma$). Therefore, the expression of gradients in the explained relative way also allows a smoothing of the inter-annual variability of the annual gradients.

# 3.4 Data Analysis

## 3.4.1 Evolution of Absolute Gradients

### 3.4.1.1 Individual Glaciers

In chapter 4.1.1, the evolution of absolute annual $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$ is individually presented for the selected glaciers for their time coverage of available data. The annual *db/dz* are represented on a graph by *i)* points for accuracy. Their evolution is graphically summarized by *ii)* a moving average (or running mean) curve[27] to smooth the inter-annual variability as well as *iii)* a linear regression trend-line[28] to represent the change over the total time coverage. The moving average is colored in a gradient from red to blue passing through grey where the red color represents the values above the mean and the blue color the values below the mean in grey. The three gradients are presented on the same graph to allow a visual comparison of their absolute values and of their evolution. The most relevant periods of high/low and increasing/decreasing annual *db/dz* are mentioned in the text.

A table of descriptive statistics next to the graph gives first more quantitative information about the characteristics of *db/dz*, displaying *i)* the mean annual *db/dz* in m w.e. $(100m)^{-1}$, *ii)* the mean annual $R^2$ accounting for the linearity of the mass balance change with elevation, *iii)* the standard deviation *Std.* or $\sigma$ in m w.e. $(100m)^{-1}$, witnessing the variability of the annual gradients, *iv)* the minimal value and *v)* the maximal value. The mean and the $\sigma$ of the annual *db/dz* are mentioned in the text as being relatively *low* or *high* only if they are respectively below the 1st quartile or above the 3rd quartile of the two datasets distribution for each of the three gradients (6 datasets in total). Note that the distribution of $\sigma$ is analyzed in % relative to the mean of each gradient instead of the absolute $\sigma$ in order to allow the relative comparison between glaciers. Annex 8 displays the mean and the $\sigma$ given in absolute and relative values for the 49 glaciers. It also shows the descriptive statistics of their distribution between glaciers for wich the overview will be analyzed later in chapter 4.1.2.1 (mean) and chapter 4.1.2.2 ($\sigma$). The $R^2$ is mentioned in the text only if the minimal and maximal values are reached for each of the three gradients dataset.

[27] It refers to the *detailed evolution curve* mentioned in the research question 1 b.)
[28] It corresponds to the *linear evolution trend* in the research question 1 c.)

In the table, the linear evolution trend based on the linear trend estimation technique through a least-squares fit is also quantified. As the annual *db/dz* are treated as a time series (i.e. the mass balance data are expressed as a function of time[29]), *i)* the linear trend direction (i.e. increasing ↗ or decreasing ↘) - referred to as the *general trend* in the table - can be mentioned. In addition, *ii)* the change over the total period along the linear regression line and *iii)* the annual rate of change are shown. The change over the total period is obtained as follow: the mass balance gradients $x_1$ *and* $x_2$ from the first year $y_1$ and the last year $y_2$ of the period are calculated as according to the linear regression model $y = ax + b$. The calculated absolute gradient difference ($x_2 - x_1$) is then expressed in % relative to the mean *db/dz* for each glacier. As an example, a modelled *db/dz* of 0.202 m w.e. $(100\ m)^{-1}$ in the first year and 0.679 m w.e. $(100\ m)^{-1}$ in the last year gives a difference of 0.477 m w.e. $(100\ m)^{-1}$. As the mean gradient over the total period of the example glacier is 0.437 m w.e. $(100\ m)^{-1}$, the gradient change over the total period corresponds to +109%. To allow the comparison between glaciers, the annual rate of change is calculated as glacier have different total time coverage. It is simply obtained by the change over the total period divided by the number of years inside the period. The change over the total period is mentioned in the text as relatively *low* or *high* only if the annual rate of change is respectively below the 1st quartile or above the 3rd quartile of the distribution of the three gradients datasets (3 datasets in total).

The modelled gradients in the first and last year, the resulting difference, the calculated change over the total period, the number of years of the period and the mean annual rate of change expressed in m w.e. $(100\ m)^{-1}$ and in % relative to the mean gradient are shown in Annex 9 for each glacier and each gradient. Annex 10 displays the annual rates of change organized by gradient and the corresponding descriptive statistics of the distribution between glaciers for which the overview will be analyzed in chapter 4.1.2.3.

The correlation coefficient *r* (Pearson product moment) is then calculated to test the similarity of the evolution between the three sets of annual *db/dz* and the direction of the relationship (i.e. positive or negative). The significance of *r* is evaluated from the critical value in a two-tailed test corresponding to a significance level of 0.05 (i.e. the null hypothesis is rejected 5% of the time). In other words, when the *r* is higher than the critical value, the correlation is considered as significant with a 95% confidence level. Annex 11 lists the *r* critical values for each glacier and the degree of freedom. The *r* is mentioned in the text only when there is a significant correlation between two datasets. The overview of the correlation between the gradients will be analyzed in chapter 4.1.2.4.

[29] In this study, the time refers to the total period of data coverage for each individual glacier

Note that 11 glaciers are presented in the result chapter 4.1.1 and the remaining glaciers have their graphs and tables available in Annex 18.

#### 3.4.1.2 Overview

An overview of the main descriptive characteristics, of the evolution and of the correlation between gradients from the 49 individual glaciers is presented in chapter 4.1.2 through a statistical analysis of selected parameters. These parameters are: *i)* the mean gradient in m w.e. $(100m)^{-1}$, to account for the central representative value (chapter 4.1.2.1), *ii)* the standard deviation $\sigma$ in % relative to the mean gradient of each glacier to account for the variability of the gradients (chapter 4.1.2.2), *iii)* the annual rate of change in % relative to the mean gradient to account for the evolution trend (chapter 4.1.2.3) and *iv)* the correlation between gradients (chapter 4.1.2.4). These parameters (all except the last) are presented on overview graphs showing the distribution of individual glaciers values and the relevant descriptive statistics are mentioned. The chapter 4.1.2.3 is divided in different sections where the distribution is first analyzed for each gradient separately and then the values are compared between the three gradients. Chapter 4.1.2.5 gives a summarized overview of the individual evolution trend of the annual $db/dz$, exposing the values and directions of the annual rates of change where the glaciers are classed from largest to smallest mean $db/dz_{gw}$ values. These overviews enable a relative comparison of the parameters from one glacier to another and gives synthetic evolution results.

Note that in the overview of the annual rates of change (chapter 4.1.2.3), the total change over the median year coverage of all 49 glaciers is also calculated (Annex 10). In order to test these results, a comparison of the obtained total change with a selection of glaciers is conducted. The aim is to keep only the 30 more meaningful glaciers for the present study aims. As the evolution of each glacier is different and can undergo some important up and downs (which can be either attributed to the natural inter-variability of the gradients or of external physical factors), a $R^2$ or $r$ test to determine the correlation between years and annual mass balance gradients is not relevant. What is more, glaciers with smaller datasets will show a higher correlation. Therefore, the criteria for the selection of the 30 glaciers is related to the period length and year coverage of data, assuming that the glaciers with longer data series give more trustworthy results and that the analysis ideally targets the evolution of mass balance gradients until recent years. As a result, the glaciers with mass balance data beginning before 1993 and going until at least 2014 are considered. Even if it fits the mentioned criteria, Graasubreen glacier is set aside on purpose as the raw data only allow the calculation of $db/dz_{acc}$. This procedure also enables to extend the median year coverage of the dataset because it is higher for the 30 selected glaciers than for the initial glacier population.

## 3.4.2 Evolution of Relative Gradients

### 3.4.2.1 General Procedure

The relative annual $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$ (Annex 7.1, 7.2 and 7.3) are first analyzed in the aim of giving synthetic evolution results for the 49 glaciers together. After a glacier classification process, they will enable detecting similarities and differences of evolution between the glaciers sharing common characteristics according to different climatic, geometric and gradient parameters.

First, the result chapter 4.2.1 presents in a graph the evolution curves of the three relative gradients for the total period of analysis. For each year, the weighted mean of annual relative gradients for each glacier with available data is calculated. In the text, these results are described and periods of high/low and decreasing/increasing $db/dz$ are mentioned.

In the next result chapters, the three obtained relative evolution curves are used as a reference for the comparison of the relative evolution curves of classified glaciers. The result chapter 4.2.2 presents the relative evolution of the glaciers classified according their characteristics of four different climatic parameters: the continentality, the region, the latitude and the minimum elevation. Chapter 4.2.3 displays the relative evolution of glaciers classified according to five geometric parameters: the length, the area, the length/area ratio, the slope and the elevation coverage of the upper half area. Chapter 4.2.4 targets the relative evolution of glaciers classified according to two gradient-related parameters: the mean $db/dz_{gw}$ and the standard deviation of $db/dz_{acc}$.

The next methodological chapters present the climatic, geometric and gradient-related parameters considered as well as the specification of the different classes inside the parameter.

### 3.4.2.2 Classification according to Climatic Parameters

The values of median elevation, latitude, region and minimum elevation of all glaciers, which are used for the classification of the glaciers according to climatic parameters, can be found in the *Glacier characteristics* file from Annex 1. The class assignation of the 49 glaciers for the four climatic parameters as well as the glacier frequency in each class is contained in Annex 12.

#### Continentality

As mentioned earlier in this work, the continentality of a glacier reflects its climatic environment and it can be well estimated by the elevation of the *ELA* above the 0°C free air isotherm (*Meier and Post, 1962*; *Oerlemans, 2001*). Therefore, the air temperature at the *ELA* can be considered as a proxy for continentality (*Huss and Farinotti, 2012*). In their study, *Huss and Farinotti* (*2012*) define

continentality from a latitude-dependant reference *ELA*, $ELA_{lat}$, corresponding to neither particularly maritime nor continental climatic conditions (Figure 15). Around this line, the temperature at the *ELA* is mentioned for different latitudes and median glacier elevations: the lower the temperature at the *ELA* is, the higher the *ELA* is situated above the 0°C free air isotherm and the more continental the glacier is. From their median altitude and their geographic latitude, the corresponding temperature at the *ELA* is extracted for the 49 glaciers.

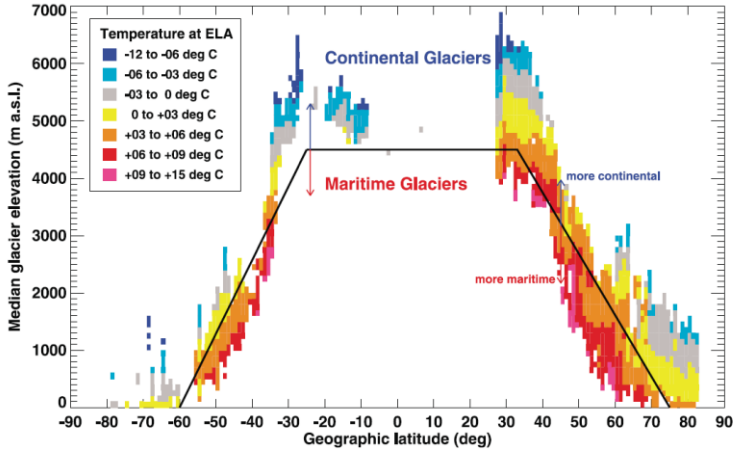



**Figure 15** : Air temperature of the warmest month at the median glacier elevation for different latitudes. The solid line is the $ELA_{lat}$ corresponding to average continentality (*modified after Cogley, 2012, in Huss and Farinotti, 2012*).

Note that depending on the latitude, the results can be confusing: the median elevation of some glaciers is located well above the $ELA_{lat}$, indicating more continental conditions but the temperature at the *ELA* indicates highly positive values, indicating more maritime conditions. For this reason, this information is complemented with a climatic description (i.e. the measured temperature at the *ELA* and/or precipitation data from the literature when available). Annex 13 displays all data used for the classification of the glaciers in the three following classes: *Continental*, *Transitional* and *Maritime*.

## Region

The WGMS (*2017*) classes glaciers by proximity in 19 different glaciarized regions presented in chapter 2.1.3.1. The 49 selected glaciers in this study can be classified in 8 of these regions: *1) Central Europe*, *2) Scandinavia*, *3) Asia* (where the official *ASC* and *ASN* regions are grouped for the present analysis due to the proximity of the glaciers), *4) Arctic Canada North*, *5) Svalbard and Jan Mayen*, *6) Western North America*, *7) Alaska* and *8) Caucasus and Middle East*. Zongo glacier is set out from the region classification as it is the only glacier in its region (*TRP*). The 8 regions are showed on the world map in Figure 16.




**Figure 16** : location of the 49 selected glaciers (stars) and their corresponding assigned identification numbers classified in their 8 different regions according to the WGMS (2017). The region numbers are given in the present study.

## Latitude

Solar radiation plays an important role in glacier's melt and the received solar radiation on the earth's surface is mainly a function of latitude (i.e there is a latitudinal gradient in global radiation) (*Ohmura et al., 2007*). As a consequence, latitude and median elevation are generally related (the 49 glaciers show a $R^2$ correlation of 0.78) because the two parameters contain a simplified temperature signal. Figure 17 shows on the world map the location of the glaciers as well as the delimitation of the three latitudes zones chosen for the classification.

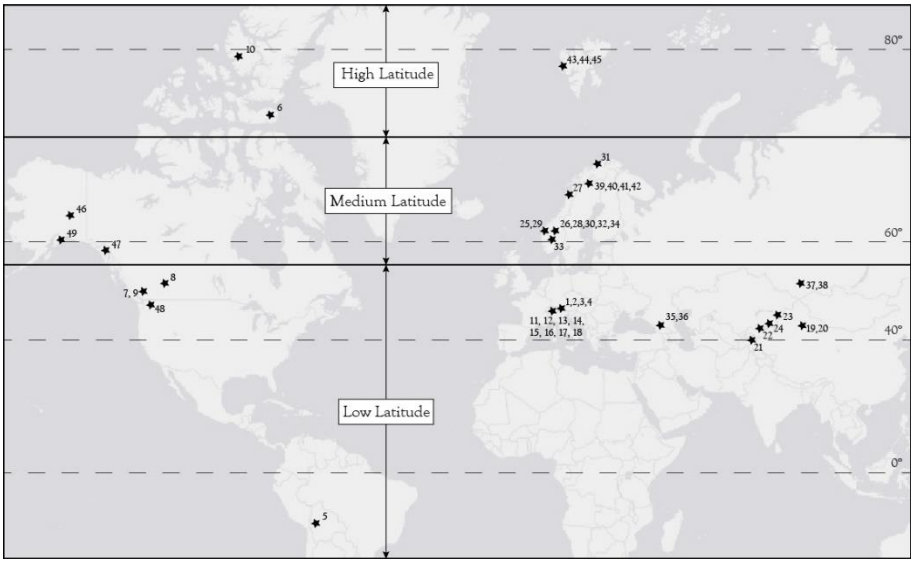



**Figure 17** : location of the 49 selected glaciers (stars) and their assigned identification numbers classed in the three latitude classes showed on the map and delimitated by the solid lines.

According to the latitudinal distribution of the glaciers, it appears relevant to split the glacier in the following classes referring to the degree of latitude: *High*, *Medium* and *Low*. The *High* latitudes glaciers are located >71°N, the *Medium* latitude glaciers between 52°N and 71°N and the *Low* latitude glaciers <52°N.

**Minimum Elevation**

The minimum elevation of a glacier can show a significant relationship with the mean winter precipitation signal. As investigated for Austrian glaciers by *Abermann et al.* (*2011*), generally lower values of minimum elevation correspond to regional above-average precipitation. As it seems more relevant to investigate this relationship at the regional level, the three regions with the higher number of glaciers are targeted: *1) Central Europe*, *2) Scandinavia* and *3) Asia*. For each region, the glaciers are classified in two or three minimum elevation ranges: *High*, *Medium* and *Low*.

In Central Europe, two classes split up the dataset: the *High* minimum elevation glaciers are located >2500 m a.s.l. and <2500 m a.s.l. for the *Low* class. Grosser Aletsch has been set out of the analysis as it has a much lower value than the other glaciers (1649 m a.s.l.).

In Scandinavia, three classes separate the minimum elevation values: the *High* minimum elevation glaciers are located >1200 m a.s.l., the *Medium* class glaciers display values between 500 and 1200 m a.s.l. and <500 m a.s.l. for the *Low* class. Aalfotbreen glacier is set out of the analysis as it is located exactly at 1200 m a.s.l., in the aim to better differentiate the *High* and *Medium* classes.

In Asia, two classes cut the dataset: the *High* minimum elevation glaciers, located >3500 m a.s.l., and the *Low* class with glaciers <3500 m a.s.l. Maliy Aktru has been set out of the analysis as it has a much lower value than the other glaciers (2246 m a.s.l).

#### 3.4.2.3 Classification according to Geometric Parameters

The length and the area values of each glacier can be found in Annex 2. The values of the calculated length/area ratio, slope and elevation coverage of the upper half area can be found in Annex 14 which also displays the class assignation and frequency of the glaciers for the five geometric parameters.

**Length**

The 49 glaciers are classed in three different length classes: *Short* (<3 km), *Medium* (3 < and < 6 km) and *Long* (>6 km). Figure 18 shows the length values on a logarithmical scale for the different glaciers.

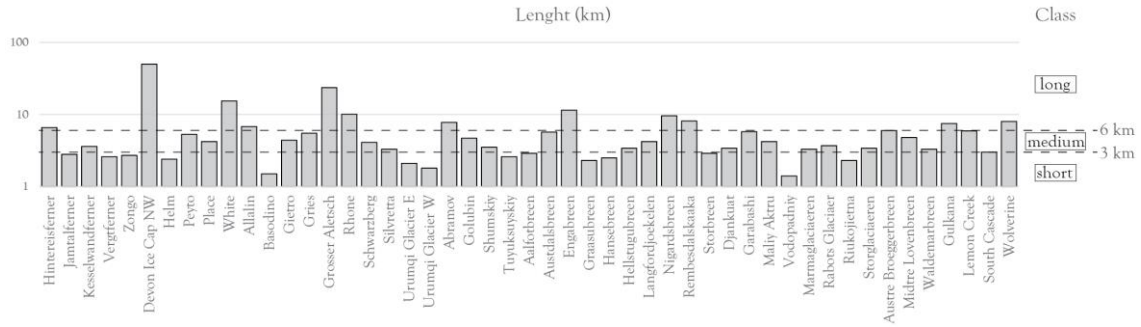



**Figure 18** : lenght of the 49 selected glaciers in km (on a logarithmical scale) and the three lenght classes separating the dataset, delimited by the dotted lines.

The 49 glaciers are very heterogeneous in length. The minimal length is 1.4 km (Vodopadniy) whereas the maximal is 50 km (Devon Ice Cap NW). The mean length is 6.05 km and the median is 4.1 km. 50% of the glaciers have a length between 2.9 km (1st quartile) and 6 km (3rd quartile).

## Area

The correlation of determination $R^2$ between glacier length and area from the 49 glaciers is 0.78, indicating a relation (the longer the glacier, the larger the area) but that the datasets display some differences. Therefore, the 49 glaciers are also classified according to their size. The glaciers are classed in three different area intervals: *Small* (< 3 $km^2$), *Medium* (3 < and <15 $km^2$) and *Large* (> 15 $km^2$). Figure 19 presents the area values of the 49 glaciers next to their length values for comparison.

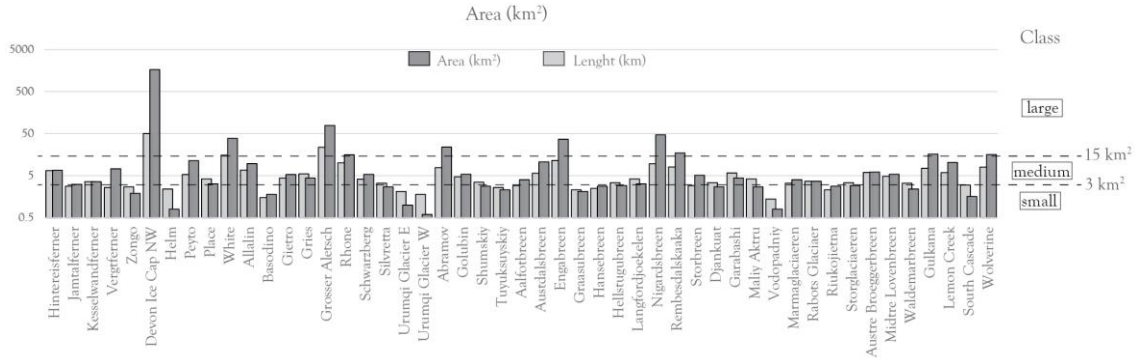



**Figure 19 :** area of the 49 selected glaciers in $km^2$ (on a logarithmical scale) and the three area classes separating the dataset, delimited by the dotted lines. The lengths values in km are shown in light grey for comparison.

The 49 glaciers display very different extreme area values: the minimal area is 0.6 $km^2$ (Urumqi Glacier W) whereas the maximal is 1668 $km^2$ (Devon Ice Cap NW). The mean area is 43.11 $km^2$ and the median is only 4 $km^2$, indicating that extreme positive values influence the mean. 50% of the glaciers have an area between 2.7 $km^2$ (1st quartile) and 10.3 $km^2$ (3rd quartile).

## Length/Area Ratio

The rough shape of the glacier is here expressed by the length/area ratio obtained by the total glacier length in km divided by the total glacier area in $km^2$. Interestingly, the length/area ratio show no clear correlation with the length parameter ($R^2$ = 0.12), neither with the area of the glaciers ($R^2$ = 0.04). A length/area ratio of 1 means that the glacier is mathematically a perfect square (i.e. the area is equal to the squared length). Glaciers with a ratio below 1 have a bigger area than squared length, meaning in reality that they are larger than long. On the opposite, glaciers with a ratio above 1 are longer than large. The glaciers are classified according to if the length/area ratio is *Low* (<0.8), *Medium* (0.8< and <1.2) or *High* (>1.2) (Figure 20).

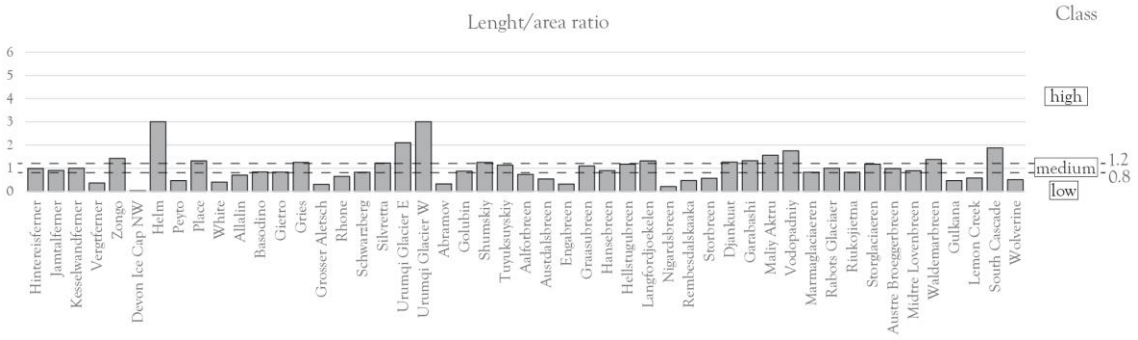



**Figure 20 :** length/area ratio of the 49 selected glaciers (no unit) and the three length/area ratio classes separating the dataset, delimited by the dotted lines.

The minimal length/area ratio is 0.03 (Devon Ice Cap NW) and the maximal is 3 (Helm and Urumqui Glacier W). The mean is 1 and the median is 0.89. 50% of the glaciers have a ratio between 0.59 (1st quartile) and 1.25 (3rd quartile).

## Slope

The slope is calculated through the elevation difference between the maximal and minimal glacier elevation divided by the length in m. It must be noted that the calculated slope doesn't represent the real slope of the glacier surface but it is a mean approximation of it. The $R^2$ of the slope of the glaciers is 0.22 with their length, indicating that longer glacier does not necessarily have smaller slopes. The glaciers are classed in three slope classes: *Small* (<0.15), *Medium* (0.15< and <0.25) and *Steep* (>0.25) (Figure 21).

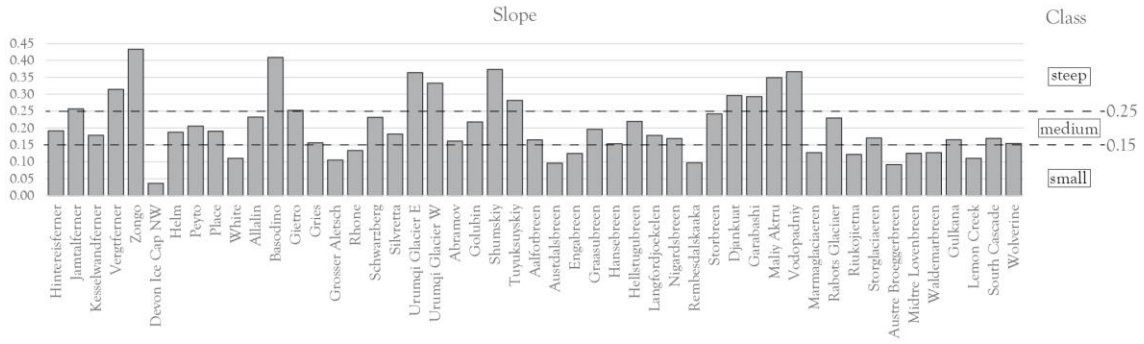



**Figure 21 :** slopes of the 49 selected glaciers (no unit) and the three slope classes separating the dataset, delimited by the dotted lines.

The minimal slope is 0.04 (Devon Ice Cap NW) whereas the maximal is 0.43 (Zongo). The mean slope is 0.21 and the median is 0.18, witnessing a normal distribution of the slope among the glaciers. 50% of the glaciers have a slope between 0.13 (1st quartile) and 0.25 (3rd quartile).

## Elevation Coverage of the Upper Half Area

The detailed analysis of the hypsometry of each of the 49 glaciers would require too much work. Therefore, the elevation coverage in % of the upper half area of the glacier is calculated to express a simplified and quantitatively comparable hypsometric information. It is obtained by the difference between the maximal and the median glacier elevation divided by the difference between maximal and the minimal glacier elevation, the median elevation halving the area of the glacier. If the result equals 50%, it means that the mean and median glacier elevation are identical, if it is below 50%, the upper half area is concentrated above the mean elevation of the glacier, if it is above 50%, the upper half area extends below the mean glacier elevation. The 49 glaciers are classified in three different classes: *Small* (<42%), *Medium* (42% < and <52%) and *Large* (>52%) (Figure 22). Note that the glaciers from Sweden are set out of the classification for the present parameter as the median glacier elevation is not available.

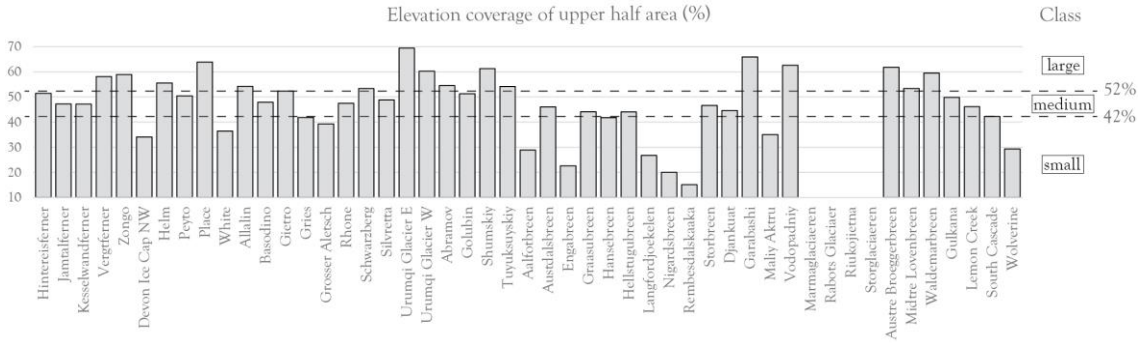



**Figure 22 :** elevation coverage of the upper half area of the 49 selected glaciers (%) and the three classes separating the dataset by the dotted lines.

The minimal elevation coverage of the upper half area is 15.1% (Devon Ice Cap NW) whereas the maximal is 69.41% (Zongo). The mean value is 47.23% and the median is 47.88%, indicating a normal distribution of the parameter value among the glaciers. 50% of the glaciers have a value between 41.81% (1st quartile) and 54.57% (3rd quartile).

#### 3.4.2.4 Classification according to Gradient-related Parameters

The distribution of the mean $db/dz_{gw}$ and the standard deviation of $db/dz_{acc}$ of the 49 glaciers is analyzed in chapter 4.1.2.1 and chapter 4.1.2.2 and is therefore not presented here. The individual glacier values can be found in Annex 8. Annex 15 contains the class assignation and the frequency of the glaciers for the two gradient-related parameters.

**Mean Glacier-Wide Gradient**

Glaciers with greater mass balance gradients are known to react more sensitively to climate change and to be located in more maritime climate (*Oerlemans, 2001*). Even if the glaciers have already been classed by continentality (according to external source of information), an independent test according to the calculated absolute $db/dz_{gw}$ values found in the present study seems relevant for validation purposes. The 49 glaciers are classified in three different classes according to their mean $db/dz_{gw}$: *Small* (< 0.540 m w.e. $(100m)^{-1}$), *Medium* (0.540 < and < 0.720 m w.e. $(100m)^{-1}$) and *Large* (> 0.720 m w.e. $(100m)^{-1}$).

**Standard Deviation of Accumulation Gradients**

The relative standard deviation $\sigma$ of the $db/dz$ of glaciers show no correlation with mean $db/dz$. The relative $\sigma$ is also analyzed as it allows a comparison of the standard deviation between glaciers and gradients, unlike the absolute $\sigma$ for which the value is dependant on the mean $db/dz$ value. Indeed, the correlation $R^2$ between the mean $db/dz$ and the absolute $\sigma$ of the glaciers are 0.57, 0.44 and 0.63 for, respectively, $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$.

Accumulation gradients display both the higher mean absolute value of standard deviation (0.221 m w.e. $(100\ m)^{-1}$) and mean relative value (45.9%), indicating that the $db/dz_{acc}$ show the greater inter-annual variability from the three gradients (see chapter 4.1.2.2). What is more, the standard deviation of $db/dz_{acc}$ is contrasted between glaciers, ranging from 15.4% to 97.4%, this is why glaciers are also classified according to their $db/dz_{acc}$ standard deviation. The three different classes are: *Small* (<38%), *Medium* (38< and <52%) and *Large* (>52%).

# 4 Results

## 4.1 Evolution of Absolute Mass Balance Gradients

### 4.1.1 Individual Glaciers

Hereafter, the individual results of 11 glaciers with a strong dataset[30] are presented. The graphs and tables of the remaining 38 glaciers can be found in Annex 18.

#### 4.1.1.1 Hintereisferner

| Hintereisferner | 1964-2017 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 1.076 | 0.783 | 0.375 |
| Mean annual $R^2$ | 0.98 | 0.94 | 0.94 |
| Std. | 0.138 | 0.097 | 0.108 |
| Min. | 0.731 | 0.595 | 0.190 |
| Max. | 1.315 | 1.102 | 0.675 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +19% | +4% | +27% |
| Annual rate of change (%) | +0.35% | +0.07% | +0.49% |
| $r$ with $db/dz_{abl}$ | x | 0.53 | 0.04 |
| $r$ with $db/dz_{gw}$ | 0.53 | x | 0.52 |
| $r$ with $db/dz_{acc}$ | 0.04 | 0.52 | x |




**Figure 23 :** Evolution of the absolute ablation, glacier-wide and accumulation gradients of Hintereisferner from 1964 to 2017

Hintereisferner is a valley glacier located in the Austrian Alps at a latitude of 46°N. It is covering an elevation range from 2450 to 3715 m a.s.l. It is 6.6 km long and its size is 6.7 km$^2$ (*WGMS, 2017*).

From 1964 to 2017, Hintereisferner shows a relatively high mean annual $dz/dz_{abl}$ and $db/dz_{gw}$ of 1.076 and 0.783 m w.e. (100m)$^{-1}$ respectively (Figure 23). The $\sigma$ is relatively low for the three $db/dz$. The three $db/dz$ have a general increasing trend. The greatest increasing trend is from $dz/dz_{acc}$ with a 27% increase over the total year coverage. There are significant positive $r_{ablgw}$ and $r_{gwacc}$ correlations

[30] Glaciers with a long time series and with no to few data gaps

of 0.53 and 0.52. The moving average shows that there was a period of smaller $dz/dz_{abl}$ and $db/dz_{gw}$ approx. from 1980 to 1990, followed by a rapid increase, as well as around 2010. $dz/dz_{acc}$ are the smallest between 1970 and 1975 and the highest around 1995.

#### 4.1.1.2 Kesselwandferner

| Kesselwandferner | 1967-2017 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 1.168 | 1.028 | 0.437 |
| Mean annual $R^2$ | 0.90 | 0.93 | 0.95 |
| Std. | 0.289 | 0.214 | 0.182 |
| Min. | 0.369 | 0.070 | 0.663 |
| Max. | 1.974 | 1.048 | 1.486 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +10% | +5% | +109% |
| Annual rate of change (%) | +0.19% | +0.10% | +2.14% |
| $r$ with $db/dz_{abl}$ | x | 0.69 | -0.13 |
| $r$ with $db/dz_{gw}$ | 0.69 | x | 0.23 |
| $r$ with $db/dz_{acc}$ | -0.13 | 0.23 | x |

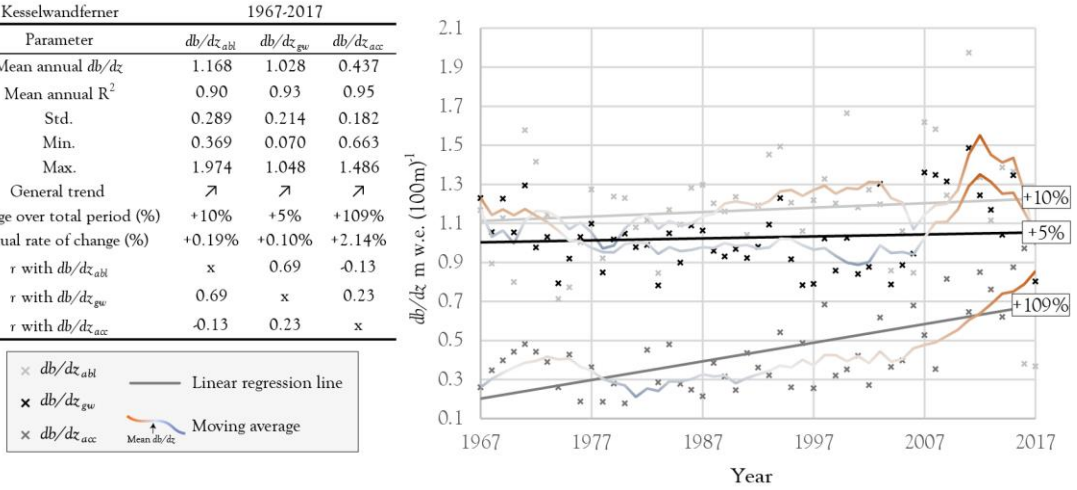



**Figure 24 :** Evolution of the absolute ablation, glacier-wide and accumulation gradients of Kesselwandferner from 1967 to 2017

Kesselwandferner is mountain glacier adjacent to Hintereisferner. Its length is 3.6 km and its area is 3.6 $km^2$. The glacier expends from 2850 to 3493 m a.s.l (*WGMS, 2017*).

From 1967 to 2017, Kesselwandferner has relatively high mean $db/dz_{abl}$ and $db/dz_{gw}$ (Figure 24). The three $db/dz$ show a general increasing trend, $bz/dz_{acc}$ displaying the greatest increasing trend with a 109% increase over the total year coverage, corresponding to a relatively high annual rate of change of +2.14%. There is a significant positive $r_{ablgw}$ correlation of 0.69. $db/dz_{abl}$ and $db/dz_{gw}$ both show a strong increase since 2005 before decreasing in the last years, even if they stay higher than the mean. $bz/dz_{acc}$ displays their lowest values around 1980 and a more or less continuous increasing trend since then marked by a strong recent increase since 10 years.

#### 4.1.1.3 Zongo

Zongo is the only selected glacier from the Southern Hemisphere. It is a low latitude valley glacier located at 16°S in the tropical Andes. Its elevation coverage is the highest of the 49 selected glaciers. It ranges from 4939 to 6109 m a.s.l. Its length is 2.7 km and its area is 1.9 $km^2$ (*WGMS, 2017*).

From 1992 to 2015, Zongo has contrasted mean $db/dz$ values: a relatively high $db/dz_{abl}$ of 1.704 m w.e. (100 m)$^{-1}$ and relatively low $bz/dz_{acc}$ of 0.241 m w.e. (100 m)$^{-1}$ (Figure 25). The $\sigma$ is relatively high for $db/dz_{abl}$ and $db/dz_{gw}$. The mean annual $R^2$ of $db/dz_{gw}$ is relatively low. While $db/dz_{abl}$ has a

general decreasing trend of -7%, $db/dz_{gw}$ and $bz/dz_{acc}$ are increasing of +47% and +26% respectively. The increase of $db/dz_{gw}$ is relatively important and corresponds to an annual rate of change of +1.98%. There is a significant positive $r_{gwacc}$ correlation of 0.54. $db/dz_{abl}$ have low values at the beginning of the period and high values around 2000 and 2010. In addition, they show a much greater inter annual variability than the two other gradients. $db/dz_{gw}$ display a rather continuous increasing trend with some variations. $bz/dz_{acc}$ are high in 1992 and around 2005.

| Zongo | 1992-2015 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 1.704 | 0.571 | 0.221 |
| Mean annual $R^2$ | 0.88 | 0.71 | 0.86 |
| Std. | 0.582 | 0.235 | 0.115 |
| Min. | 0.449 | 0.285 | 0.047 |
| Max. | 2.632 | 1.303 | 0.412 |
| General trend | ↘ | ↗ | ↗ |
| Change over total period (%) | -7% | +47% | +26% |
| Annual rate of change (%) | -0.30% | +1.98% | +1.07% |
| r with $db/dz_{abl}$ | x | 0.40 | -0.32 |
| r with $db/dz_{gw}$ | 0.40 | x | 0.54 |
| r with $db/dz_{acc}$ | -0.32 | 0.54 | x |

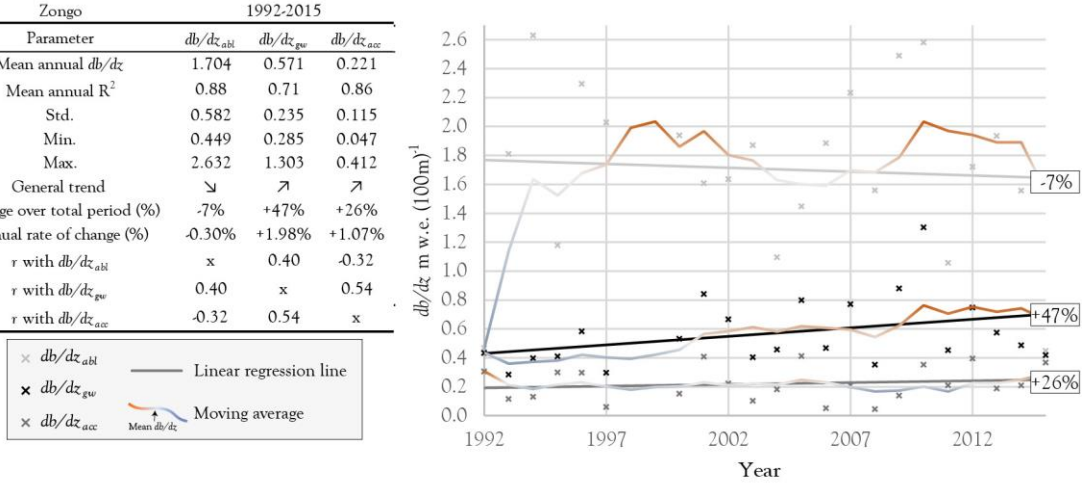



**Figure 25 :** Evolution of the absolute ablation, glacier-wide and accumulation gradients of Zongo from 1992 to 2015

#### 4.1.1.4 Devon Ice Cap NW

Devon Ice Cap NW is an ice cap located at 75°N in the high Canadian arctic on Devon Island. The ice mass ends at sea level and starts flowing at an elevation of 1820 m a.s.l. It is the longest and biggest selected glacier with a length of 50 km and an area of 1668 km$^2$ (*WGMS, 2017*).

From 1961 to 2000, Devon Ice Cap NW displays the minimal values of all 49 glaciers for the 3 gradients: 0.105 m w.e. (100 m)$^{-1}$ for $bz/dz_{abl}$, 0.099 m w.e. (100 m)$^{-1}$ for $db/dz_{gw}$ and 0.071 m w.e. (100 m)$^{-1}$ for $bz$/dzacc (Figure 26). $db/dz_{gw}$ and $bz/dz_{acc}$ are both showing a relatively high general increasing trend of respectively +28% and +58%, corresponding to annual rates of change of +0.71% and +1.46%. There are significant positive $r_{ablgw}$ and $r_{gwacc}$ correlations of 0.60 and 0.59. $bz/dz_{abl}$ increases from its lowest to highest values from 1981 to 1987. $db/dz_{gw}$ are higher than the mean since 1987 and lowest in the beginning of the period. $bz/dz_{acc}$ have two different periods of low values: approx. 1963 to 1968 and 1982 to 1987 separated by high values. Since 1987, $bz/dz_{acc}$ increase until 1995 to stay high and rather constant until 2000.

| Devon Ice Cap NW | 1961-2000 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.105 | 0.099 | 0.071 |
| Mean annual $R^2$ | 0.95 | 0.96 | 0.90 |
| Std. | 0.032 | 0.022 | 0.035 |
| Min. | 0.048 | 0.039 | 0.005 |
| Max. | 0.186 | 0.142 | 0.161 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +2% | +28% | +58% |
| Annual rate of change (%) | +0.06% | +0.71% | +1.46% |
| $r$ with $db/dz_{abl}$ | x | 0.60 | 0.07 |
| $r$ with $db/dz_{gw}$ | 0.60 | x | 0.59 |
| $r$ with $db/dz_{acc}$ | 0.07 | 0.59 | x |







**Figure 26 :** Evolution of the absolute ablation, glacier-wide and accumulation gradients of Devon Ice Cap NW from 1961 to 2000

### 4.1.1.5 White

| White | 1960-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.215 | 0.180 | 0.110 |
| Mean annual $R^2$ | 0.97 | 0.95 | 0.92 |
| Std. | 0.053 | 0.050 | 0.061 |
| Min. | 0.117 | 0.067 | 0.011 |
| Max. | 0.402 | 0.305 | 0.275 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +1% | +18% | +48% |
| Annual rate of change (%) | +0.01% | +0.32% | +0.84% |
| $r$ with $db/dz_{abl}$ | x | 0.54 | 0.13 |
| $r$ with $db/dz_{gw}$ | 0.54 | x | 0.79 |
| $r$ with $db/dz_{acc}$ | 0.13 | 0.79 | x |

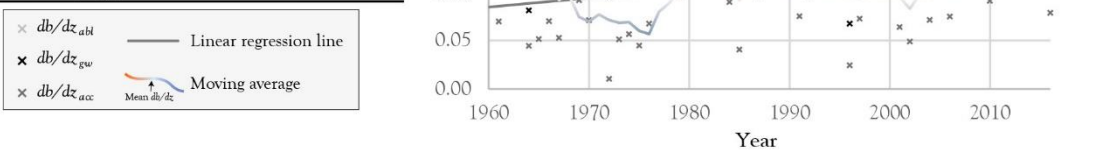






**Figure 27 :** Evolution of the absolute ablation, glacier-wide and accumulation gradients of White from 1960 to 2016

White is a valley glacier situated at the highest latitude (79°N) in this study. On Axel Heiberg Island, in arctic Canada, it extends from 80 up to 1780 m a.s.l. It is 15.4 km long and its area is 38.5 $km^2$ (*WGMS, 2017*).

From 1960 to 2016, White has relatively low means for the three gradients: 0.215, 0.180 and 0.110 m w.e. $(100m)^{-1}$, whereas the $\sigma$ of $db/dz_{gw}$ (27.9%) and $db/dz_{acc}$ (55.4%) are relatively high (Figure 27). The three gradients show an increasing evolution trend with $db/dz_{acc}$ showing the highest change over the total period (+48%). There are significant positive $r_{ablgw}$ and $r_{gwacc}$ correlations of 0.54 and 0.79. $db/dz_{gw}$ and $db/dz_{acc}$ decrease at the beginning of the period until 1975 followed by a first marked increase until 1983 and, after a decreasing period, a second increase from 2000 until

reaching their peak values in 2012. The evolution of $db/dz_{abl}$ is mostly marked by high values from 1986 to 1991.

#### 4.1.1.6 Schwarzberg

| Schwarzberg | 1956-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.716 | 0.527 | 0.351 |
| Mean annual $R^2$ | 0.98 | 0.96 | 0.96 |
| Std. | 0.214 | 0.148 | 0.108 |
| Min. | 0.353 | 0.245 | 0.165 |
| Max. | 1.319 | 0.916 | 0.744 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +16% | +33% | +22% |
| Annual rate of change (%) | +0.26% | +0.54% | +0.36% |
| r with $db/dz_{abl}$ | x | 0.83 | 0.44 |
| r with $db/dz_{gw}$ | 0.83 | x | 0.80 |
| r with $db/dz_{acc}$ | 0.44 | 0.80 | x |

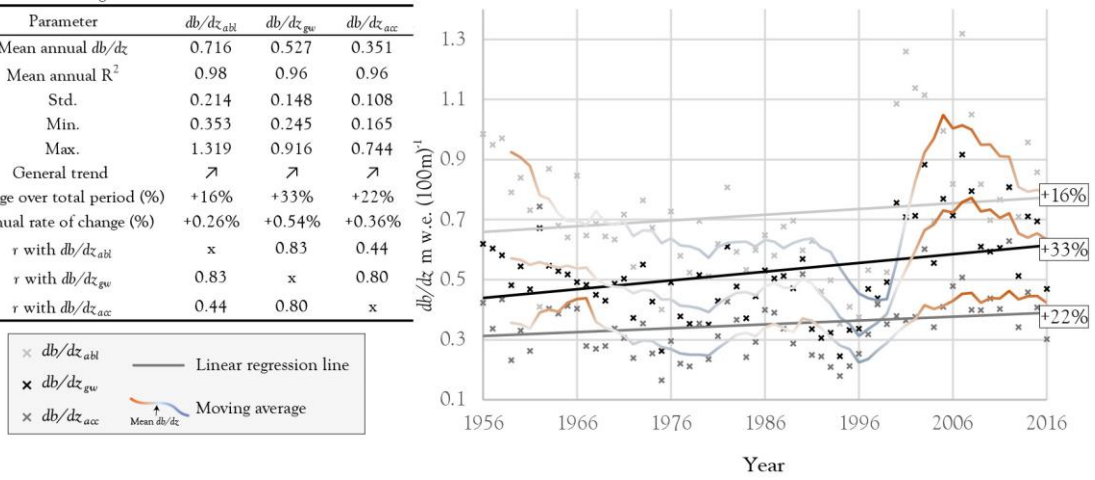



**Figure 28 :** Evolution of the absolute ablation, glacier-wide and accumulation gradients of Schwarzberg from 1956 to 2016.

Schwarzberg is a mountain glacier belonging to the Rhone basin in the Swiss Alps at 46°N. It is situated between 2600 and 3551m a.s.l. It is 4.1 km long and its area is 5.1 $km^2$ (*WGMS, 2017*).

From 1956 to 2016, Schwarzberg has a relatively low mean $db/dz_{gw}$ of 0.527 m w.e. $(100m)^{-1}$ (Figure 28). The $\sigma$ is relatively high for $db/dz_{gw}$ (28%) and low for $db/dz_{acc}$ (30.7%). The three gradients show a general increasing evolution trend, $db/dz_{gw}$ having the stronger one (+33%). The three gradients have significant positive correlations of 0.83 for $r_{ablgw}$, 0.80 for $r_{gwacc}$ and 0.44 for $r_{ablacc}$. The three gradients are lowest during the period 1970 to 1998 and then undergo a very strong increase until 2005-2007 and display high values until present.

#### 4.1.1.7 Silvretta

Located in the Swiss Alps at 46°N, Silvretta is a mountain glacier from the Rhein basin. It covers the elevation range between 2475 and 3075 m a.s.l, is 3.3 km long and 2.7 $km^2$ big (*WGMS, 2017*).

From 1954 to 2016, Silvretta has a relatively high mean $db/dz_{abl}$ of 0.985 m w.e. $(100m)^{-1}$ (Figure 29). The $\sigma$ is relatively high for $db/dz_{gw}$ (27%). The three gradients have an increasing general evolution trend with $db/dz_{gw}$ displaying a relatively marked increase of +46% (+0.73% annually). There are significant positive correlations of 0.68 for $r_{ablgw}$, 0.73 for $r_{gwacc}$. $db/dz_{abl}$ are high from 1971 to 1983 approx. and even higher from 1993 to 2010. $db/dz_{gw}$ and $db/dz_{gw}$ are mostly high from 2002 to 2010. $db/dz_{abl}$ and $db/dz_{gw}$ undergo a marked decrease in the recent years.

| Silvretta | 1954-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.985 | 0.595 | 0.349 |
| Mean annual $R^2$ | 0.96 | 0.91 | 0.93 |
| Std. | 0.290 | 0.161 | 0.143 |
| Min. | 0.427 | 0.276 | 0.145 |
| Max. | 1.519 | 1.200 | 0.785 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +13% | +46% | +71% |
| Annual rate of change (%) | +0.21% | +0.73% | +1.12% |
| $r$ with $db/dz_{abl}$ | x | 0.68 | 0.16 |
| $r$ with $db/dz_{gw}$ | 0.68 | x | 0.73 |
| $r$ with $db/dz_{acc}$ | 0.16 | 0.73 | x |







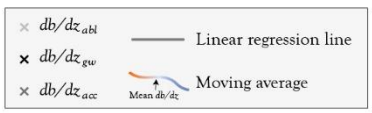
**Figure 29 :** Evolution of the absolute ablation, glacier-wide and accumulation gradients of Silvretta from 1954 to 2016

### 4.1.1.8 Abramov

Abramov is a valley glacier located at 39°N in the Pamir Alai range in Kyrgyzstan. Its minimal elevation is 3659 m a.s.l. and it starts flowing at 4918 m a.s.l. It is 7.8 km long and its area is 24 km$^2$ (*WGMS, 2017*).

From 1968 to 2016, Abramov has a relatively low mean $db/dz_{acc}$ of 0.208 m w.e. (100m)$^{-1}$ (Figure 30). The $\sigma$ is relatively low for $db/dz_{abl}$ (18.5%). The general evolution trends are increasing for the three gradients with a relatively strong increase for $db/dz_{abl}$ and $db/dz_{gw}$ of +37% and +44% respectively (+0.75% and +0.91% annually). The three gradients have significant positive correlations of 0.89 for $r_{ablgw}$, 0.70 for $r_{gwacc}$ and 0.53 for $r_{ablacc}$. They are low at the beginning of the period and undergo a strong increase since 1993 until 1998. The data gap between 1999 and 2011 prevents a further analysis. The values from the recent years still indicate high gradients.

| Abramov | 1968-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.722 | 0.608 | 0.208 |
| Mean annual $R^2$ | 0.98 | 0.96 | 0.92 |
| Std. | 0.134 | 0.134 | 0.099 |
| Min. | 0.503 | 0.336 | 0.051 |
| Max. | 1.057 | 0.902 | 0.517 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +37% | +44% | +59% |
| Annual rate of change (%) | +0.75% | +0.91% | +1.20% |
| $r$ with $db/dz_{abl}$ | x | 0.89 | 0.53 |
| $r$ with $db/dz_{gw}$ | 0.89 | x | 0.70 |
| $r$ with $db/dz_{acc}$ | 0.53 | 0.70 | x |



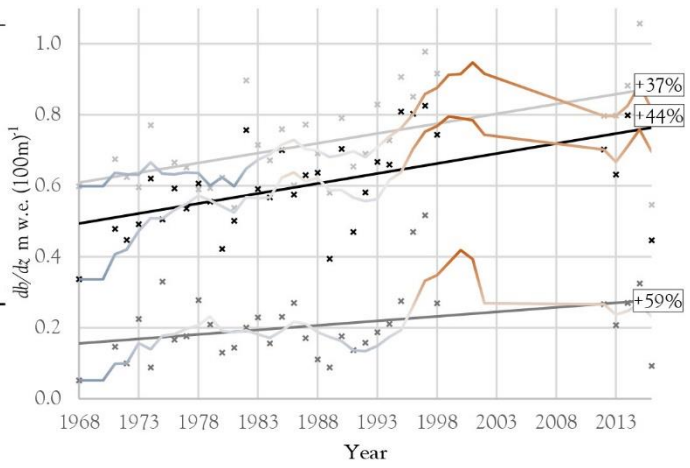




**Figure 30 :** Evolution of the absolute ablation, glacier-wide and accumulation gradients of Abramov from 1968 to 2016

### 4.1.1.9 Hellstugubreen

Hellstugubreen is a valley glacier located at 61°N in the highest mountain massif in Norway (Jotunheimen). It is covering an elevation range from 1482 to 2229 m a.s.l. Its length is 3.4 km and its area is 2.9 km$^2$ (*WGMS, 2017*).

From 1962 to 2016, Hellstugubreen shows relatively high mean $db/dz_{acc}$ of 0.537 m w.e. (100m)$^{-1}$. The $\sigma$ is relatively low for $db/dz_{abl}$ (18.7%) (Figure 31). The three gradients display a similar positive evolution trend, with $db/dz_{acc}$ showing the highest increase. There are significant positive correlations of 0.64 for $r_{ablgw}$ and 0.68 for $r_{gwacc}$. The three gradients are rather low from 1962 to 1986 and then increase until 1990. The increase is especially strong for $db/dz_{acc}$. $db/dz_{abl}$ and $db/dz_{gw}$ peak between 2004 and 2008 and $db/dz_{acc}$ a few years later.

| Hellstugubreen | 1962-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.696 | 0.601 | 0.537 |
| Mean annual $R^2$ | 0.95 | 0.96 | 0.95 |
| Std. | 0.130 | 0.101 | 0.190 |
| Min. | 0.429 | 0.422 | 0.210 |
| Max. | 0.988 | 0.845 | 1.010 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +22% | +23% | +27% |
| Annual rate of change (%) | +0.40% | +0.42% | +0.49% |
| $r$ with $db/dz_{abl}$ | x | 0.64 | 0.18 |
| $r$ with $db/dz_{gw}$ | 0.64 | x | 0.68 |
| $r$ with $db/dz_{acc}$ | 0.18 | 0.68 | x |

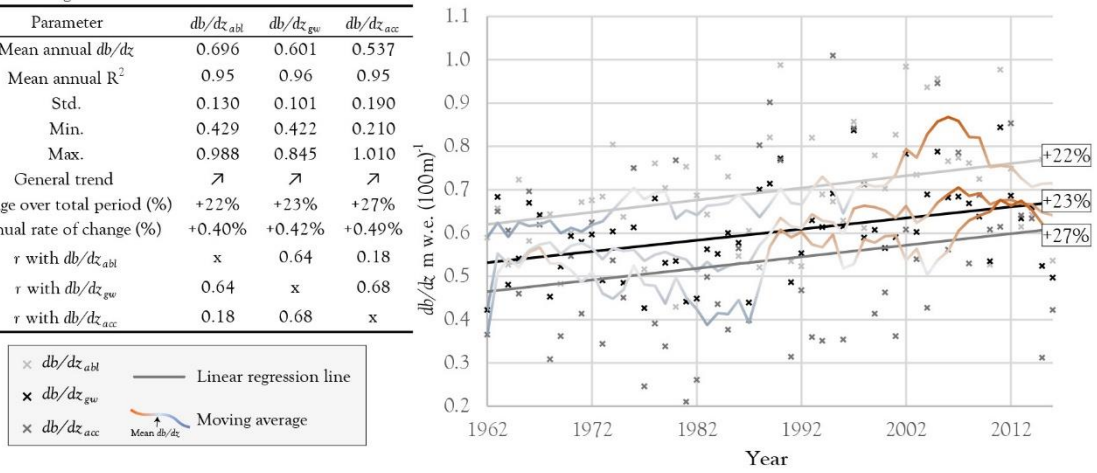



**Figure 31 :** Evolution of the absolute ablation, glacier-wide and accumulation gradients of Hellstugubreen from 1962 to 2016

### 4.1.1.10 Nigardsbreen

Nigardsbreen is an outlet glacier in western Norway from the Jostedalsbreen Ice Cap located at 61 °N. It ranges in elevation from 330 to 1952 m a.s.l. It is 9.6 km long and its area is 46.6 km$^2$ (*WGMS, 2017*).

From 1962 to 2016, Nigardsbreen has a relatively high mean $db/dz_{gw}$ of 0.794 m w.e. (100m)$^{-1}$. The $\sigma$ is relatively low for $db/dz_{abl}$ (14.5%) and $db/dz_{gw}$ (11.4%) (Figure 32). The $db/dz_{abl}$ has a general increasing evolution trend whereas the two other gradients are decreasing over the total period. The total decrease of -31% is relatively high for $db/dz_{acc}$ (-0.14% of annual rate of change). There is a high positive $r_{ablgw}$ correlation of 0.88. $db/dz_{abl}$ and $db/dz_{gw}$ undergo a lot of variations characterized by a marked decrease from 1975 to 1981 and then an increase until 2000. $db/dz_{acc}$ are low in 1962 and show a more or less continuous increase until 1994 to then decrease until 2016.

| Nigardsbreen | 1962-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.865 | 0.794 | 0.463 |
| Mean annual $R^2$ | 0.99 | 0.98 | 0.97 |
| Std. | 0.125 | 0.091 | 0.178 |
| Min. | 0.566 | 0.580 | 0.176 |
| Max. | 1.153 | 1.009 | 0.988 |
| General trend | ↗ | ↘ | ↘ |
| Change over total period (%) | +3% | -8% | -31% |
| Annual rate of change (%) | +0.06% | -0.14% | -0.56% |
| $r$ with $db/dz_{abl}$ | x | 0.88 | -0.24 |
| $r$ with $db/dz_{gw}$ | 0.88 | x | 0.12 |
| $r$ with $db/dz_{acc}$ | -0.24 | 0.12 | x |

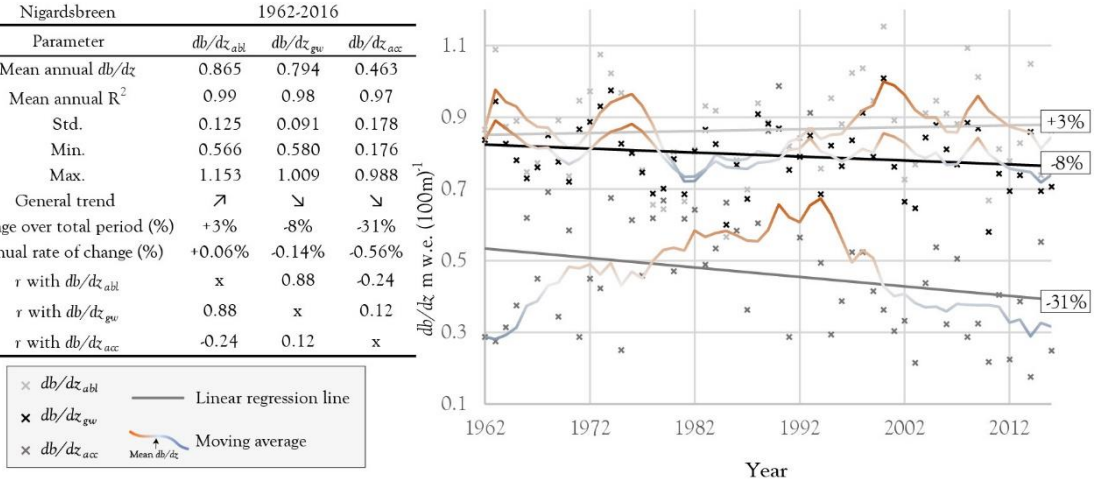



Figure 32 : Evolution of the absolute ablation, glacier-wide and accumulation gradients of Nigardsbreen from 1962 to 2016

### 4.1.1.11 Storglaciaeren

| Storglaciaeren | 1971-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.828 | 0.986 | 1.088 |
| Mean annual $R^2$ | 0.86 | 0.90 | 0.96 |
| Std. | 0.217 | 0.199 | 0.336 |
| Min. | 0.430 | 0.620 | 0.375 |
| Max. | 1.489 | 1.508 | 1.731 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +22% | +24% | +51% |
| Annual rate of change (%) | +0.49% | +0.51% | +1.10% |
| $r$ with $db/dz_{abl}$ | x | 0.79 | 0.39 |
| $r$ with $db/dz_{gw}$ | 0.79 | x | 0.74 |
| $r$ with $db/dz_{acc}$ | 0.39 | 0.74 | x |




**Figure 33 :** Evolution of the absolute ablation, glacier-wide and accumulation gradients of Storglaciaeren from 1971 to 2016

Storglaciaeren is located in the Kebnekaise Mountains in northern Sweden, at almost 68°N. It is a valley glacier with minimum and maximum elevations of 1160 and 1720 m a.s.l. It is 3.4 long and it has a surface of 2.9 km$^2$ (*WGMS, 2017*).

From 1971 to 2016, Storglaciaeren shows relatively high means for $db/dz_{gw}$ and $db/dz_{acc}$ with values of 0.986 and 1.088 m w.e. (100m)$^{-1}$ respectively (Figure 33). $db/dz_{acc}$ have the greatest mean value comparing to the two other gradients. In contrast, the $\sigma$ is relatively small for $db/dz_{acc}$ (30.9%). The mean annual $R^2$ of $db/dz_{abl}$ is the lowest of the dataset with a value of 0.86. The three gradients have a positive evolution trend, with the highest value displayed by the $db/dz_{acc}$ for which the annual rate of change is +1.10% and the total change over the period is +51%. The three gradients have significant positive correlations of 0.79 for $r_{ablgw}$, 0.74 for $r_{gwacc}$ and 0.39 for $r_{ablacc}$. The three gradients

are low at the beginning of the period and increase until around 1993-1995. The gradients then stay rather high until present.

### 4.1.2 Overview

#### 4.1.2.1 Mean Gradient

The mean $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$ for each glacier as well as the distribution of the three datasets in boxplots is presented in Figure 34. For most of the glaciers, the mean $db/dz_{abl}$ is the greatest, followed by the $db/dz_{gw}$ and the smallest is the $db/dz_{acc}$. The exceptions are: Shumskiy, which has a much greater mean $db/dz_{acc}$ comparing to the two other gradients; Tuyuskuyskiy, for which the mean $db/dz_{abl}$ is slightly smaller than the two other mean gradients; Hansebreen and Riukojietna, for which the mean $db/dz_{gw}$ is the greatest; Garabashi, Marmaglaciaeren and Storglaciaeren, for which the mean $db/dz_{acc}$ is the largest and the mean $db/dz_{abl}$ is the smallest.

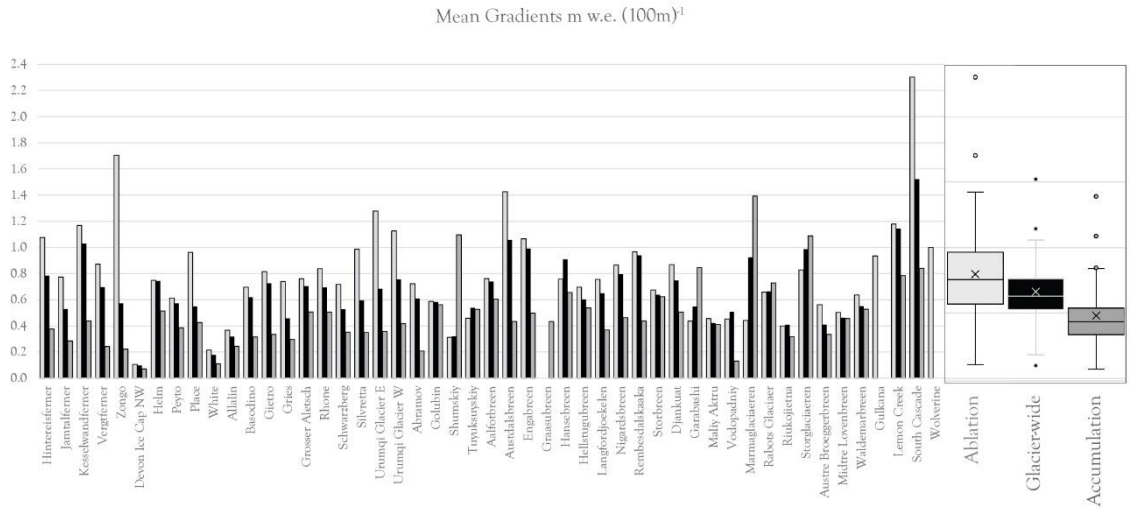



**Figure 34 :** Mean ablation, glacier-wide and accumulation gradients in m w.e. (100m)-1 for the 49 glaciers (left) and their distribution summarized in three boxplots (right)

The distribution of the mean $db/dz_{abl}$ dataset shows both the higher mean (**0.797 m w.e. (100m)$^{-1}$**) and absolute spreading out of the data (0.375 m w.e. (100m)$^{-1}$). Two glaciers show extreme mean values: Zongo with a mean $db/dz_{abl}$ of 1.704 m w.e. (100m)$^{-1}$ and South Cascade with 2.302 m w.e. (100m)$^{-1}$. The minimal value is reached by Devon Ice Cap NW which has a mean $db/dz_{abl}$ of 0.105 m w.e. (100m)$^{-1}$.

$db/dz_{gw}$ show a smaller mean value (**0.663 m w.e. (100m)$^{-1}$**). The three extreme values are reached by South Cascade with a high 1.523 m w.e. (100m)$^{-1}$, Lemon Creek with 1.145 m w.e. (100m)$^{-1}$ and Devon Ice Cap NW for the smallest $db/dz_{gw}$ with 0.099 m w.e. (100m)$^{-1}$.

$db/dz_{acc}$ have the smallest mean (**0.480 m w.e. (100m)$^{-1}$**) with three extremes values above the mean: Storglaciaeren (1.088 m w.e. (100m)$^{-1}$); Shumskiy (1.096 m w.e. (100m)$^{-1}$); and Marmaglaciaeren (1.392 m w.e. (100m)$^{-1}$). Annex 8 displays the descriptive statistics (i.e., the mean, median, standard deviation, minimal, 1st quartile, 3rd quartile and maximal values) of the mean gradient datasets.

#### 4.1.2.2 Standard Deviation

Figure 35 shows the relative standard deviation $\sigma$ of $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$ for each glacier and boxplots to summarize the distribution of the datasets. Annex 8 lists the absolute $\sigma$ (m w.e. (100m)$^{-1}$) and the relative $\sigma$ (% of the mean) with the descriptive statistics.

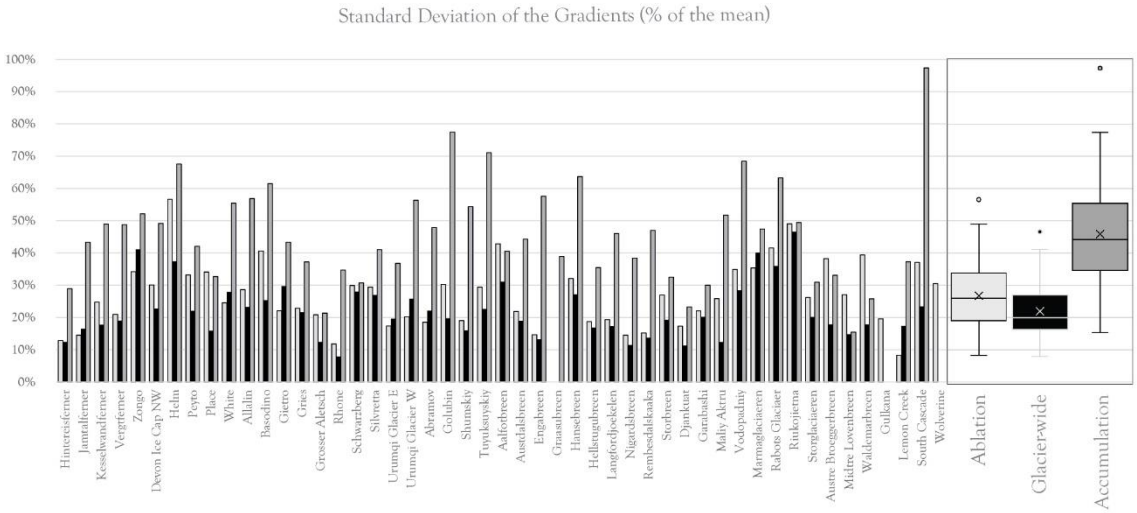



**Figure 35 :** Standard deviation of the ablation, glacier-wide and accumulation gradients in m w.e. (100m)-1 for the 49 glaciers (left) and their distribution summarized in three boxplots (right)

The $\sigma$ of $db/dz_{abl}$ shows the intermediate mean (**26.8%**) amongst the three gradients with an extreme maximal value of 56.6% for Helm and a minimal value of 8.3% for Lemon Creek.

$db/dz_{gw}$ have the smallest mean of $\sigma$ (**21.9%**) indicating that the variability of the annual $db/dz_{gw}$ is the smallest. The $\sigma$ of $db/dz_{gw}$ also has the smallest dataset variability, meaning that the $\sigma$ values have a greater similarity between glaciers. For $db/dz_{gw}$, Riukojietna has the greatest extreme value (46.6%) and Rhone the smallest (7.9%).

The $\sigma$ of the $db/dz_{acc}$ dataset shows the higher mean (**45.9%**), witnessing a high variability of the annual $db/dz_{acc}$. The distribution also has a wide spread of data around the mean indicating that the $\sigma$ can be very different between glaciers. The greater $\sigma$ is an extreme value reached by South Cascade (97.4%) and the smallest value is from Midtre Lovenbreen (15.4%). For most of the glaciers, the $\sigma$ of $db/dz_{acc}$ is greater than for the two other gradients. The only exceptions are: Place,

Austre Broeggerbreen, Midtre Lovenbreen and Waldemarbreen which have a largest $\sigma$ of their $db/dz_{abl}$.

#### 4.1.2.3 Annual Rate of Change

**Ablation Gradient**

Figure 36 represents the annual rate of change in % of $db/dz_{abl}$ for all 49 glaciers as well as a boxplot to summarize the distribution of the dataset.

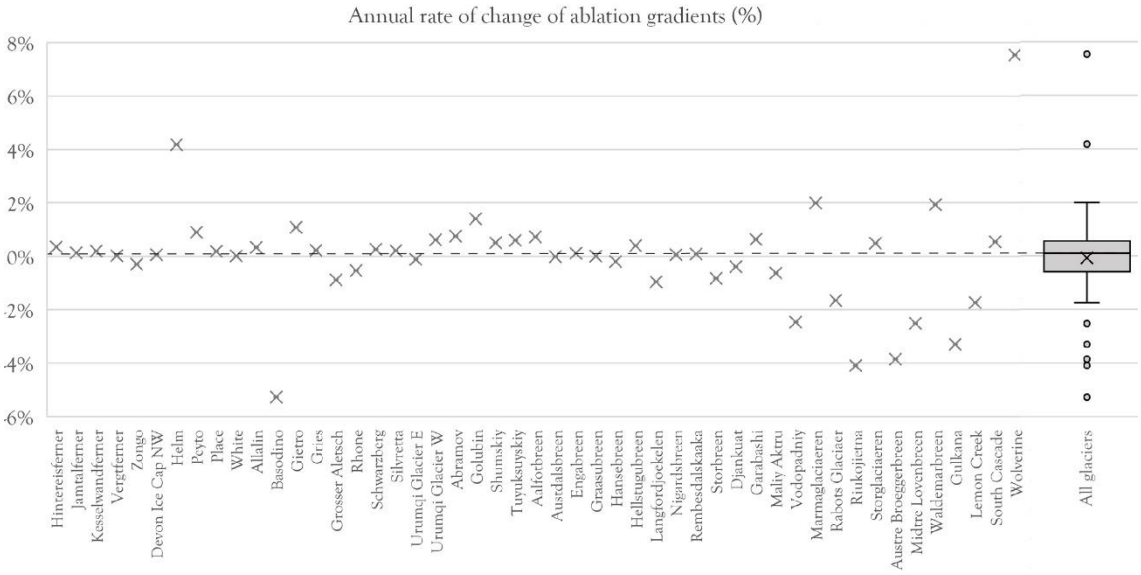



**Figure 36 :** Annual rates of change in % of the ablation gradients for the 49 glaciers (left) as well and their distribution summarized in a boxplot (right)

The mean annual rate of change of all glaciers is – 0.07% whereas the median annual rate of change is +0.12%. The $\sigma$ is 1.94%, the minimum value is -5.27% (Basodino) and the maximal value is + 7.54% (Wolverine). 50% of the values fall between -0.56% (1st quartile) and +0.56% (3rd quartile). Due to the presence of significant outliers and skewed data, the median value is considered as a better representation of the central tendency of the dataset. As the median time coverage of the annual gradients of all glaciers is 36 years, the $db/dz_{abl}$ underwent a positive total evolution trend of **+4.3**% during this time frame (+0.12% * 36).

As a comparison, the 30 glaciers selected for the comparison (see chapter 3.4.1.2) have a median annual rate of change of +0.20% (as compared to +0.12%) during a median period of 50 years. Therefore, during the mentioned time coverage, there is a total positive $db/dz_{abl}$ evolution trend of **+9.9%** for the 30 selected glaciers (+0.20% * 50). Annex 10 displays the annual rate of change in % from all glaciers and the 30 selected glaciers for the three gradients as well as the descriptive statistics values mentioned above.

## Glacier-wide Gradient

As for $db/dz_{abl}$, Figure 37 shows the annual rate of change of $db/dz_{gw}$ for all 49 glaciers as well as a boxplot to witness their distribution.

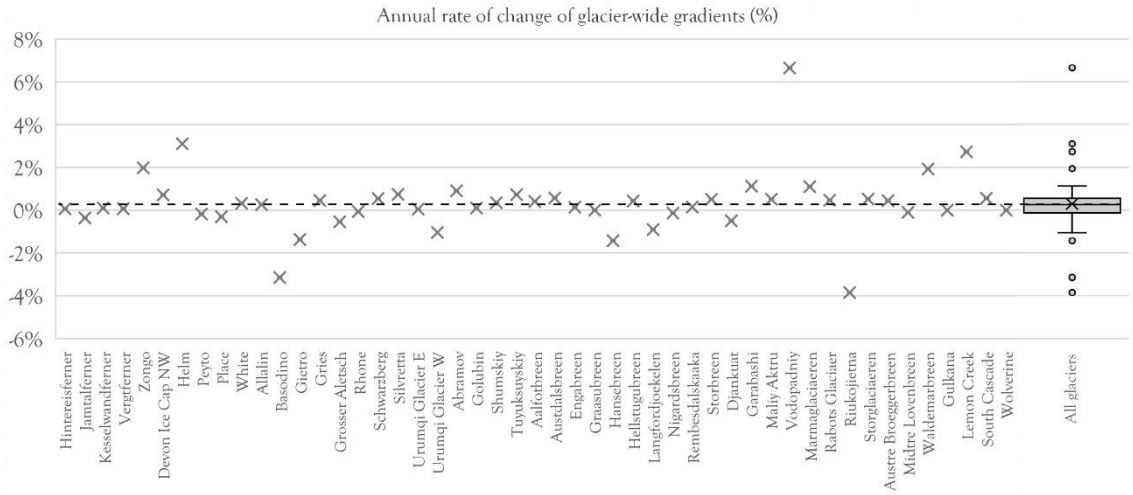



**Figure 37 :** Annual rates of change in % of the glacier-wide gradients for the 49 glaciers (left) as well and their distribution summarized in a boxplot (right)

The mean annual rate of change of all glaciers is +0.32% and the median annual rate of change is +0.33%. The $\sigma$ is 1.50%, the minimum value is -3.86% (Riukojietna) and the maximal value is +6.65% (Vodopadniy). 50% of the values fall between -0.13% (1st quartile) and +0.56% (3rd quartile). Most of the $db/dz_{gw}$ are distributed closer to the mean than the $db/dz_{abl}$ are. Nevertheless, significant outliers exist so the median value is considered again as the most representative central tendency of the dataset. The $db/dz_{gw}$ show a positive evolution trend of **+12**% during the median time coverage of all glaciers (0.33% * 36).

As a comparison, the 30 glaciers selected for the comparison give a median annual rate of change of 0.29% (as compared to 0.33%) during a median period of 50 years. Therefore, during the time coverage, there is a total positive $db/dz_{gw}$ evolution trend of **+14.3%** for the 30 selected glaciers.

## Accumulation Gradient

Figure 38 shows the annual rate of change of $db/dz_{acc}$ for all 49 glaciers and a boxplot to summarize the distribution.

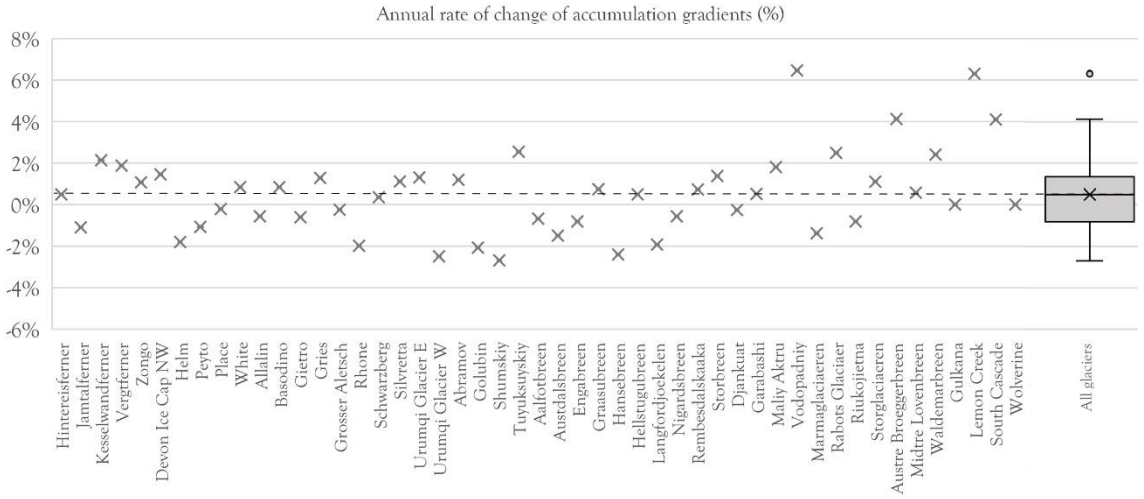



**Figure 38 :** Annual rates of change in % of the accumulation gradients for the 49 glaciers (left) as well and their distribution summarized in a boxplot (right)

The mean and the median annual rate of change of all glaciers are both +0.52%. The $\sigma$ is 2.02%, the minimum value is -2.69% (Shumskiy) and the maximal value is +6.47% (Vodopadniy). 50% of the values fall between -0.81% (1st quartile) and +1.34% (3rd quartile), witnessing that the $db/dz_{acc}$ are more widely dispersed around the mean than the two other gradients. As the mean and the median annual rate of change are equal, the central tendency of the dataset is not subject to debate. The accumulation gradients have a positive evolution trend of **+18.7**% during the median time coverage of all glaciers (0.52% * 36).

As a comparison, the 30 glaciers selected for the comparison give the same median annual rate of change of 0.51% than for the 49 glaciers during a median period of 50 years. Therefore, during the mentioned period, there is a total positive $db/dz_{acc}$ evolution trend of **+25.4%** for the 30 selected glaciers.

## Comparison of the three Gradients

Figure 39 summarizes the distribution of the annual rate of change in % to the mean gradient for all glaciers and for the 30 selected glaciers, for the three gradients. When comparing the three gradients, $db/dz_{acc}$ stand out as they have both a higher mean and median as well as a wider spreading out of values. The three gradients all show a positive annual rate of change, except for the mean annual rate of change of $db/dz_{abl}$ of all glaciers. When selecting only 30 glaciers: the median and mean annual rate of change of $db/dz_{abl}$ increase and the mean becomes positive; the median and mean of $db/dz_{gw}$ do not change; and the mean for $db/dz_{acc}$ is reduced but the median stays the same. The three sets of values are cleared out from the greatest outliers when considering only 30 glaciers, reducing the spreading out of the datasets. This effect is weaker for $db/dz_{acc}$.

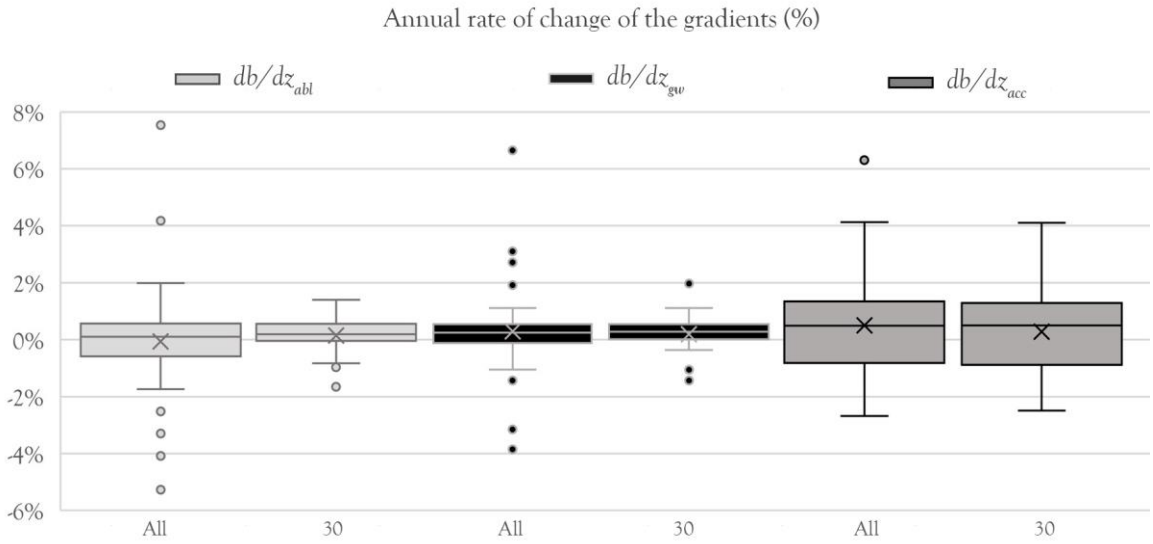



**Figure 39 :** Distribution of the annual rates of change in % for all glaciers and for the 30 glaciers for the ablation gradients (left), glacier-wide gradients (middle) and accumulation gradients (right) summarized in boxplots

### 4.1.2.4 Correlation between Gradients

The strength of the coefficient of correlation *r* as well as the direction of the relationship between each pair of dataset of annual gradients are mentioned for each individual glacier presented in chapter 4.1.1. As explained earlier, when *r* is higher than the critical value, the correlation is considered as significant, the contrary if *r* is below the critical value (see Annex 11 for critical values). Figure 40 gives an overview of the number of glaciers with the existence of significant correlations between each pair of gradient.

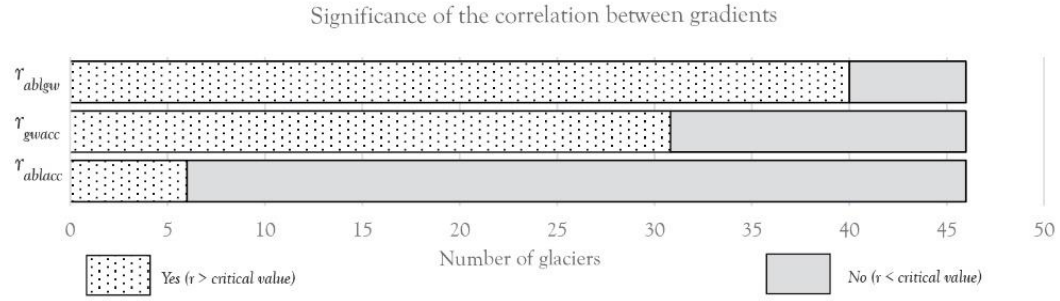



**Figure 40 :** data bars showing the number of glaciers with a significant correlation *r* between each pair of its annual gradients. The number of glaciers with significant correlation are shown in dotted surface and in grey surface when the correlation is below the critical value.

The correlation $r_{ablgw}$ between $db/dz_{abl}$ and $db/dz_{gw}$ is significant for 40 glaciers whereas only 6 glaciers show no significant correlation between the two gradients. The correlation $r_{gwacc}$ between $db/dz_{gw}$ and $db/dz_{acc}$ concerns less glaciers, but still 31 glaciers, against 15 with no significant correlation. The correlation $r_{ablacc}$ between $db/dz_{abl}$ and $db/dz_{acc}$ is significant for only 6 glaciers against 40, indicating

that the datasets of the evolution between these two gradients are different for most glaciers. As a complement, Figure 41 shows the significance of the correlation between gradients for each glacier. Vodopadniy is the only glacier with no significant correlation between its gradients. On the opposite, five glaciers have a significant correlation between all their gradients: Schwarzberg, Abramov, Riukojietna, Storglaciaeren and Midtre Lovenbreen. These five glaciers as well as Rhone glacier are the only ones showing a significant $r_{ablacc}$, meaning that for 40 glaciers, the evolution of $db/dz_{abl}$ and $db/dz_{acc}$ is not significantly correlated.

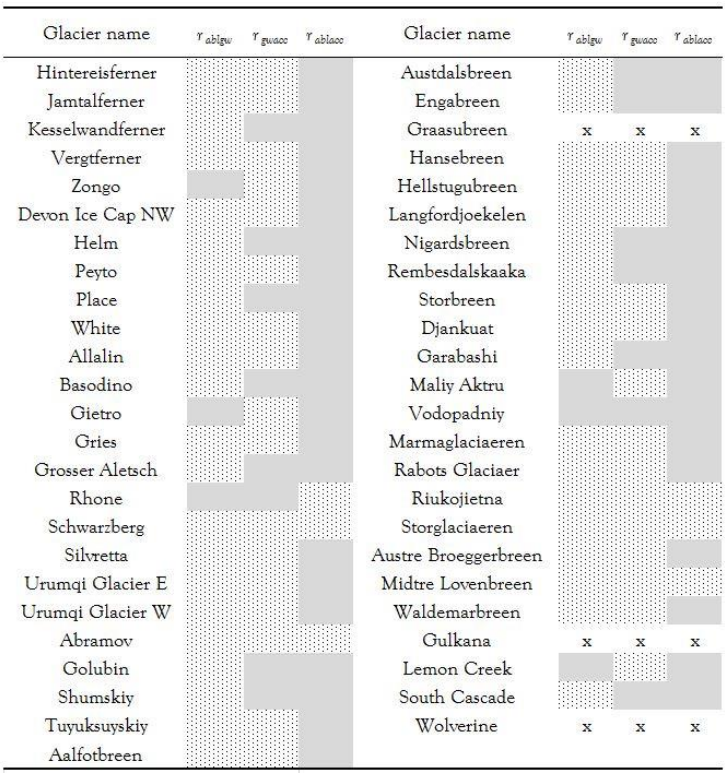



**Figure 41:** Existance of significant correlations $r$ between the ablation, glacier-wide and accumulation gradients for each glacier. The significant correlations are shown in dotted surface and in grey surface when the correlation is below the critical value.

#### 4.1.2.5 Summary

Figure 42 shows the annual rate of change (in % relative to the mean $db/dz$) in a data bar for glaciers classified from largest to smallest mean $db/dz_{gw}$. The summarized general evolution tendency of the three gradients for each glacier indicates whether all gradients are increasing ↗ (i.e. the annual rate of change is positive), decreasing ↘, or if the three gradients show disparate tendencies →. The aim is to roughly summarize the evolution of the three gradients while giving an overview of the differences between the annual rates of change of $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$. It also allows to see if there is a tendency when glaciers are classified by $db/dz_{gw}$, as glaciers with greater $db/dz_{gw}$ are expected to have a higher climate sensitivity (e.g. *Oerlemans, 2001*). In the aim of giving more

meaningful results, the glaciers considered are the same as the 30 selected glaciers from chapter 4.1.2.3.

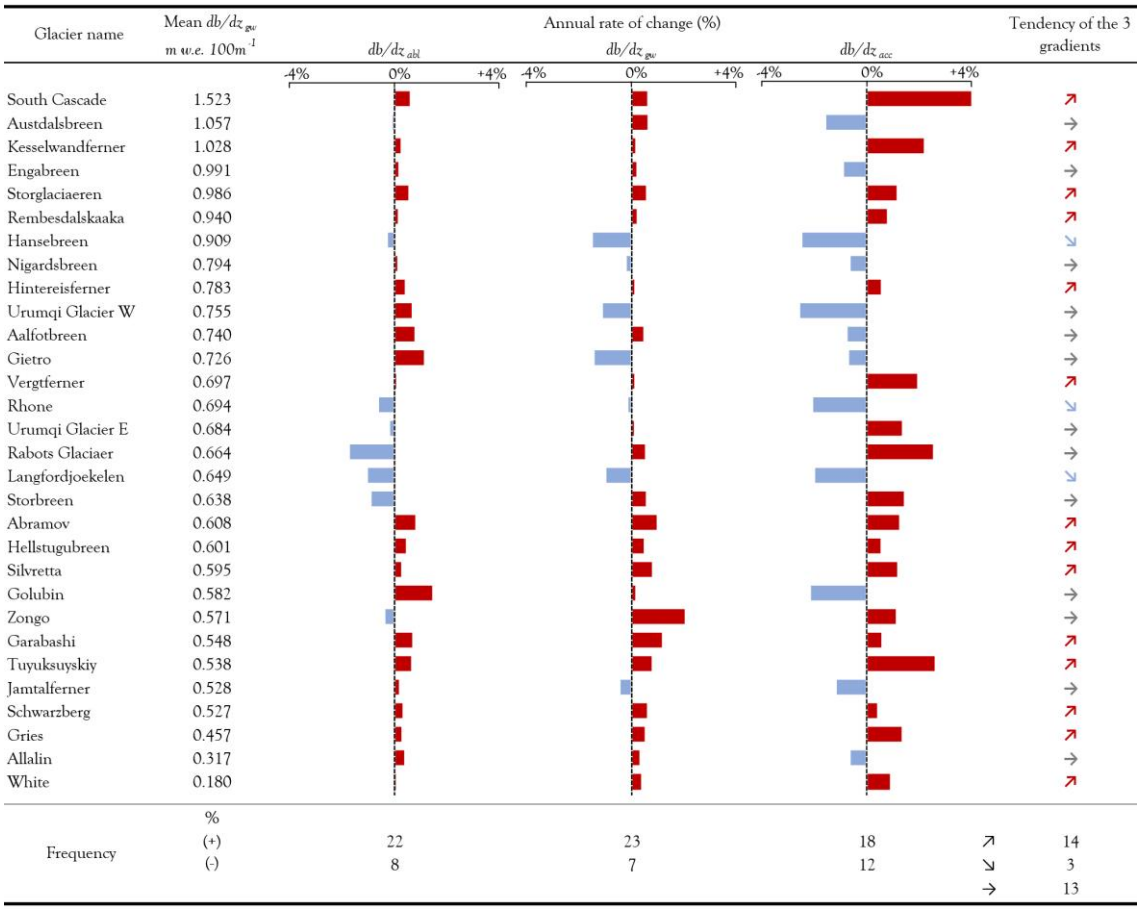



**Figure 42 :** annual rates of change (in % relative to the mean *gradient*) of the ablation (left), glacier-wide (middle) and accumulation (right) gradients for the 30 selected glaciers classified from largest to smallest mean gradient. Below the data bars, the number of glaciers showing a positive (+) and negative (-) annual rate of change are mentioned. The general trend of the gradients over the period is mentioned on the right of the Figure.

As a result, almost all of the 30 glaciers (22 glaciers) show a positive annual rate of change of $db/dz_{abl}$. From the 8 glaciers displaying a negative rate, 5 of them display a mean $db/dz_{gw}$ between 0.638 and 0.694 m w.e. $(100m)^{-1}$, corresponding to neither maritime nor continental conditions.

Even more glaciers (23 glaciers) display a positive annual rate of change of $db/dz_{gw}$ but their link with mean $db/dz_{gw}$ is less clear. All glaciers having a mean $db/dz_{gw} < 0.639$ m w.e. $(100m)^{-1}$ (except Jamtalferner) show a positive annual rate of change. These gradient values are rather characteristic of more continental glaciers. All glaciers with a mean $db/dz_{gw} > 0.939$ m w.e. $(100m)^{-1}$, characterising more maritime conditions, also have a positive annual rate of change.

In contrast, annual rates of change of $db/dz_{acc}$ are very variable and no link with mean $db/dz_{gw}$ can be established. 18 glaciers show a positive annual rate of change while 12 glaciers have a negative

rate of change, indicating that the positive evolution trend concerns less glaciers than for the two other gradients, where there is a greater gradient steepening consensus amongst glaciers.

For the three gradients, the value of the annual rate of change is not proportional to the mean $db/dz_{gw}$, i.e. more maritime glaciers do not show higher annual rate of changes, whether the change is negative or positive.

Almost half of the glaciers (14 glaciers) have positive annual rates of change for all their three gradients while only 3 glaciers show a tendency of general negative rates only. The 13 remaining glaciers show contrasted direction of their rate of changes between their gradients (e.g. $db/dz_{acc}$ is positive while $db/dz_{gw}$ is negative).

# 4.2 Evolution of Relative Mass Balance Gradients

## 4.2.1 All Glaciers

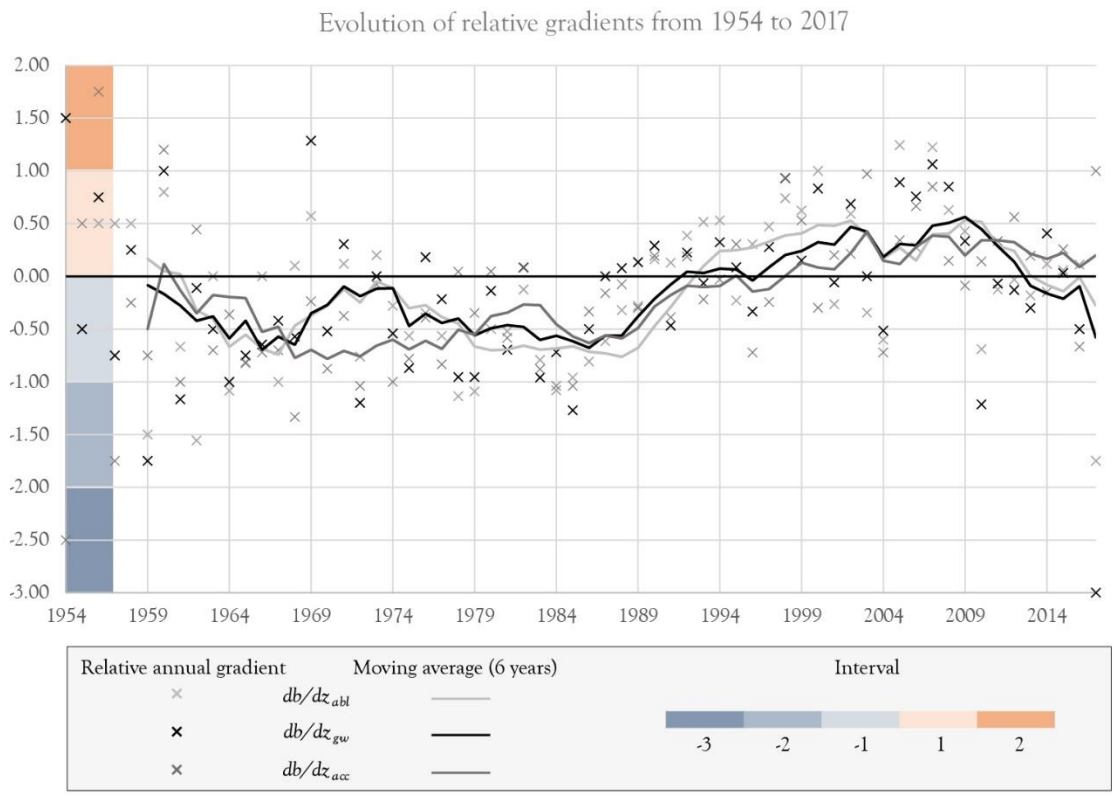



**Figure 43 :** evolution of the relative ablation (light grey), glacier-wide (black) and accumulation (dark grey) gradients represented by a 6 years moving average curve (line) and the annual gradient values (crosses) over the period 1954-2017

The evolution over the total period of analysis of the weighted mean relative $db/dz_{abl}$, $db/dz_{gw}$ and $db/dz_{acc}$ for the 49 glaciers is shown in Figure 43. It must be reminded that all glaciers do not cover

the whole total period of analysis (i.e. the number of glaciers with data is variable from year to year), this is why the data show a greater variability at the beginning of the period and in 2017 because only the years 1963 to 2016 averages 10 or more glaciers. This period is therefore considered as giving more trustworthy results. Annex 16 shows the relative mean mass balance gradients over the total period as well as the annual number of glaciers from which relative annual gradients have been averaged.

As a first result, the three gradients are evoluting during the period (i.e. they don't display constant values), witnessing periods of lower and higher gradients. More in detail, the evolution curve from the beginning of the period shows a tendency of decreasing gradient until approx. 1967. Then, the evolution is contrasted: while $db/dz_{acc}$ do not display important changes for the following 10 years, $db/dz_{abl}$ and $db/dz_{gw}$ undergo an increase until 1973 and decrease again until 1979 where they approximate $db/dz_{acc}$ relative values. Until 1988, $db/dz_{abl}$ and $db/dz_{gw}$ stay low, especially $db/dz_{abl}$, while $db/dz_{acc}$ values increase until 1983 to decrease again. Since 1988 (1986 already when the annual $db/dz$ is considered), the three gradients undergo a simultaneous strong steepening phase until 1992 for $db/dz_{gw}$ and $db/dz_{acc}$ and until 1994 for $db/dz_{abl}$. Then, the increasing trend continues at a smaller rate for the three gradients until 2002/2003. During this period, $db/dz_{abl}$ are especially high and show a very continuous increase. From 2002/2003 to 2005/2006, the three gradients decrease and the annual $db/dz$ are particularly low in 2004. $db/dz_{abl}$ and $db/dz_{gw}$ increase again until 2009 to then show a decreasing trend until present. $db/dz_{acc}$ stay rather constant and high until present, unlike the two other gradients.

If the years with less than 10 glaciers taken into account for the relative gradients evolution are set out, it is clear on the graph that the glaciers show low gradients until the late 1980s and higher gradients since then. In quantitative terms, the mean of the relative gradients from 1963 to 1990 are -0.46 ($db/dz_{abl}$), -0.40 ($db/dz_{gw}$) and -0.52 ($db/dz_{acc}$), whereas from 1991 to 2016, they are respectively 0.27, 0.16 and 0.13. The steepening phase can be described as almost step-like, very clear and linear. It concerns simultaneously the three gradients.

Through the analyzed period, the three gradients show roughly similar evolution curves but also some differences. $db/dz_{abl}$ and $db/dz_{gw}$ datasets show a strong significant positive fit of $r = 0.82$. Even if the correlation is much weaker, there is also a significant positive relationship between $db/dz_{acc}$ and $db/dz_{gw}$ of $r = 0.28$ (critical value = 0.23). There is no significant relationship between the evolution of $db/dz_{acc}$ and $db/dz_{abl}$, even if they are undergoing a simultaneous increase in the mid-1980s.

The 6 years running mean of the three gradients stays within the -1 and 1 intervals, i.e. within ½ $\sigma$ from the glacier's mean gradients over their total period of data coverage. In reality, individual glaciers show more extreme relative values but they are smoothed by the averaging process.

### 4.2.2 Classified Glaciers according to Climatic Parameters

Hereafter, the main evolution differences between glaciers classified according to climatic parameters are presented. The chapter 3.4.2 explained how the different glaciers have been classified, therefore this chapter must be referred to for detailed information about the classification[31].

#### 4.2.2.1 Continentality

For each gradient, the mean relative *db/dz* evolution curve of all 49 glaciers and the mean relative[32] *db/dz* evolution curves of the glaciers belonging to the different continentality classes are shown in Figure 44. Note that the annual *db/dz* values of the different classes are all colored in grey to give an overview of the spreading of the datasets because they are not meant for detailed description.

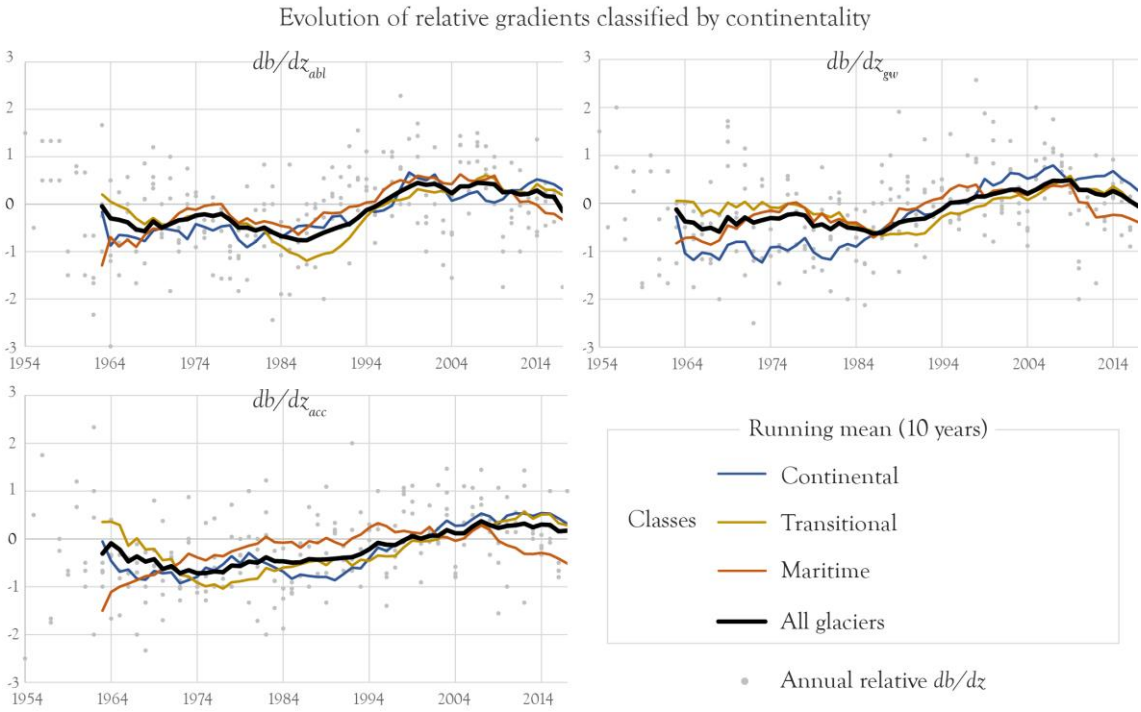



**Figure 44 :** Mean relative moving average curves of all 49 glaciers (black line) for the ablation (upper left), glacier-wide (upper right) and accumulation (down left) gradients, with the mean relative moving average curves of the glaciers belonging to the different continentality classes (colored lines) for each gradient. The moving average period is 10 years. The annual gradients are shown in grey dots.

[31] It is also valid for the glaciers classified according to geometric and gradient-related parameters.
[32] From now on until the end of the chapter 4.2, the term *relative* is implied when the words *gradient* or *db/dz* are mentioned to avoid repetitions.

**Ablation gradients:** transitional glaciers show much lower $db/dz_{abl}$ in the 1980s than continental and maritime glaciers and their subsequent increase is much shorter and more linear.

**Glacier-wide gradients:** continental glaciers show particularly low $db/dz_{gw}$ until the mid-1980s and rather high $db/dz_{gw}$ since 2000 as compared to maritime and transitional glaciers. Maritime glaciers are the ones displaying the lower $db/dz_{gw}$ values in the recent years. The steepening phase in $db/dz_{gw}$ happens earlier for continental glaciers (in the late 1970s) than for maritime glaciers (in the late-1980s) and even later for transitional glaciers (in the early 1990s).

**Accumulation gradients:** $db/dz_{acc}$ of maritime glaciers are higher than the ones of the two other glacier for most of the period (1972 to 2001) but much lower (and decreasing) in recent years. Their evolution curve is well decorelated from the reference and they don't display any clear evolution patterns.

#### 4.2.2.2 Region

The mean gradient evolution curves of the glaciers classified according to their reference regions are shown in Figure 45. Note that glaciers from region 5 (*Svalbard and Jan Mayen*) and 7 (*Alaska*) could not be calculated as there were not enough years with at least 2 glaciers for these regions. In addition, the running mean has to be increased to 15 years for all regions as the small sample sizes of the classes creates unstable curves due to the high inter-annual variability of the gradients.

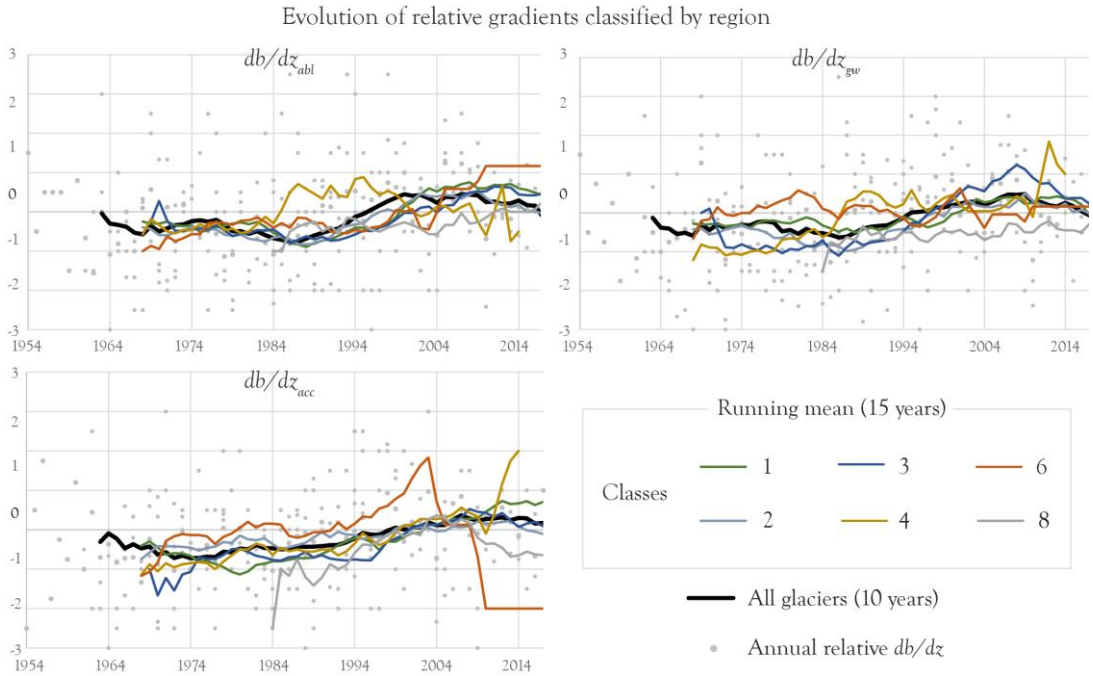



**Figure 45 :** Mean relative moving average curves of all 49 glaciers (black line) for the ablation (upper left), glacier-wide (upper right) and accumulation (down left) gradients, with the mean relative moving average curves of the glaciers belonging to the different region classes (colored lines). The region 1 is *Central Europe*, region 2 is *Scandinavia*, region 3 is *Asia*, region 4 is *Arctic Canada North*, region 6 is *Western North America* and region 8 is *Caucasus and Middle East*. The moving average period is 10 years for all 49 glaciers and 15 years for the classified glaciers. The annual gradients are shown in grey dots.

**Ablation gradients:** glaciers from *Arctic Canada North* show a very different evolution of their $db/dz_{abl}$ compared to other glacier classes. Their $db/dz_{abl}$ is increasing much earlier, i.e. in the early 1980s already and the steepening is much quicker. Their gradients stay much higher than in the other regions until the early 2000s. Even if the inter-annual variability is high, they show rather low values in recent years.

**Glacier-wide gradients:** glaciers from *Western North America* had the highest $db/dz_{gw}$ until the mid-1980s. Their evolution do not witness a steepening phase as recorded for the other regions, similarly to glaciers from *Caucasus and Middle East*. Glaciers from *Arctic Canada North* display a $db/dz_{gw}$ steepening phase with the same magnitude and timing than $db/dz_{abl}$. They seem to be high in recent years. Glaciers from *Asia* show a particularly clear and long increase in $db/dz_{gw}$ from the mid-1980s until almost 2010.

**Accumulation gradients:** glaciers from *Arctic Canada North* show a long and continuous $db/dz_{acc}$ increase through the whole period. They recently undergo a sharp increasing trend since 2010. Glaciers from Central Europe also show a similar pattern, with a continuous steepening trend starting in the early 1980s and their $db/dz_{acc}$ are rather high in recent years. Glaciers from *Western North America* display the highest $db/dz_{acc}$ values for most of the period, peak in 2003 and then undergo a pronounced decrease until present.

#### 4.2.2.3 Latitude

The mean gradient evolution curves of the glaciers classified according to their latitude are displayed in Figure 46.

**Ablation gradients:** high latitude glaciers show a very contrasted $db/dz_{abl}$ evolution curve comparing with the low and medium latitude glaciers. $db/dz_{abl}$ are abruptly increasing since the late 1970s or early 1980s until the mid/end of the decade. They stay high until approx. 2000 and then sharply decrease.

**Glacier-wide gradients:** $db/dz_{gw}$ of high latitude glaciers are clearly increasing since the early/mid 1970s until the late 1980s and are much higher than the ones of low and medium latitude glaciers in the 1980s. Their general evolution is towards an increasing trend since the early/mid 1970s until present. Medium latitude glaciers show a particularly marked decreasing trend and low $db/dz_{gw}$ from the mid-1970s until the mid-1980s.

**Accumulation gradients:** $db/dz_{ac}$ of high latitude glaciers are almost continuously increasing since the early 1970s already (they undergo a short decreasing phase in the mid-1980s). They show much higher $db/dz_{acc}$ than low and medium latitude glaciers in recent years.

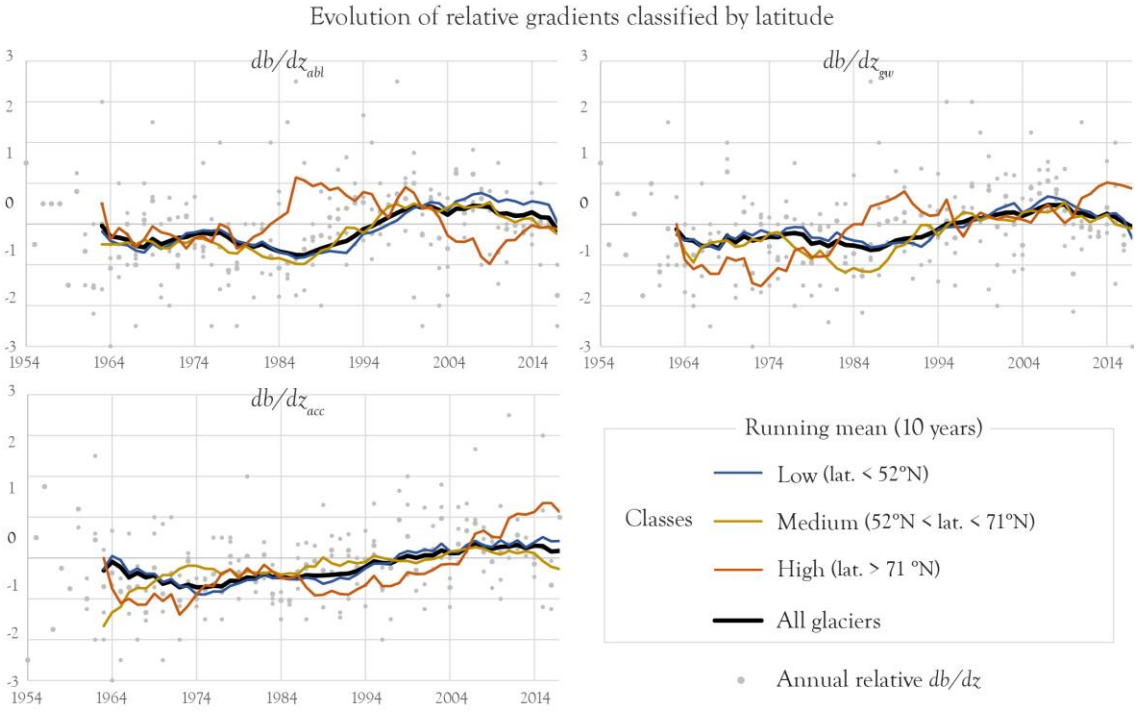



**Figure 46 :** Mean relative moving average curves of all 49 glaciers (black line) for the ablation (upper left), glacier-wide (upper right) and accumulation (down left) gradients, with the mean relative moving average curves of the glaciers belonging to the different latitude classes (colored lines) for each gradient. The moving average period is 10 years. The annual gradients are shown in grey dots.

### 4.2.2.4 Minimal Elevation

Figure 47 displays selected mean gradient evolution curves of the glaciers classified according to their minimal elevation. As explained in chapter 3.4.2.1, the glaciers have been classified after having been separated by region (*Central Europe*, *Scandinavia* and *Asia*). For simplicity, only the regions showing the most different evolution curves between the glacier classes are presented. Note that due to the small population size of the classes, the running mean is increased to 15 years for the region *Asia*.

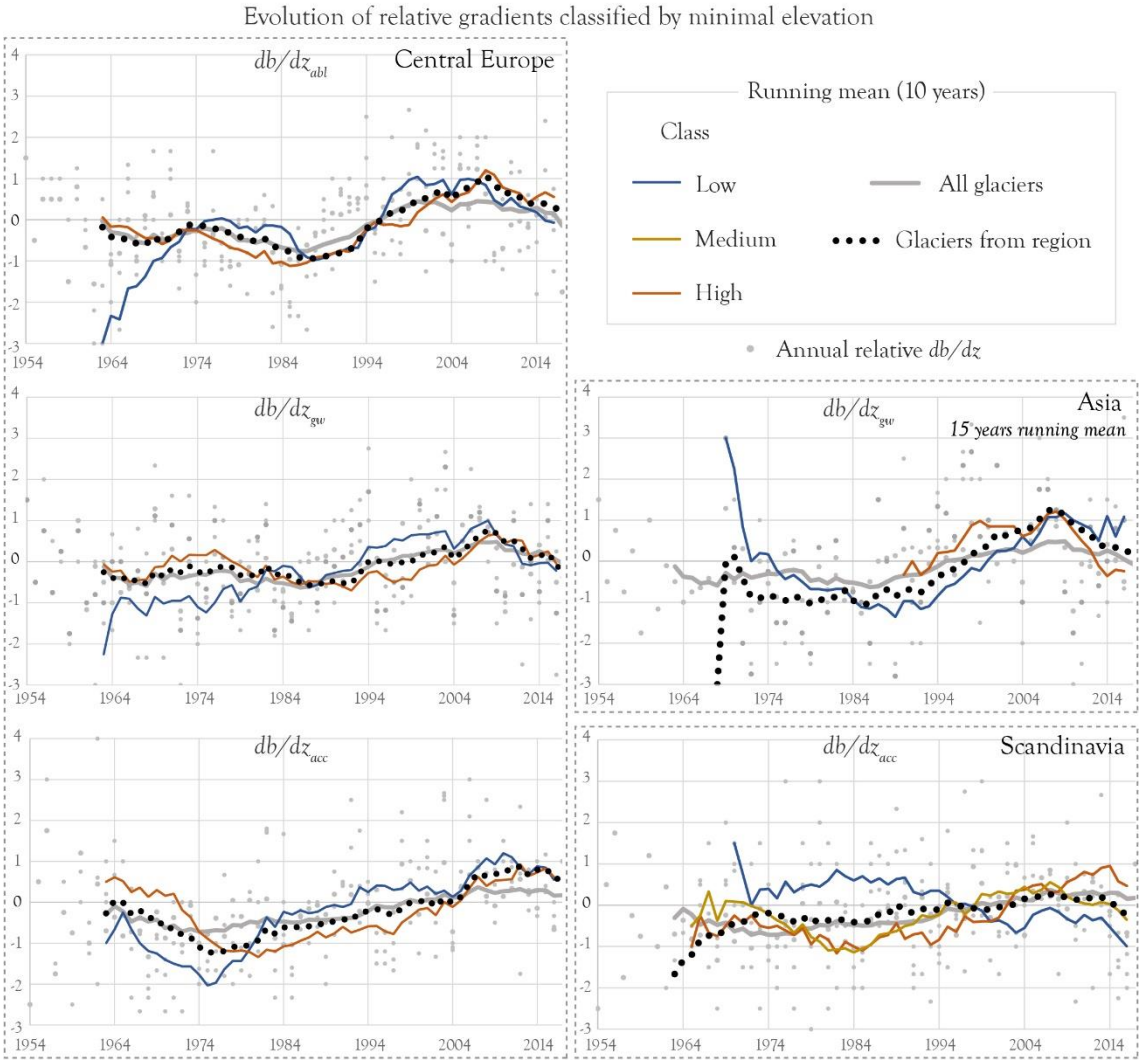



**Figure 47 :** Mean relative moving average curves of all 49 glaciers (grey line) and the glaciers in the selected region (dotted black line) for ablation (up), glacier-wide (middle) and accumulation (down) gradients, with the mean relative moving average curves of the glaciers belonging to the different minimal elevation classes (colored lines) for selected regions only with the bigger evolution differences between the classes. The moving average period is 10 years except for *Asia* where it is 15 years. The annual gradients are shown in grey dots.

**Ablation gradients:** *Central Europe* is the only region where the minimal elevation of glaciers has an influence on the evolution of $db/dz_{abl}$. Glaciers at low minimal elevation tend to have higher $db/dz_{abl}$ until the mid-2000s and their steepening phase (in the early 1990s) is more pronounced.

**Glacier-wide gradients:** in *Central Europe*, glaciers with low minimal elevation seem to have a general trend of continuous increase of $db/dz_{gw}$ from the beginning of the period until the late 2000s. Their $db/dz_{gw}$ are also lower than the ones of high located glaciers until the late-1970s, but higher until the late-2000s. Then, they show a synchronous decrease in $db/dz_{gw}$. In *Asia*, glaciers with a lower minimal elevation in contrast have lower $db/dz_{gw}$ until the mid-2000s. They display high $db/dz_{gw}$ in the recent years.

**Accumulation gradients:** similarly to the evolution of $db/dz_{gw}$, low minimal elevation glaciers in *Central Europe* have a rather continuous (but not linear) increase of their $db/dz_{acc}$, since the mid-1970s already. The continuous steepening trend is similar but starts later from glaciers located at higher elevation. In Scandinavia, the $db/dz_{acc}$ evolution difference between curves of low and high minimal glacier elevation is very contrasted. Glaciers at low minimal elevation display very high $db/dz_{acc}$ at the beginning of the period until the mid-1990s but have much lower $db/dz_{acc}$ values in recent years. Glacier at high and medium minimal elevation show more or less the opposite trend.

### 4.2.3 Classified Glaciers according to Geometric Parameters

#### 4.2.3.1 Length

Figure 48 shows the mean gradient evolution curves of the glaciers classified according to their length.

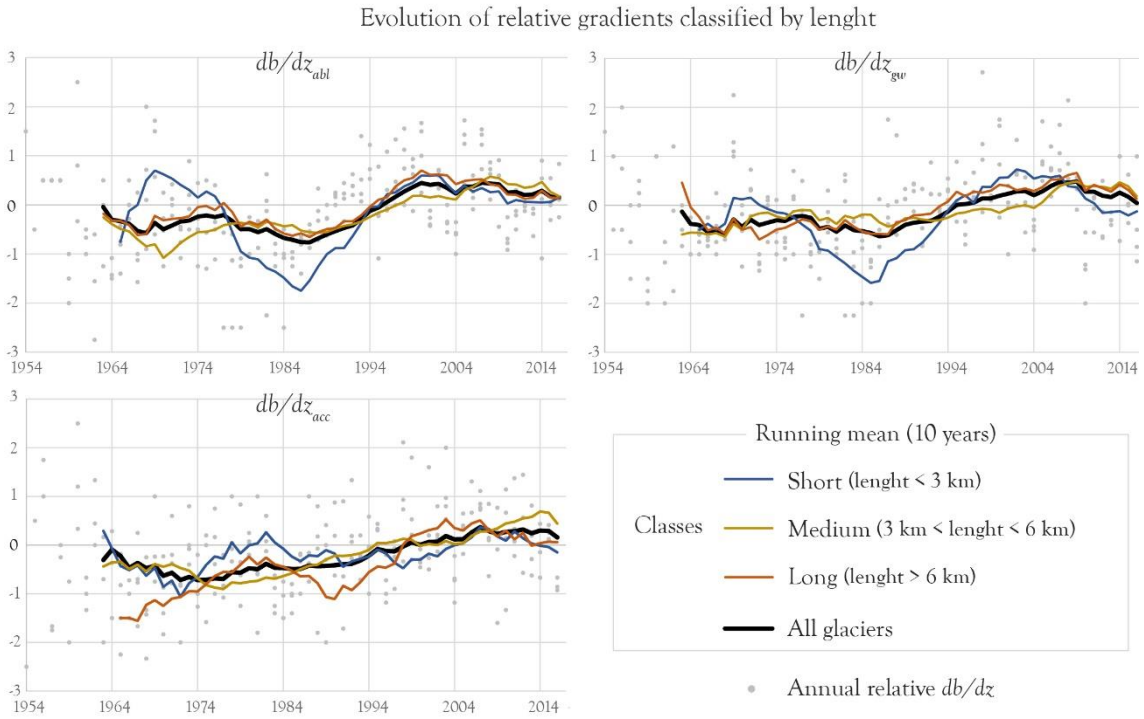



**Figure 48 :** Mean relative moving average curves of all 49 glaciers (black line) for the ablation (upper left), glacier-wide (upper right) and accumulation (down left) gradients, with the mean relative moving average curves of the glaciers belonging to the lenght classes (colored lines) for each gradient. The moving average period is 10 years. The annual gradients are shown in grey dots.

**Ablation gradients:** shorter glaciers display a similar evolution to the reference curve but with amplified values: $db/dz_{abl}$ are much higher than the ones of medium and long glaciers at the beginning of the period and much lower in the 1980s.

**Glacier-wide gradients:** the evolution of $db/dz_{gw}$ shows the similar behavior for short glaciers. Short glaciers show an ongoing decreasing $db/dz_{gw}$ trend since the early 2000s already.

**Accumulation gradients:** for most of the period, longer glaciers show smaller $db/dz_{acc}$ comparing to short glaciers. Short glaciers have particularly high $db/dz_{acc}$ from the mid-1970s until the late-1980s.

#### 4.2.3.2 Area

Figure 49 displays the mean gradient evolution curves of the glaciers classified according to their area.

**Ablation gradients:** the reference evolution curve of $db/dz_{abl}$ is well correlated with the evolution of small glaciers. Large and medium glaciers show contrasted $db/dz_{abl}$ values at the beginning of the period until the mid-1990s when the values are much higher for large glaciers and than for medium glaciers.

**Glacier-wide gradients:** glaciers from all area do not show important $db/dz_{gw}$ evolution differences.

**Accumulation gradients:** large glaciers show the most different evolution with the reference curve. Their $db/dz_{acc}$ steepen in the early 1970s and then slightly decrease. They are especially high between the mid-1970s until the late-1980s comparing to smaller glaciers. Since then, their evolution is rather constant until present.

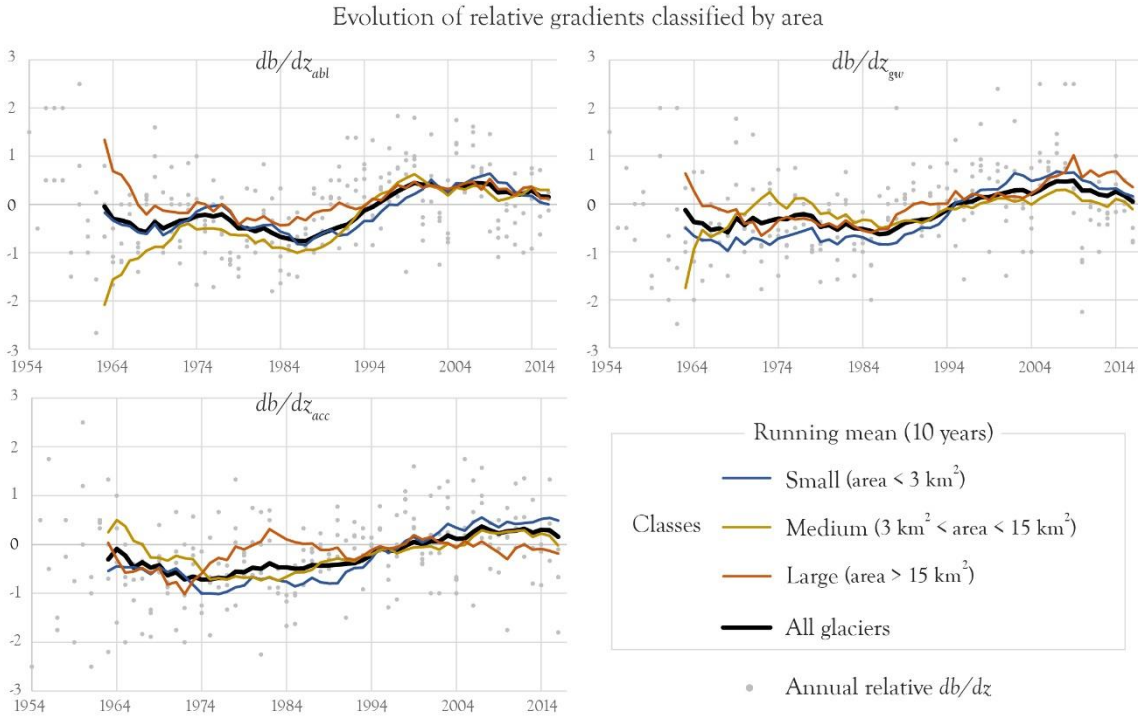



**Figure 49 :** Mean relative moving average curves of all 49 glaciers (black line) for the ablation (upper left), glacier-wide (upper right) and accumulation (down left) gradients, with the mean relative moving average curves of the glaciers belonging to the different area classes (colored lines) for each gradient. The moving average period is 10 years. The annual gradients are shown in grey dots.

#### 4.2.3.3 Length/Area Ratio

The mean gradient evolution curves of the glaciers classified according to their length/area ratio are shown in Figure 50.

**Ablation gradients:** glaciers with a high length/area ratio display a very different $db/dz_{abl}$ evolution than the ones of the other glaciers, with no clear periods of especially high or low gradients. In contrast, glaciers with a medium length/area ratio have particularly low $db/dz_{abl}$ at the beginning of the period and start increasing dramatically in the mid-1980s until the late 1990s.

**Glacier-wide gradients:** glaciers with different length/area ratio do not show particular differences.

**Accumulation gradients:** the evolution of $db/dz_{acc}$ of low length/area ratio glaciers is decorrelated with the reference evolution curve. They are not showing marked evolution patterns through the period. Glaciers of medium length/area ratio show a long and continuous increase in $db/dz_{acc}$ from the mid-1970s until present.

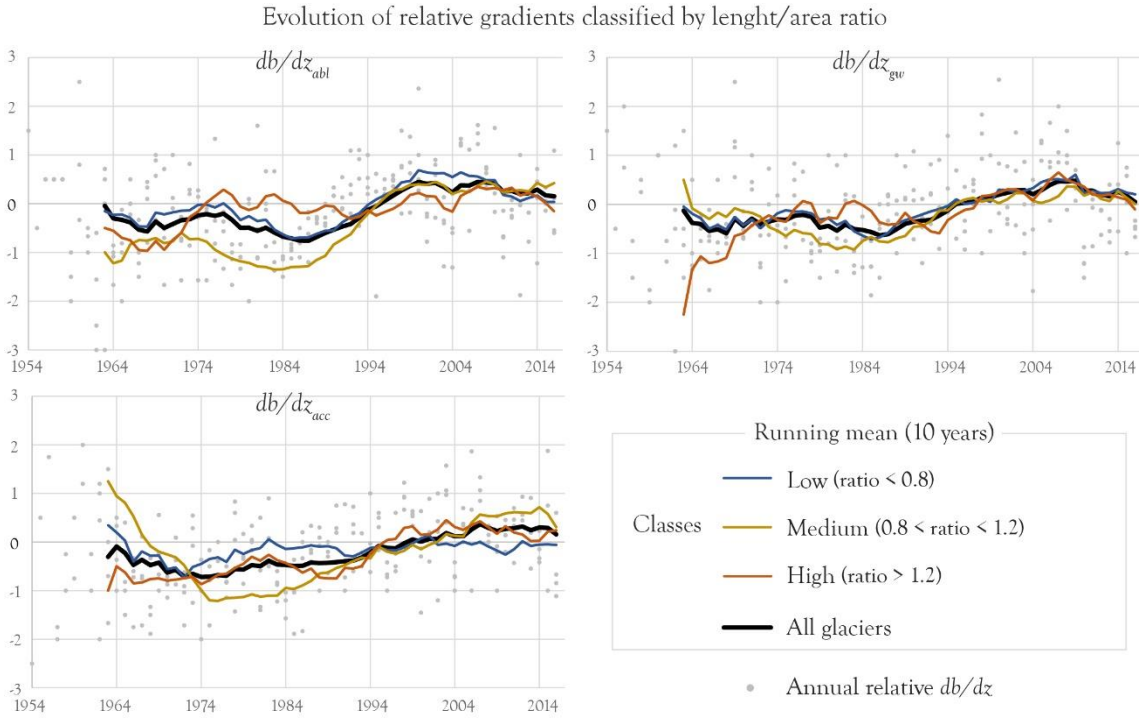



**Figure 50 :** Mean relative moving average curves of all 49 glaciers (black line) for the ablation (upper left), glacier-wide (upper right) and accumulation (down left) gradients, with the mean relative moving average curves of the glaciers belonging to the different minimal elevation classes (colored lines) for each gradient. The moving average period is 10 years. The annual gradients are shown in grey dots.

#### 4.2.3.4 Slope

Figure 51 presents the mean gradient evolution curves of the glaciers classified according to their slope.

**Ablation gradients:** the $db/dz_{abl}$ evolution curves of the three slope classes are highly different from one another. Glaciers with steep slopes show very high $db/dz_{abl}$ at the beginning of the period followed by a strong decreasing phase until the mid-1980s and start increasing again until present. On the opposite, small slope glaciers do not share particular increasing or decreasing trends through the whole period, being always more or less constant.

**Glacier-wide gradients:** the roughly similar evolution differences between glaciers of small and steep slopes described above is also valid for $db/dz_{gw}$. Small slope glaciers have a slight increasing $db/dz_{gw}$ trend since the early 1970s until present.

**Accumulation gradients:** steep glaciers have particularly low $db/dz_{acc}$ from the mid-1980s until the mid-1990s. Their $db/dz_{acc}$ undergo a strong increase in the early 1970s, simultaneous to the one of small slope glaciers, and in the early 1990s. Glaciers with small slope show no clear evolution patterns since the mid-1980s. $db/dz_{acc}$ of medium slope glaciers are continuously increasing since the mid-1970s.

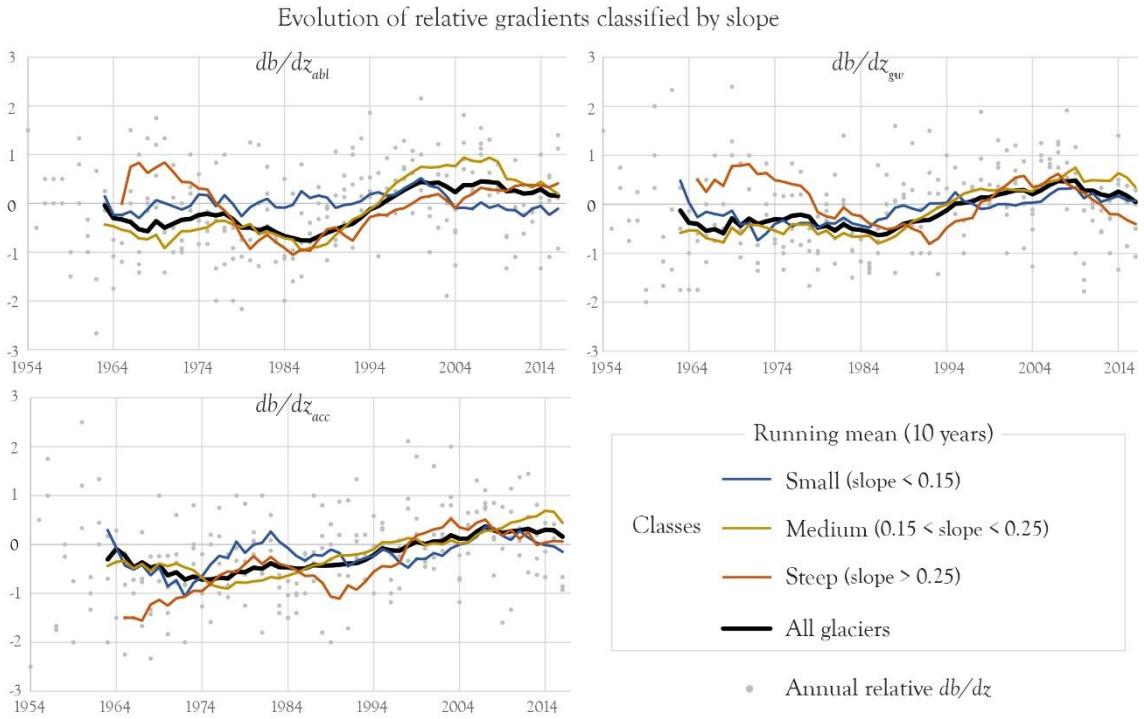



**Figure 51 :** Mean relative moving average curves of all 49 glaciers (black line) for the ablation (upper left), glacier-wide (upper right) and accumulation (down left) gradients, with the mean relative moving average curves of the glaciers belonging to the slope classes (colored lines) for each gradient. The moving average period is 10 years. The annual gradients are shown in grey dots.

#### 4.2.3.5 Elevation Coverage of Upper Half Area

Figure 52 shows the mean gradient evolution curves of the glaciers classified according to the elevation coverage of their upper half area.

**Ablation gradients:** the evolution of $db/dz_{abl}$ from the different elevation coverage of the upper half area classes do not show strong differences. Glaciers with a larger coverage display a stronger steepening phase which is also shifted in time (start in the early/mid-1990s) as compared to the other glaciers (start in the mid-1980s).

**Glacier-wide gradients:** the evolution of $db/dz_{gw}$ of glaciers with a small elevation coverage of the upper half area display a smoother curve than the one of other glaciers but with similar evolution patterns. In recent years, glaciers with a large elevation coverage of their upper half area show high $db/dz_{gw}$ gradients.

**Accumulation gradients:** glaciers with a large elevation coverage of their upper half area display high $db/dz_{acc}$ at the beginning and end of the period but are lower than the ones of the other glaciers from the early-1980s until the late 1990s. Glaciers with a small parameter value do not show any marked evolution pattern but a rather constant trend.

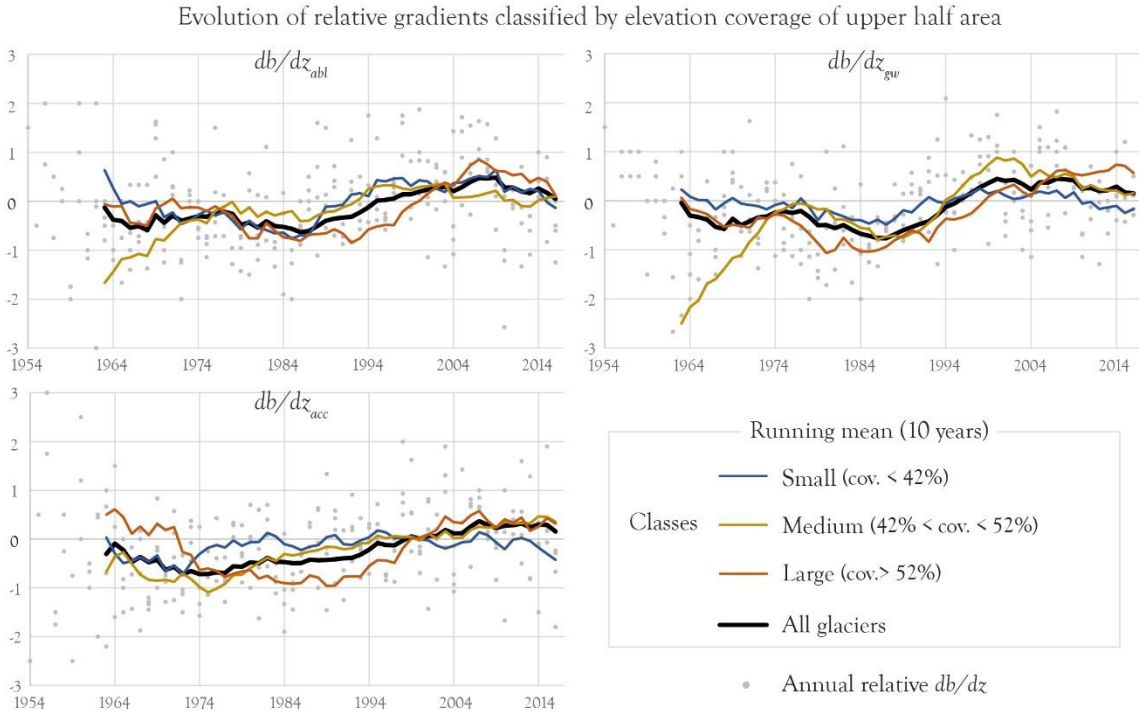



**Figure 52 :** Mean relative moving average curves of all 49 glaciers (black line) for the ablation (upper left), glacier-wide (upper right) and accumulation (down left) gradients, with the mean relative moving average curves of the glaciers belonging to the different coverage of upper half area (colored lines) for each gradient. The moving average period is 10 years. The annual gradients are shown in grey dots.

### 4.2.4 Classified Glaciers according to Gradient-related Parameters

#### 4.2.4.1 Mean Glacier-wide Gradient

The mean gradient evolution curves of the glaciers classified according to the value of their mean $db/dz_{gw}$ are shown in Figure 53.

**Ablation gradients:** glaciers with a smaller mean $db/dz_{gw}$ display higher $db/dz_{abl}$ gradients in the 1980s as compared to the other glaciers. During the whole period, they are roughly constant, in opposition to the other glaciers who undergo a pronounced steepening trend from the mid-1980s until the mid/late-1990s.

**Glacier-wide gradients:** glaciers with large mean $db/dz_{gw}$ have higher $db/dz_{gw}$ values than glaciers with small mean $db/dz_{gw}$ from the mid-1970s until the late-1990s but are much lower in recent years. Glaciers with small mean $db/dz_{gw}$ show a continuous and quasi linear increase of their $db/dz_{gw}$ since the mid-1980s until present.

**Accumulation gradients:** Glaciers with small mean $db/dz_{gw}$ show a continuous increase of their $db/dz_{acc}$ since the mid-1970s until present despite some sub-decadal variations. Glaciers with large mean $db/dz_{gw}$ display a similar $db/dz_{acc}$ and $db/dz_{abl}$ evolution pattern. These gradients display lower values during the 1980s.

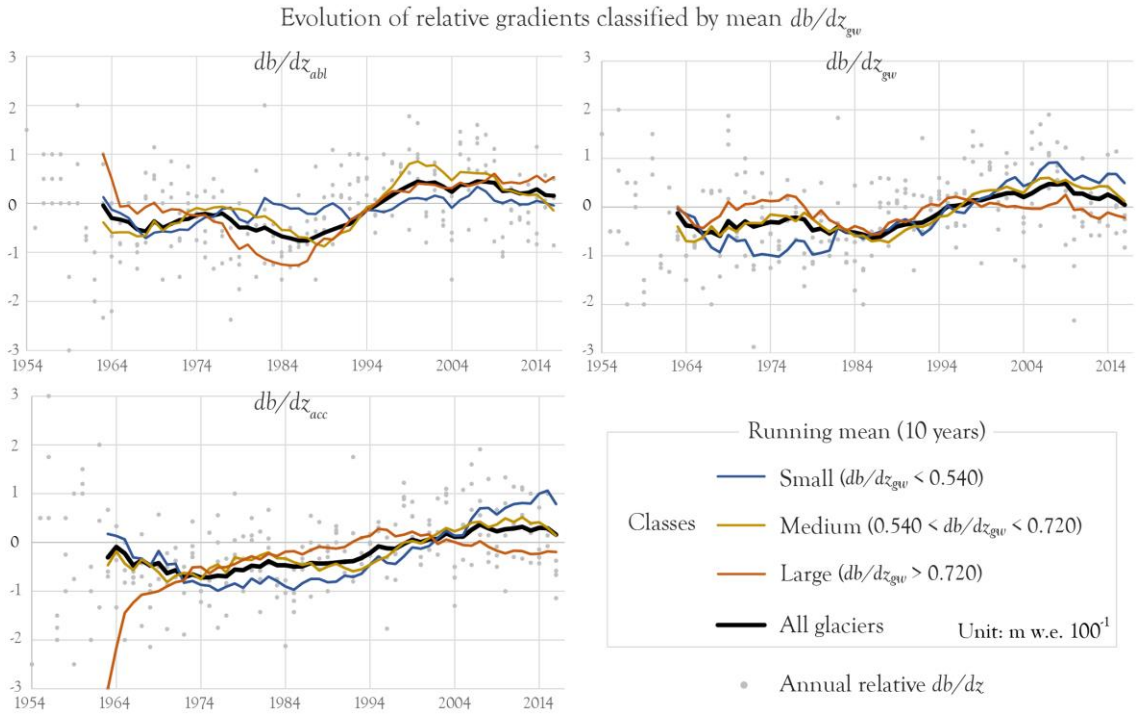



**Figure 53 :** Mean relative moving average curves of all 49 glaciers (black line) for the ablation (upper left), glacier-wide (upper right) and accumulation (down left) gradients, with the mean relative moving average curves of the glaciers belonging to the different mean glacier-wide gradient classes (colored lines) for each gradient. The moving average period is 10 years. The annual gradients are shown in grey dots.

### 4.2.4.2 Standard Deviation of Accumulation Gradients

Figure 54 shows the mean gradient evolution curves of the glaciers classified according to the value of their standard deviation of $db/dz_{acc.}$

**Ablation gradients:** if the first years of the period are not considered due to the low number of averaged glaciers, glaciers with different standard deviations of $db/dz_{acc}$ do not show important evolution differences.

**Glacier-wide gradients:** glaciers with smaller standard deviations of $db/dz_{acc}$ display slightly smaller $db/dz_{gw}$ values than the other glaciers since the early-1980s until the mid-2000s.

**Accumulation gradients:** glaciers with larger standard deviations of $db/dz_{acc}$ tend to display slightly smaller $db/dz_{acc}$ values than the other glaciers since the mid-1980s until present.

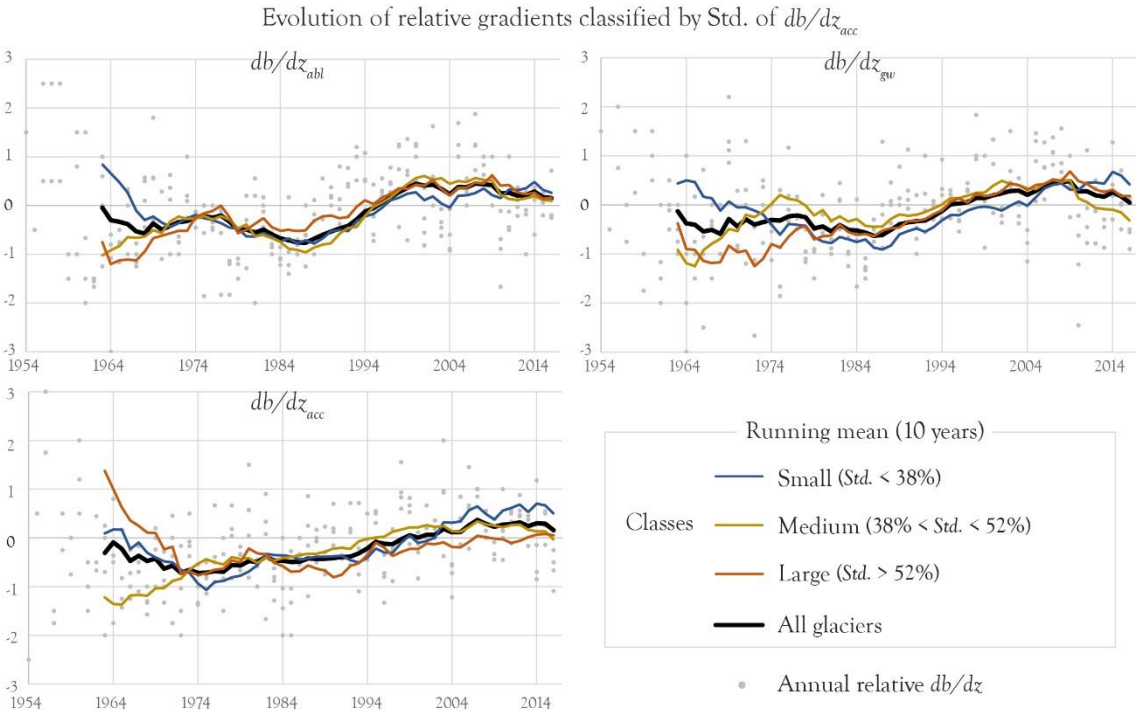



**Figure 54 :** Mean relative moving average curves of all 49 glaciers (black line) for the ablation (upper left), glacier-wide (upper right) and accumulation (down left) gradients, with the mean relative moving average curves of the glaciers belonging to the different standard deviation of accumulation gradient classes (colored lines) for each gradient. The moving average period is 10 years. The annual gradients are shown in grey dots.

# 5 Discussion

## 5.1 Uncertainties of the Results

Before interpreting the results, one important point is to be aware of their uncertainties. First, the mass balance data downloaded from the WGMS database are subject to errors and inaccuracies related to the field measurements and calculation procedures (*Zemp et al., 2009*). In the present analysis, from the gradient calculation to the obtaining of evolution trends and evolution curves, several simplification steps created additional uncertainties in the results. As a consequence, the representativity of the results as compared to the real glaciological and physical world processes are impacted.

### 5.1.1 Mass Balance Gradient

#### 5.1.1.1 Glacier Selection

An obvious simplification related to this work is the selection process of the glaciers which is first of all dependent on the availability of the mass balance data. In the WGMS database from 2018, 467 glaciers have mass balance data series with mostly annual glacier-wide *B* information, whereas annual *b* data distributed with elevation are needed for the gradient calculation. These targeted data are available for 233 glaciers only. Considering the other criteria listed in chapter 3.1.2 for the glacier selection, the glacier number is reduced to 49, the length of the data coverage being the main cause of the reduction. How representative are these 49 glaciers from *i)* the WGMS database and *ii)* the 170,000 glaciers estimated worldwide (*Vaughan et al., 2013*)? It can clearly be stated that there is a strong bias for northern hemisphere glaciers, mostly from the Central European Alps and Norway, which together form 53% of the selected glaciers. Important glacierized regions are not represented at all in this analysis due to the unavailability of the data like: Iceland, New-Zealand, the Himalaya, the Southern Andes, the Russian Arctic, the south of Arctic Canada and, of course, the two ice sheets. The results of this work should therefore not be extrapolated to these regions.

For a better reliability of mass balance gradient studies, there is a clear need for a better regional representativity of the glaciers as well as longer time series of mass balance data distributed with elevation.

#### 5.1.1.2 Mass Balance Data

A perfectly accurate mass balance gradient is per definition the slope of the tangent line of the balance profile at one particular elevation. As glaciological mass balance data are available as discrete elevation points (or elevation bands), the mass balance gradients can only be expressed through the slope of the existing mass balance data. Therefore, the calculated gradients do not consider the mass balance at every altitude point along the glacier vertical extend.

Elevation band data, expressing an average mass balance for the whole elevation coverage of the elevation bands (typically 20m, 50m or 100m), are already a simplification of the mass balance as compared to the point mass balance data which give more precise results at a defined location. The shorter the width of the elevation band is, the more accurate the mass balance will be for the concerned elevation range. Glaciers with smaller elevation bands have therefore a more detailed mass balance dataset with elevation because more information is available. To fit the gradient calculation method, the elevation references of the elevation bands are given by the average altitude of the elevation band, which is again a simplification. In reality, the given elevation reference doesn't necessary correspond to the median mass balance value inside the band. What is more, much spatial variability exist.

In addition, the removal of decreasing accumulation values is a huge simplification because the accumulation and glacier-wide gradients do not consider the mass balance in the higher parts of the glaciers. For the glaciers concerned by this procedure, the gradients are steeper than they should be if the whole elevation range of the glacier was take into account because of the decreasing mass balance with elevation up to a certain altitude. Nevertheless, this procedure allows the mass balance gradient to be captured with more accuracy as the remaining (i.e. not deleted) mass balance data shows a rather linear behavior ($R^2$ = 0.92). This simplification is not considered as compromising for the study aims as a potential increase in accumulation gradient triggered by more snowfall would still be captured.

#### 5.1.1.3 Linear Regression Model

The mass balance gradients are calculated from the slope of the linear regression line passing through the mass balance data distributed with elevation. The linear regression line never shows a perfect fit of the data, indicating that the change of mass balance with elevation is simplified and doesn't take into account all altitudinal variations in mass balance. Nevertheless, the mean of the

mean annual $R^2$ of all glaciers are 0.95 for $db/dz_{abl}$, 0.92 for $db/dz_{acc}$ and 0.94 for $db/dz_{gw}$, witnessing a rather high goodness of the linear model fit to the mass balance data, the accumulation gradient being the one for which the linear regression line creates the biggest simplification. These results justify the chosen approach for the gradient calculation.

By simplifying the rate of change of mass balance with elevation, the linear regression line has the advantage not to take into account local variations in mass balance which are normally due to topographic or geometric factors (e.g. a local change in glacier aspect or slope, local shading or albedo effects) (see chapter 2.2.2). As the aim of the study is to analyze glacier-climate interaction, this simplification is more an advantage.

#### 5.1.1.4 $ELA_0$ versus ELA

Taking the $ELA_0$ as a reference point for delimitating the ablation zone from the accumulation zone is a huge simplification in terms of mass balance processes as *i)* the *ELA* of the glacier changes every year and *ii)* the $ELA_0$ gives the mean *ELA* of a glacier in steady-state conditions while most of the glaciers are losing mass over the analysed period. On the annual time scale, choosing the $ELA_0$ instead of the *ELA* implies that it is not the "real" annual ablation and accumulation zones in terms of strict glaciological definition that are taken into account for the calculation of annual $db/dz_{abl}$ and $db/dz_{acc}$. A problem for the ablation and accumulation gradient representativity is that there is often a "kink" of the balance profile near the *ELA* caused by the albedo change (see chapter 2.2.2.1). When the seasonal snow disappears below the *ELA*, the albedo is dramatically reduced and the energy absorption on the glacier surface increases (*Cuffey and Paterson, 2010*). The $ELA_0$ thus do not always set the limit of mass balance data at the balance profile "kink".

However, it is relevant to consider the $ELA_0$ for climate-glaciers interaction taking into account the natural shift of the balance profiles from year to year resulting from the inter-annual glacier-wide mass balance change $\Delta B$. Indeed, the years with an important negative $B$ over the glacier, the balance profile may lie completely or be considerably shifted in the negative mass balance zone. As a consequence, the real *ELA* could lie above the glacier margin or very high up, strongly compromising the calculation of any accumulation gradients. Nevertheless, it is not because the mass balance is strongly negative one year that the glacier did not experience accumulation[33]. Setting an $ELA_0$ allows to still capture accumulation processes even in negative mass balance years. The opposite effect is true for ablation processes during highly positive mass balance years. Thus, the

[33] Because the mass balance is the sum of accumulation and ablation.

$ELA_0$ allows to calculate the mass balance gradients independently of the annual *B* and so relate for ablation and accumulation processes every year at the same elevations.

A test with Hellstugubreen glacier (randomly chosen) has been conducted to see the differences in annual $db/dz_{acc}$ resulting from the two methods of separating the ablation from the accumulation area to calculate the gradients ($ELA_0$ vs annual *ELA*). The correlation coefficient between the two $db/dz_{acc}$ datasets is a significant $r = 0.77$. The $ELA_0$ gives slightly higher $db/dz_{acc}$ (mean of 0.698 m w.e. $(100m)^{-1}$) than with the annual *ELA* consideration values (mean of 0.679 m w.e. $(100m)^{-1}$).

In addition, that the fact that 40 glaciers on 46 showed no correlation between their $db/dz_{abl}$ and $db/dz_{acc}$ evolution (see chapter 4.1.2.4) suggests that the two calculated gradients are able to account for the evolution of two different processes (i.e glacier melt and solid precipitation). Finally, the $db/dz_{gw}$ evolution, which is independent of the *ELA* position, show a significant correlation with $db/dz_{acc}$ for 31 glaciers on 46. Taking into account the fact that more mass balance data are used to calculate $db/dz_{abl}$ than $db/dz_{acc}$, this is a very good fitting result. It proves that $db/dz_{acc}$ relates for accumulation rates and is not a complete artefact created by the position of the *ELA*.

A methodological advantage of the $ELA_0$ is that it simplifies the calculation of $db/dz_{acc}$ and $db/dz_{abl}$ (i.e. the annual *ELA* doesn't have to be integrated to the calculation) and also allows its calculation in years where information about the *ELA* are missing. For a better repesentativity of the real *ELA* position, it is suggested for further works that the $ELA_{"0"}$ limit is not set according to balanced conditions but according to the mean mass balance conditions over the analysis period (which are probably negative) if this information can be calculated.

#### 5.1.1.5 Relative gradients

The relative expression of $db/dz$ contains some simplification by making all annual $db/dz$ values fall into only 8 intervals. Therefore, it considerably reduces the accuracy of the annual $db/dz$ comparing to absolute gradients in m w.e. $(100m)^{-1}$. At the same time, it smooths the inter-annual variability of the dataset, which is rather an advantage to detect longer-term trends and link them to climate change.

In addition, expressing the interval limits as a function of the standard deviation of the glaciers is considered as a good way to fairly take into account the spread of the inter-annual variability of the annual $db/dz$ dataset of each glacier. Indeed, the standard deviation is a statistical parameter which takes into account the distribution of a normal dataset: 34.1% of the data should fall in the first intervals -1 and 1 (within ½ $\sigma$), 34.1% in the second intervals -2 and 2 (between ½ $\sigma$ and $\sigma$), 27.2% in the third intervals -3 and 3 (between $\sigma$ and 2 $\sigma$) and 4.6% in the fourth intervals -4 and 4. A test

with the annual relative $db/dz_{abl}$ values from all glaciers has been done and 38.6% of the data fall into the first intervals, 30.2% in the second, 27.1% in the third and 4% in the fourth, witnessing the normal distribution of absolute $db/dz_{abl}$ values from all glaciers. The fourth interval is clearly under represented but it is rather an advantage as it means that the influence of extreme annual $db/dz$ values on the mean evolution curves are not a common occurrence.

## 5.1.2 Evolution Results

### 5.1.2.1 Linear Evolution Trend and Annual Rate of Change

For each individual glacier, the general evolution trend is represented on the graph by the linear regression line of each $db/dz$ and quantitatively by the annual rate of change derived from the total rate of change along the linear regression line over the period. It is expressed in % of the mean $db/dz$. In mathematical terms, it is incorrect to use the linear regression in this case as the assumption of a linear distribution of the dataset is not met ($R^2$ between annual $db/dz$ and increasing years is very low for most of the glaciers). This is also a result in itself, meaning that the evolution of gradients over the years is not following a constant increase or decrease but show some variations. Therefore, this representation strongly simplifies the evolution results and poorly considers variations inside the period. The linear trend has the problem to be strongly influenced by the values at the end and the beginning of the period. Therefore, depending on the extremity years, the results can change. For an example glacier, if the first years correspond to a period of particularly low gradients and the last years to a period of strongly high gradients, the rate will be highly positive. If the example glacier had a different data coverage - for example the first years of data begin 10 years earlier, corresponds to a period of higher gradients - the rate of change will be lower and might even be negative. As the 49 glaciers show different year coverage, this effect is surely present in the results. For more accurate results, the total period of analysis should be separated into different smaller time spans but this would raise other problems such as: glaciers would still show different data coverage inside the smaller periods; the results would be more influenced by the inter-annual variability of the gradients; the choice of the period years would highly influence the results and; it would not capture a long term trend and therefore the results would have a lesser climatic-change relevance.

As gradients can show a high inter-annual variability, glaciers with a longer data coverage are considered as giving more trustworthy results even if they are not spared by the problematic of the influence of the $db/dz$ values of the first and last years. Therefore, the general evolution trend and annual rate of change results from glaciers with a particularly low number of years with data should

be considered with care. These glaciers are: Helm, Rhone, Gulkana, Lemon Creek and Wolverine. They all have a number of years with data of 10 years or less.

The analysis of the distribution of the annual rate of changes of the three gradients gives useful information for the reliability of the median annual rates of change summarized for all glaciers and the 30 selected glaciers in chapter 4.1.2.3. Indeed, $db/dz_{acc}$ show a rather high spreading out of its dataset for the two glacier populations while $db/dz_{abl}$ and $db/dz_{gw}$ have a much more concentrated distribution, especially for the 30 glaciers sample. It means that the median annual rate of change and total evolution trend results for $db/dz_{acc}$ of all glaciers (+18.7% in 36 years) and the 30 selected glaciers (+25.4% in 50 years) comes from a rather heterogeneous dataset - raising the question of their reliability. To confirm this effect, chapter 4.1.2.5 shows that the annual rates of change are very variable from one glacier to another. In conclusion, even if $db/dz_{acc}$ show the highest rate of change over the period, this positive evolution trend relates more for the central tendency of a very variable dataset rather than for a consensus between glaciers (it seems to be more the case for the two other gradients).

#### 5.1.2.2 Evolution Curves

There are two kinds of evolution curves enabling a detailed analysis in this study: the ones of individual glaciers representing the evolution of absolute annual $db/dz$ values and the mean evolution curves of all glaciers and classified glaciers coming from relative annual $db/dz$ values. All these evolution curves have been identically obtained - it is only the nature of the data and the glacier samples that are different. The evolution curves are showing the evolution of the moving average (or running mean) of the annual $db/dz$ values. Therefore, they are not representing the inter-annual variability of the dataset, smoothed by the averaging process. The mean is a parameter particularly sensitive to extreme values. Therefore, a year with extreme $db/dz$ can influence the value of the evolution curve for many years, which do not mirror the reality. This is why the evolution curves of relative gradients - which do not display statistically extreme values - is smoother compared to the ones of absolute $db/dz$. Nevertheless, considering the inter-annual variability of the dataset by representing the evolution through a curve linking all annual $db/dz$ would give unreadable and therefore useless results. Thus, the mean is a useful statistical parameter, but it does not consider the whole picture.

As mentioned in chapter 4.2.1, the number of glaciers from which the relative mean evolutions curves are calculated fluctuates due to the different temporal coverage of the annual $db/dz$. It means that some years the evolution curve gives more representative results as the sample size is bigger than other years when the value represents the $db/dz$ of few glaciers only. The most representative

period is 1989-2015 (without 2010), with a sample size of 30 glaciers or more. Years between 1954-1962 and 2017 average less than 10 glaciers only.

#### 5.1.2.3 Classification Process

The classification process creates a reduction of the number of glaciers from which the relative evolution curves of $db/dz$ are obtained. The consequence of this sampling is that the curve is more influenced by individual glacier behaviors as non-climatically-related processes influence the mass balance gradient evolution. Therefore, the differences between the evolutions of the classified glaciers must be interpreted with care. For this reason, the aim of the classification is more to detect if and how glaciers classed according to certain parameters differ rather than accounting for meaningful evolution curves.

In addition, the choice of the limits between the classes has direct implications for the obtained results. The limits are set considering both the distribution of the parameter values between glaciers and the glaciological/physical relevance of the class limits. In a few words, it has been tried first to do maximum two or three different classes per parameter in order to minimize the reduction of the sample sizes. Then, the limits between the classes have been set to try as much as possible to create classes with even glacier numbers in them. When necessary, the limits have been adjusted to a meaningful value which do not separate glaciers with similar parameter values.

# 5.2 Interpretation of the Results

## 5.2.1 Causes of the Inter-Annual Gradient Changes

### 5.2.1.1 Hypothesis on the Possible Climatic Causes

**From mathematical and glaciological theories**

In this study the changes of mass balance gradients are analyzed in the context of glacier-climate interactions. Therefore, the chosen method of gradient extraction must enable the gradient changes to account for an external climatic-related signal influencing the gradients. This is why the nature of their causes of change must be known first. Mathematically, the linear regression is the straight line fitting all points, therefore its slope will be much influenced by the values located in the two extremities. In this study, these two poles are the maximal and minimal elevation references of the three gradients. In glaciological terms, it means that the annual $db/dz_{gw}$ is highly dependent on the annual maximal and minimal mass balance values. Therefore, any significant modification in the

rate of mass balance change with altitude, especially in the middle elevations of the glaciers, will not be captured by $db/dz_{gw}$. As the maximal and minimal mass balances values are good representatives of the annual amount of snowfall or glacier melt respectively, $db/dz_{gw}$ are considered as being able to account for annual climatic conditions. Nevertheless, analyzing the changes in $db/dz_{gw}$ do not directly allow to set apart the influence of annual ablation or accumulation processes (e.g. a year with high $db/dz_{gw}$ can be caused by strong glacier melt, high snowfall amount or both). Therefore, it seems relevant to consider $db/dz_{abl}$ and $db/dz_{acc}$ to give more information about the causes of $db/dz_{gw}$ changes (even if their respective causes of change must also be analyzed first before interpretation). What is more, other factors influencing the mass balance on the minimal and maximal glacier elevations can also be the causes of change in $db/dz_{gw}$ (see chapter 2.2.2).

The causes of change of $db/dz_{abl}$ and $db/dz_{acc}$ are rather complex. It is clear that the lowest elevation values of $db/dz_{abl}$ and highest elevation values of $db/dz_{acc}$ can translate a climatic-related signal through changes in ablation and accumulation rates respectively. However, the causes of changes are more complicated concerning the elevation extremities of the gradients next to the $ELA_0$. The years when the real *ELA* is located above the $ELA_0$, the lower elevation extremity of $db/dz_{acc}$ can be influenced by ablation processes (case 1) whereas the years where the real *ELA* is located below the $ELA_0$ can cause an influence of accumulation processes for $db/dz_{abl}$ (case 2). The strength of this influence will depend on the annual ablation sum $A_a$ (case 1) and accumulation sum $C_a$ (case 2). In the case 1, if the $A_a$ is particularly important, the lower extremity of $db/dz_{acc}$ will be shifted towards more negative values as compared to if only accumulation processes were captured in the annual $db/dz_{acc}$. The bigger the $A_a$ is, the larger is the shift and the bigger should be the influence of $A_a$ on the annual $db/dz_{acc}$ value. To sum up, a steepening of $db/dz_{acc}$ can be caused by a high $A_a$ for the years when the real *ELA* is located above the $ELA_0$, by increased snowfall in the upper elevation ranges or by both. On the opposite, a steepening of $db/dz_{abl}$ can be due to a high $C_a$ for the years when the real *ELA* is located below the $ELA_0$, by an important melt in the lower elevation ranges or by both.

It is possible that some years there is no gradient change because changes in the upper and lower elevation extremities of the gradient profile cancel each other. For example, if a glaciers receives more snow at higher elevation, $db/dz_{acc}$ and $db/dz_{gw}$ should steepen. Nevertheless, if temperature decreases at lower elevation and creates a decrease in ablation rates proportional to the increase in accumulations rates, then the gradient values do not change. As a consequence, there is only a shift in the balance profile.

Note that increasing snowfall for example can create a steepening in $db/dz_{acc}$ only if the increase is not constant with elevation. Indeed, for a modification in $db/dz_{acc}$, the change musts concern the upper elevation ranges - otherwise the accumulation profile just shifts. The same process applies to glacier melt for $db/dz_{abl}$.

**From Observed Correlation between Gradients**

The correlation between the annual $db/dz$ of the different gradients analyzed in chapter 4.1.2.4 is interesting because it confirms the positive and significant relationship between $db/dz_{gw}$ and the two other gradients. It means that when $db/dz_{gw}$ are increasing, so are the two other gradients and vice versa. This relationship concerns significantly 87% of the glaciers for $r_{ablgw}$ and 67% for $r_{gwacc}$. As mentioned in chapter 5.1.1.4, most of the changes of $db/dz_{gw}$ are probably caused by the same processes affecting $db/dz_{abl}$ changes (glacier melt) due to the higher mass balance data in this zone but are also able to relate for processes affecting $db/dz_{acc}$ (solid precipitation). The correlation between $db/dz_{gw}$ and $db/dz_{acc}$ shows that the evolution of $db/dz_{acc}$ is not always related to the evolution of the *ELA*. The quasi absence of significant correlation between $db/dz_{abl}$ and $db/dz_{acc}$ confirms that the two gradients are influenced by different processes and that these processes are not linked at the inter-annual temporal scale at least.

### 5.2.1.2 Hypothesis Test

In order to test the hypothesis about the causes of change of the inter-annual variability of mass balance gradients, mass balance-independent temperature and precipitation datasets are compared graphically and statistically to the annual $db/dz$ of Silvretta glacier. The mean annual temperature and annual precipitation sum from the meteostation of Weissfluhjoch located at 2691m a.s.l. in eastern Switzerland are downloaded from *MeteoSwiss* from 1959 (first year of meteorological data availability) to 2016 (last year of annual $db/dz$ from Silvretta).

A cross correlation analyses the correlation $r$ between the evolution of the three gradients and *i)* the mean annual temperature $T$ and *ii)* the annual precipitation sum $P$. The meteorological data can be found in Annex 17. Table 2 shows the correlation results, where the significant correlations are showed in bold. The correlations have been done separately for all years, years when $ELA > ELA_0$ and years when $ELA < ELA_0$.

| | All years | ELA > $ELA_0$ | ELA < $ELA_0$ |
|---|---|---|---|
| $r_{TP}$ | 0.18 | **0.31** | 0.03 |
| $r_{TAbl}$ | 0.12 | 0.04 | 0.37 |
| $r_{TGw}$ | **0.35** | **0.38** | 0.26 |
| $r_{TAcc}$ | **0.32** | **0.42** | 0.05 |
| $r_{PAbl}$ | 0.09 | 0.06 | 0.19 |
| $r_{PGw}$ | **0.26** | 0.30 | 0.20 |
| $r_{PAcc}$ | 0.24 | 0.29 | 0.17 |

**Table 2 :** Cross *r* correlation results between mean annual temperature *T*, mean annual precipitation sum *P* measured at Weissfluhjoch station and the annual absolute ablation, glacier-wide and accumulation gradients of Silvretta between 1959 and 2016.

When all years are considered, the only significant correlations existing are between:

1) *T* and $db/dz_{gw}$ ($r$ = 0.35)

2) *T* and $db/dz_{acc}$ ($r$ = 0.32)

3) *P* and $db/dz_{gw}$ ($r$ = 0.26)

When *ELA* > $ELA_0$, significant correlations exist between:

4) *T* and *P* ($r$ = 0.31)

The same correlations 1) ($r$ =0.38), 2) ($r$ =0.42) and 3) ($r$ =0.30[34]) as when all years are considered are also valid. What is more, the strength of the correlation 2) between mean temperature and $db/dz_{acc}$ is increased.

When *ELA* < $ELA_0$, there is an absence of significant correlations, but interesting changes of the correlation strengths as compared to when *ELA* > $ELA_0$, being:

5) $r$ between *T* and *P* becomes inexistent ($r$ = 0.03)

6) $r$ between *T* and $db/dz_{abl}$ drastically increases ($r$ = 0.37)

7) $r$ between *T* and $db/dz_{acc}$ is inexistent ($r$ =0.05)

8) $r$ between *P* and $db/dz_{abl}$ is tripled (from $r$ = 0.06 to $r$ = 0.19)

9) $r$ between *P* and $db/dz_{acc}$ is reduced (from $r$ = 0.28 to $r$ = 0.16)

The implication of these observation for the hypothesis are:

[34] The correlation is only 0.005 from the critical value so it is considered as if it was significant

- The hypothesis that annual $db/dz_{gw}$ is influenced by the annual temperature which controls glacier melt and by annual precipitation sum responsible for the amount of snowfall is confirmed through 1) and 3).

- The hypothesis postulated that in years with an *ELA* above $ELA_0$, air temperature is influencing the lowest elevations of $db/dz_{acc}$ is confirmed. Therefore, $db/dz_{acc}$ contain a temperature signal. On the contrary, when the *ELA* is below the $ELA_0$, there is no temperature signal in $db/dz_{acc}$ as confirmed through 7) and a stronger precipitation signal as suggested by 9).

- The hypothesis sets that in years with an *ELA* below the $ELA_0$, accumulation processes can influence $db/dz_{abl}$ is suggested by 8). $db/dz_{abl}$ can thefore also contain a precipitation signal.

- The hypothesis concerning the independency of temperature and precipitation on the inter-annual temporal scale is not confirmed. On the contrary, the new hypothesis that, during warmer years only, i.e. when $ELA > ELA_0$[35], temperature and precipitation could be linked is raised by 4).

- Due to the absence of significant correlation, the hypothesis that ablation processes (here temperature) in general are captured by $db/dz_{abl}$ is not suggested, except the years when *ELA* is below the $ELA_0$ as captured by 6).

- The hypothesis that accumulation processes in general are reflected in $db/dz_{acc}$ is not confirmed by statistically significant correlation, but is it suggested through a general correlation $r = 0.23$ between precipitation and accumulation, this effect being stronger when *ELA* is above $ELA_0$ as witnessed by 9).

## 5.2.2 Causes of the Long-term Gradient Evolution

### 5.2.2.1 Climatic Data

Hereafter the detailed mean evolution curves of all 49 glaciers are analyzed. The aim is to discuss a climatic interpretation on the causes of change of the observed relative evolution of the three gradients presented in chapter 4.2.1. As mentioned before, the curves summarize the weighted averaged annual relative gradients of 49 glaciers. Therefore, the detailed evolution results must not always be interpreted as witnessing a consensus between glaciers. The often contrasting annual

[35] A high *ELA* is generally the result of high melt or low snowfall or both but Silvretta shows a much higher mean of its temperature during high *ELA* years than a relative lower mean of its precipitation according to the analyzed Meteo Swiss data from 1959 to 2016.

gradient values between glaciers can be observed in Annex 7.1, 7.2 and 7.3 where the different interval colors gives a good impression of this heterogeneity.

For clarification purposes, six different periods of interpretation have been separated (Figure 55). In the following chapters, for each period, the evolution of observed air temperature, global radiation and precipitation are described. Then, possible interpretation(s) and pronounced different behavior(s) of classified glaciers are presented.

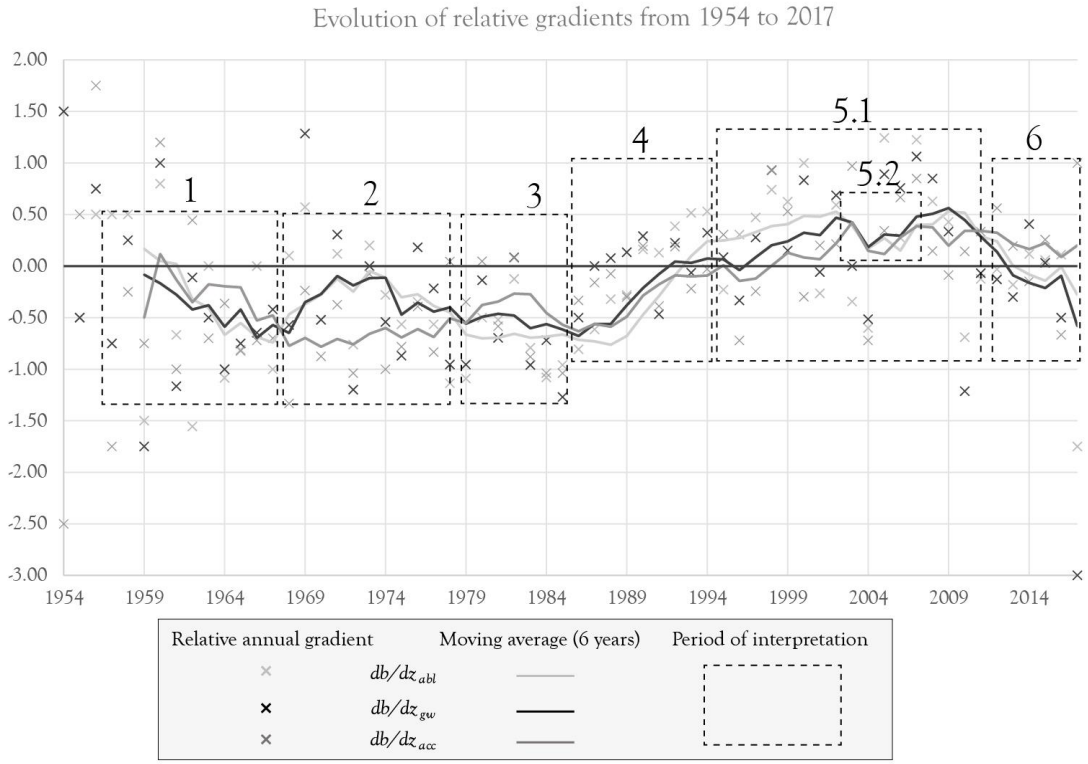



**Figure 55 :** evolution of the relative ablation (light grey), glacier-wide (black) and accumulation (dark grey) gradients represented by a 6 years moving average line and the annual gradient values (crosses) over the period 1954-2017. The 6 period of interpretation are shown (dotted squares) and numbered.

In the present interpretation, the formulated hypothesis from chapter 5.2.1 are considered valid over inter-annual and decadal time scales and will motivate the climatic interpretation of the long-term gradient evolution. Averaged time series of (summer) mean air temperatures, shortwave radiation and annual precipitation sums at each of the 49 glacier's location would be more than useful for the interpretation. Unfortunately, there is no such dataset available for the 49 glaciers.

To compare the gradient curves to independent air temperature information, *a)* the cumulative anomalies of summer air temperature for five different regions in the Austrian Alps from *Abermann et al. (2011)*, *b)* the length of the melt season in the European Alps from *Huss et al.* (2009) and *c)* the evolution of summer air temperature in the Alps and Scandinavia from *Ohmura et al. (2007)*

ending with *d)* the summer air temperature mean of the Northern Hemisphere (*GISTEMP Team, 2018*; *Hansen et al., 2010*) are taken into account (Figure 56).

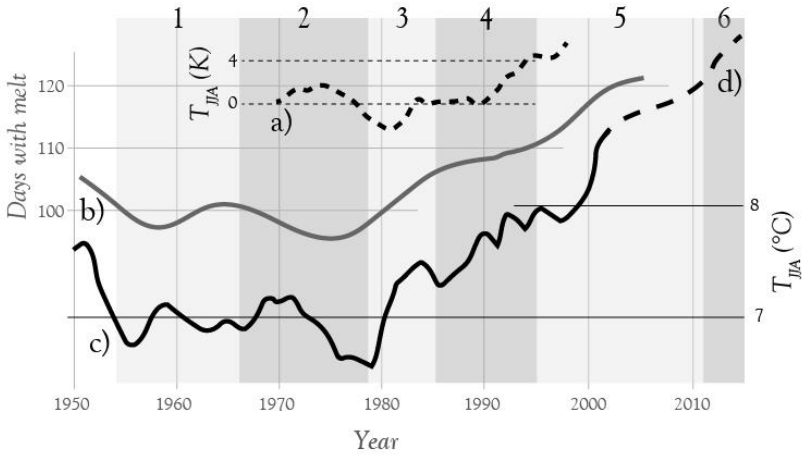



**Figure 56 :** the three evolution curves relating for air temperature information representing a) the cumulative anomalies of summer air temperature for five different regions in the Austrian Alps from *Abermann et al. (2011)* (dotted line), b) the length of the melt season in the European Alps from *Huss et al. (2009)* (grey line) and c) the evolution of summer air temperature in the Alps and Scandinavia from Ohmura et al. (2007) (black line) ending with d) the summer air temperature mean of the Northern Hemisphere (GISTEMP Team, 2018; Hansen et al., 2010)

In addition, *a)* the mean precipitation change of Northern Latitudes (*Mitchell et al., 2003*) and *b)* the annual precipitation deviation in the Alpine region calculated by *Huss et al.* (*2009*) are considered (Figure 57).

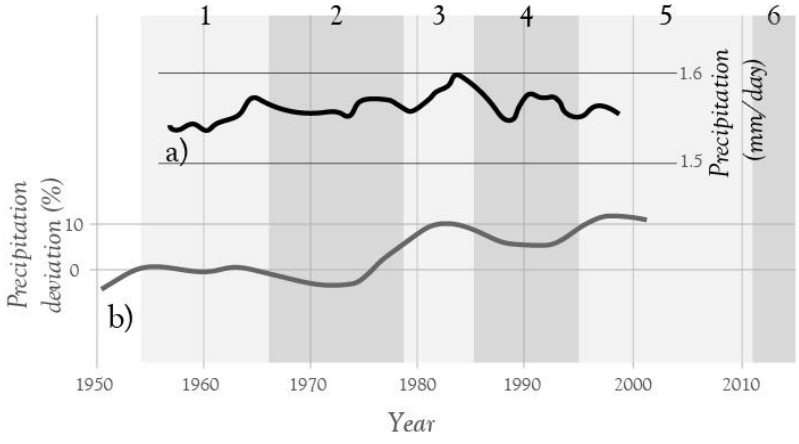



**Figure 57 :** the two evolution curves relating for precipitation information representing a) the mean precipitation change of Northern Latitudes (*Mitchell et al., 2003*) and b) the annual precipitation deviation in the Alpine region calculated (*Huss et al. 2009*).

The variations in global radiation and incoming shortwave radiation on glaciers are also analyzed due to their influence on glacier melt (see chapter 2.2.2.1). Figure 58 shows *a)* the evolution of mean global radiation for Europe from *Ohmura et al., 2007* and *b)* the evolution of shortwave radiation measured in Stockholm from *Wild et al., 2017*.

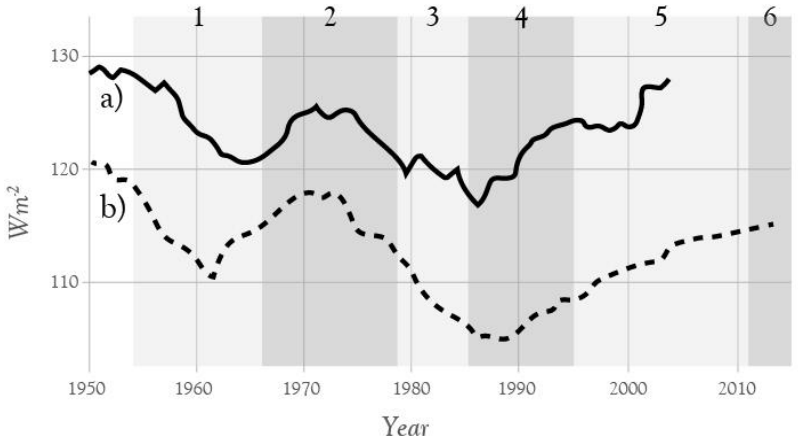



**Figure 58 :** the two evolution curves relating for solar radiation information representing a) the evolution of mean global radiation for Europe from *Ohmura et al., 2007* and b) the evolution of shortwave radiation measured in Stockholm from *Wild et al., 2017*.

The assumptions made for the interpretation are that *i)* the evolution of winter and annual precipitation accounts for the amount of snowfall which is the main factor of accumulation, *ii)* the evolution of air temperature and solar radiation relate to the amount of glacier melt responsible for ablation processes[36] and *iii)* that the evolution in these parameters are representative for all analyzed glaciers[37]. The interpretation of the comparison between the gradients evolution and the precipitation evolution should be taken with extreme care because precipitation are a very local phenomenon.

#### 5.2.2.2 Period 1 (1954-1967)

*Temperature and days with melt evolution (Figure 56)*: there is a slight increasing trend in both temperature (c) and days with melt (b) in the late 1950s until the end of the period 1.

*Precipitation evolution (Figure 57)*: precipitation could be slightly increasing in the Northern Hemisphere (a) but seems rather constant in the Alps (b).

*Radiation evolution (Figure 58)*: global solar radiation undergo a pronounced decrease over most of the period. There is a slight increasing trend in the last years as observed in Stockholm only (b).

*Interpretation:* the decreasing trend in the three *db/dz* during the period is not well explained by climatic variables as increasing days with melt, increasing temperature and precipitation should rather cause a gradient steepening. The observed decreasing gradient trend may be caused by the

[36] It is known that air temperature and solar radiation do not always influence glacier melt and that this relationship depends on many individual glacier caracteristics (see chapter 2.2.2.1).
[37] This is certainly not the case as the 49 glaciers are located in very different climates and display different locations and geometric parameters, especially for precipitation as this phenomenon can be extremely local.

decrease in global radiation decreasing ablation rates on some glaciers. This hypothesis is plausible as the mean evolution curve is averaged from few glaciers only during this period.

*Classified glaciers*: due to the relatively small number of averaged glaciers, the results of the classification of glaciers are not mentioned for this period as they are not considered as reliable.

#### 5.2.2.3 Period 2 (1968-1978)

*Temperature and days with melt evolution (Figure 56)*: air temperature seems to shortly increase at the beginning of the period 2 and decreases towards the end (a) (c). Number of days with melt undergoes a decreasing trend (b).

*Precipitation evolution (Figure 57)*: precipitation seem more or less constant for most of the period and seems to increase since the mid-1970s (a) (b). An increasing trend in winter accumulation on glaciers after the 1970s has also been witnessed by *Ohmura et al.* (2007).

*Radiation evolution (Figure 58)*: similarly to air temperature, solar radiation increases at the beginning of the period and decreases at the end (a) (b).

*Interpretation:* the increase and then decrease of $db/dz_{abl}$ and $db/dz_{gw}$ during the period 2 is well correlated to the evolution of both temperature and radiation. The variations in these parameters probably cause stronger glacier melt and then reduced melt at the end of the period, which explains the observed gradient variations. In addition, $db/dz_{acc}$ do not seem to react to any climatic signal. It could be explained by the constant precipitation trend over the period. It suggests that $ELA < ELA_0$ for most of the glaciers as the glacier melt signal do not seem to affect $db/dz_{acc}$. It is supported by the fact that this period corresponds to high mass balance conditions on glaciers (*Ohmura et al., 2007; Huss et al., 2008*).

*Classified glaciers:* the evolution patterns of $db/dz_{abl}$ and $db/dz_{gw}$ is well reflected for maritime glaciers (confirmed by glaciers with large mean $db/dz_{gw}$ but for $db/dz_{gw}$ only), low latitude glaciers, long glaciers but not at all for glaciers with higher continentality, high latitudes, short and steep glaciers. In addition, continental (confirmed by glaciers with small mean $db/dz_{gw}$) and high latitude glaciers display very pronounced low $db/dz_{gw}$ during this period comparing to the other glaciers. As a general observation, the constant trend in $db/dz_{acc}$ is more the result of the smoothing created by the averaging process rater than witnessing for a global constant $db/dz_{acc}$ concerning all glaciers. Classified glaciers show greatly divergent evolution patterns (increasing, decreasing or constant) of $db/dz_{acc}$ during this period.

#### 5.2.2.4 Period 3 (1979-1985)

*Temperature and days with melt evolution (Figure 56)*: temperature and days with melt undergo a pronounced increase over the period 3 (a) (b) (c). They display their lowest values over the total period at the beginning of the period 3.

*Precipitation evolution (Figure 57)*: precipitation seem to increase until almost the end of the period (also witnessed by *Ohmura et al., 2007*) and slightly decrease towards the end. To confirm this observation, the work from *Huss et al.* (*2008*) indicates a period of rather high winter balance for Alpine glaciers around 1980.

*Radiation evolution (Figure 58)*: solar radiation is decreasing. The lowest values since 1940 are reached at the end of the period 3. The roughly decreasing trend in global solar radiation since the 1950s until the mid/end-1980s is known as "global dimming" (*Ohmura and Lang, 1989*; *Stanhill and Cohen, 2001*).

*Interpretation*: the $db/dz_{acc}$ increase at the beggining of the period and the subsequent decrease are well correlated to the precipitation evolution during the period. Given the context of rather high winter balance and annual mass balance zero conditions during this period as stated by *Ohmura et al., 2007*, the high accumulation rates probably cause a gradient steepening as the *ELA* could still be < $ELA_0$ for most of the glaciers. $db/dz_{gw}$ are also probably influenced by this increase in accumulation as they follow a similar evolution pattern. $db/dz_{abl}$ are particularly low during the period and rather constant (even decreasing according to the annual values). Their small values probably relate for the synchronous low solar radiation and low temperatures providing less energy for melt. The increase in air temperature do not seem to trigger higher ablation rates and affect $db/dz_{abl}$ at this period as witnessed by the 49 selected glacier average. Even if they are increasing, their values are not sufficient to trigger higher glacier melt.

*Classified glaciers*: the $db/dz_{gw}$ and $db/dz_{acc}$ evolution pattern is well correlated with glaciers from *Western North America*, low latitude glaciers and Scandinavian glaciers from low minimal elevations. Short glaciers have a $db/dz_{gw}$ strong decreasing trend during this period and show no similarities with longer glaciers. Glaciers with large area show a great agreement with the increasing and subsequent decreasing $db/dz_{acc}$. In opposite to the other glaciers, high latitude glaciers display a very strong increasing trend in $db/dz_{abl}$ during this period. Short glaciers have a pronounced decreasing $db/dz_{abl}$ during the period. Glaciers with small slope do not display low $db/dz_{abl}$ gradients during this period.

#### 5.2.2.5 Period 4 (1986-1994)

*Temperature and days with melt evolution (Figure 56):* temperature and days with melt continue to substantially increase through the whole period (b) and (c). In the Austrian Alps, the temperature are rather constant until 1990 and start increasing then (a).

*Precipitation evolution (Figure 57):* the precipitation seem to undergo a decrease at the beginning of the period (a) (b). The mean precipitation change for Northern Latitudes show an increase/decrease from the late 1980s until the end of the period (a) whereas data from the Alpine region suggest a rather constant trend, potentially increasing at the end (b).

*Radiation evolution (Figure 58):* solar radiation show an increasing phase since the mid-1980s (a) and (b). This period is known as the "global brightening" (*Wild et al., 2005, Ohmura et al., 2007*).

*Interpretation:* this period is marked by a synchronous and rapid increase of all gradients. Annual gradients start to increase since the mid-1980s already but the increasing behavior is captured by the running mean only since the late-1980s. This steepening phase do not seem to be related to precipitation variations. Instead, the simultaneous and marked increase in global radiation combined with increase air temperatures seems to explain the clear increase in all gradients. These two climatic parameter certainly trigger higher glacier melt and a substantial increase in ablation rates. Due to the very synchronous increase, $db/dz_{acc}$ are probably also affected by the observed increase in radiation and temperature, suggesting that the *ELA* is probably > $ELA_0$ for most of the glaciers.

*Classified glaciers*: the increase in all gradients is captured by glaciers of all continentality. Transitional-type glaciers show the most marked $db/dz_{abl}$ increase but the weakest $db/dz_{acc}$ steepening. In addition, their $db/dz_{gw}$ starts increasing a few years later comparing to maritime glaciers. Glaciers from high latitude, *Arctic Canada North* and short glaciers have a much stronger and earlier $db/dz_{abl}$ and $db/dz_{gw}$ steepening phase. In opposition, glaciers with high length/area ratio do not show any $db/dz_{abl}$ and $db/dz_{gw}$ steepening phase as well as small slope glaciers for $db/dz_{acc}$. Steep slope glaciers show a contrasting decreasing $db/dz_{gw}$ trend during the period. Glaciers with small mean $db/dz_{gw}$ do no show an increase in $db/dz_{abl}$ during this period. The steepening gradient phase do not concern the $db/dz_{acc}$ of low minimal elevation glaciers from Scandinavia. The $db/dz_{acc}$ of short glaciers, glaciers with large area, low length/area ratio and small slope also do not steepen during this period. Glaciers classified according to their mean $db/dz_{gw}$ all show a very synchronous steepening phase in $db/dz_{acc}$.

#### 5.2.2.6 Period 5 (1995-2011)

*Temperature and days with melt evolution (Figure 56):* temperature and days with melt continue their increase over the whole period 5 (a) and (b). There seem to be a sharp increase in the late 1990s, followed by a more moderate increase (c).

*Precipitation evolution (Figure 57):* precipitation data do not cover the whole period. They display rather constant values until the early 2000s.

*Radiation evolution (Figure 58):* similarly to temperature and days with melt, solar radiation seems to continue its increase over the period (b). There is a pronounced rapid radiation increase in Europe in the early 2000s.

*Interpretation:* if the period 5.2 (Figure 55) influenced by extreme negative gradients in the year 2004) is not taken into account, the period 5 display slightly increasing or more or less constant gradients. Therefore, the increasing trend in temperature and radiation is not well correlated with gradient evolution. The stronger glacier melt signal and therefore steeper gradient that should normally result during this period might be cancelled due to *i)* a proportional snowfall amount decrease (see chapter 5.2.1.1), *ii)* by the fact that gradients might have reached a "plateau" state and cannot increase more, *iii)* because glaciers are losing their accumulation area and feedback mechanisms are at work or *iv)* by other changes inside the climate system. Note that glaciers often undergo an increase or decrease in gradients during this period but it is not visible in the mean evolution curves results due to the averaging process (see paragraph below about classified glaciers).

The period 5 also displays the highest gradients over the total analyzed period. This is certainly the result of the warm air temperature triggering stronger glacier melt. As a consequence, all gradients are steeper, even $db/dz_{acc}$ because the *ELA* is probably above the $ELA_0$. A warming-induced increase in accumulation rates during this period could also participate to the steeper gradient values but cannot be proven here.

*Classified glaciers:* all gradients of continental and transitional glaciers are roughly steepening (confirmed by small and medium mean $db/dz_{gw}$ glaciers - except for $db/dz_{abl}$). In opposition, maritime glaciers (confirmed by glaciers with large $db/dz_{gw}$) show constant or even decreasing gradient trends during this period. Glaciers from *Asia* show a particularly strong steepening trend in $db/dz_{gw}$ until almost the end of the period (their two other gradients also steepen). High latitude glaciers show very different evolution patterns: their $db/dz_{abl}$ is strongly decreasing until 2010 but their $db/dz_{acc}$ undergo a pronounced increase. In Scandinavia, glaciers at low minimal elevation show a marked

$db/dz_{acc}$ decreasing but an increase for glaciers at higher minimal elevation. Glaciers with a high elevation coverage of their upper half area display a steepening trend in all gradients.

#### 5.2.2.7 Period 6 (2012-2017)

*Temperature evolution (Figure 56)*: air temperature continues its strong increase (d).

*Precipitation evolution (Figure 57)*: no reliable mean precipitation data series was found.

*Radiation evolution (Figure 58)*: shortwave radiation also continues its increase (b).

*Interpretation*: the evolution of $db/dz_{acc}$ is rather constant and the values are similar than during the end of the previous period. In contrary, $db/dz_{abl}$ and $db/dz_{gw}$ clearly decrease over the period and their values pass below the mean relative gradients over the total period. In the most recent years, the values are even lower than in the early 1970s. This observation doesn't seem to be explained by temperature or radiation, which increase during the period. This could theoretically be triggered by lower snowfall but it doesn't appear to be the case as $db/dz_{acc}$ are constant. Therefore, this decrease is currently unexplainable with the available climatic data and could be due for example to mechanisms related to glacier dynamics or other processes.

*Classified glaciers*: the decreasing trend in $db/dz_{gw}$ and $db/dz_{abl}$ particularly concerns maritime glaciers. On the opposite, glaciers from high latitude do not show a decrease in these gradients. $db/dz_{acc}$ of high latitude glaciers is not constant but is steepening and are decreasing for maritime glaciers and Scandinavian glaciers. Glaciers from Central Europe have a high agreement with the observed mean gradients evolution, independently of their minimal elevation. $db/dz_{gw}$ and $db/dz_{acc}$ of glaciers with small mean $db/dz_{gw}$ are much higher than the ones of glaciers with larger mean $db/dz_{gw}$.

#### 5.2.2.8 Summary

As stated by *Huss et al.* (2009) and also observed in the present analysis with mass balance gradients, the effect of decadal changes in solar radiation can significantly alter the relationship between glacier melt and air temperature. For example, the steepening phase in all gradients starting in the mid-1980s shows a synchronous timing with the beginning of the "global brightening" phase when solar radiation are observed to increase in Europe and Scandinavia. Temperatures are also increasing during this period, certainly participating to the gradient steepening, but they do not seem to trigger the gradient steepening. Indeed, they globally start to increase earlier (late-1970s and early 1980s) and cause no gradient steepening except for the $db/dz_{abl}$ of high latitude glaciers.

The observed steepening phase marks a clear shift from lower gradients before to steeper gradients afterwards that are well in line with the warmer air temperature conditions. Solar radiation has

similar levels (or is even potentially higher) in the 1970s and after the gradient steepening phase (mid-1990s until 2011), whereas gradients are much steeper in the second period. The steep gradient situation seems then to be better related to the warmer air temperature situation. Air temperature generally showed great agreement with the mass balance gradient evolutions, sometimes explaining mass balance gradients better than solar radiation. What is more, it must be mentioned that the increase in solar radiation from the mid-1980s concerns Europe and Scandinavia and therefore strongly influence the analyzed gradients because most of the selected glaciers are from these regions.

The roughly constant (or slightly increasing) gradient situation detected from the mid-1990s until 2011 do not show a high agreement with the air temperature and solar radiation evolution which undergo a pronounced increase. Nevertheless, it is important to mention that high latitude glaciers and glaciers from *Asia* show an increase in all gradients during this period (except for $db/dz_{acc}$ of high latitude glaciers). In opposition, maritime glaciers and Scandinavian glaciers located at low minimal elevation are the ones showing constant or decreasing gradients. Therefore, the different climatic environments of the glaciers seem to create different response to the air temperature and solar radiation signals.

The variations in these two climatic variables is also not able to explain the recent decreasing trend in $db/dz_{gw}$ and $db/dz_{abl}$ since approx. 2010 until present because air temperature and solar radiation are increasing. This enigmatic situation raises the hypothesis that some processes in recent years significantly influence the relationship between mass balance gradients and climate. These processes could be related to the accelerating glacier decline causing substantial ice loss, a strong decrease of accumulation area and decrease in overall albedo due to a prolonged ablation season (*Hock, 2005*). Strong changes in glacier mass balance affect glacier dynamics and can cause positive feedback mechanisms. In addition, changes in the climate system affecting atmospheric circulation patterns (*Meier et al., 2003*) are not to be excluded.

When the glacier mass balance situation is high (like during the 1970s and early-1980s), precipitation evolution seem to be able to explain the observed (lack of) variations in $db/dz_{acc}$ and even $db/dz_{gw}$. For example, a (potentially warming-induced) increase in accumulation rates seem to trigger higher $db/dz_{acc}$ and $db/dz_{gw}$ in the late-1970s. Unfortunately, it is hard to estimate the precipitation influence on the gradients in the most recent years as *i)* the *ELA* of most glaciers is certainly above the $ELA_0$, causing $db/dz_{acc}$ to be strongly influenced by the variations in glacier melt and *ii)* insufficient precipitation data are available.

### 5.2.3 Evolution Differences of Classified Glaciers over the Period

Hereafter, some important results about the evolution of gradients over the total period from glaciers classified according to climatic (5.2.3.1) and geometric (5.2.3.2) parameters are discussed.

#### 5.2.3.1 Influence of Climatic Parameters

**Continental vs Maritime Glaciers**

The $db/dz_{gw}$ evolution of continental glaciers (i.e. glaciers classified as continental and with small $db/dz_{gw}$) is very interesting as it shows a rather long, continuous and quasi linear steepening trend of $db/dz_{gw}$ since the late-1970s until recent years. This evolution corresponds well to the $db/dz_{abl}$[38] and $db/dz_{acc}$ evolution throughout the whole period of analysis. The start of the steepening in gradients is synchronous with a global air temperature and precipitation increasing trend. This result is in favor of the hypothesis that for continental glaciers, a long-term warming- induced increase in accumulation rates could participate to the observed mass balance gradient steepening.

In the opposite, maritime glaciers (particularly glaciers with large $db/dz_{gw}$) shows a shorter steepening phase of $db/dz_{abl}$ and $db/dz_{gw}$ that is also starting later in time (in the mid-1980s), apparently reacting to the observed global increase in solar radiation. In addition, they show no special evolution patterns of their $db/dz_{acc}$ during the total period of analysis except a decreasing and low trend in the last decade. This effect is especially well shown by the decreasing $db/dz_{acc}$ trend of lower minimal elevation (i.e. more maritime glaciers) in Scandinavia. It might be due to the fact that a greater fraction of precipitation fall as rain instead of snow at lower elevation and thus a reduction in accumulation rates are decreasing $db/dz_{acc}$.

In addition, continental glaciers (confirmed by glaciers with small $db/dz_{gw}$) display much lower $db/dz_{gw}$ gradient values until the early/mid-1980s and significantly higher values after the steepening phase compared to the other glaciers. The high magnitude and continuous signal of the increase in $db/dz_{gw}$ clearly hints for a climate regime shift in the continental environments of glaciers.

**High Latitude Glaciers and the Arctic Amplification**

The evolution of $db/dz_{gw}$ and $db/dz_{acc}$ from continental glaciers described above is particularly characteristic of high latitude glaciers, all located in the Arctic Circle. These glaciers display a similar continuous increasing trend in these gradients since as soon as the early/mid-1970s (whereas it was more in the late-1970s for continental glaciers) until present. These observations suggests the hypothesis of a long-term increase in accumulation rate causing gradient steepening in the Arctic.

[38] It is true for glaciers classified as continental but not really for glaciers with small mean $db/dz_{gw}$.

In this direction, the study of *Førland and Hanssen-Bauer* (*2001*) conducted for the *Svalbard and Jan Mayen* region detected an increase in precipitation of +25% approx. during the 20th century.

In addition, $db/dz_{gw}$ seem to strongly react to the $db/dz_{abl}$ steepening phase starting in the late-1970s. This phase is synchronous with the increase in summer air temperature mean in the Northern Hemisphere but also to an increase in precipitation detected in Northern Latitudes. As a result, the $db/dz_{abl}$ and $db/dz_{gw}$ of high latitude glaciers starts to steepen at least 5 years earlier than the other glaciers undergoing their steepening phase simultaneously to the global increase in radiation from the mid-1980s. It is probably the result of the so-called "Arctic amplification" effect, indicating that the arctic warms faster than the global average since the mid-20th century (*Serreze and Francis, 2006*). As shown in Figure 59, higher latitudes undergo a rise in annual mean surface air temperature as soon as in the late-1960s whereas it only increases in the late-1970s when lower latitudes are taken into account.

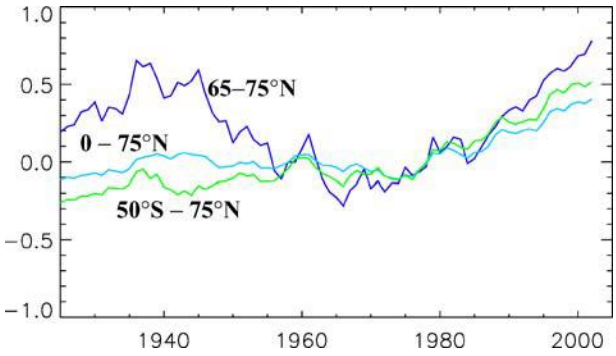



**Figure 59 :** Anomalies in annual mean SAT (deg. C) versus time in three zonal bands (both land and ocean, but there are no data from over the Arctic Ocean) smoothed with 5-year box-car filter. Data are from *Jones et al. (2003)*, available at http://www.cru.uea.ac.uk/cru/data/temperature/. Figure is from *Serreze and Francis, 2006*.

Moreover, the sea-ice extend over the arctic is drastically reducing since the 1970s, simultaneously with air the temperature warming in the Arctic (*Serreze and Francis, 2006*), creating a positive ice-albedo feedback and so contributing to the Arctic warming amplification.

Since 2000, the increasing trend in $db/dz_{gw}$ is well correlated with the $db/dz_{acc}$ increase but not at all with $db/dz_{abl}$, indicating that in recent years, increased accumulation rates could cause the relatively high $db/dz_{gw}$ observed for arctic glaciers.

Arctic glaciers are located so far away from the other ones and in a very different environment that the climate change signal appears to be of different magnitude and shifted in time. In addition, slightly higher summer temperatures melting sea ice could mark a tipping point in the Arctic climate with more extratropical cyclones and an increase in precipitation (*Braithwaite, 2005*). Therefore, it is probable that mass balance gradients of Arctic glaciers continue steepening in the future.

### 5.2.3.2 Influence of Geometric Parameters

**Adjacent Glaciers with Different Hypsometry**

The elevation coverage of the upper half area used as a parameter relating for the glacier's hypsometry in the present study may too much simplify the distribution of area with elevation. Indeed, the gradient of glaciers classified according to this parameter didn't differ much, except for glaciers with a small elevation coverage of their upper half area. These glaciers did not show any special $db/dz_{acc}$ evolution trend during the analyzed period whereas the ones with a large parameter display clear periods of low and high gradients. It can be explained by the important elevation coverage of the accumulation area, allowing a better detection of mass balance change with elevation in this zone.

Glacier's hypsometry is known to play an important role on climate sensitivity (*Oerlemans, 2001*). As a concrete example, Urumqi Glacier E and Urumqi Glacier W, two adjacent glaciers[39] of similar size, area and elevation coverage, show completely different gradient changes over their analyzed period (1989-2016) (see Annex 18). While $db/dz_{abl}$ and $db/dz_{gw}$ of Urumqi Glacier E show no particular evolution trend and $db/dz_{acc}$ undergo a +37% increase, $db/dz_{abl}$ of Urumqi Glacier W increases, $db/dz_{gw}$ decreases and $db/dz_{acc}$ show a very contrasted decrease of -70%. Certainly, it is not a different climatic signal causing these unequal long-term glacier changes. Interestingly, the hypsometry of these two glaciers are significantly different as shown in Figure 60 (*WGMS, 2017*).

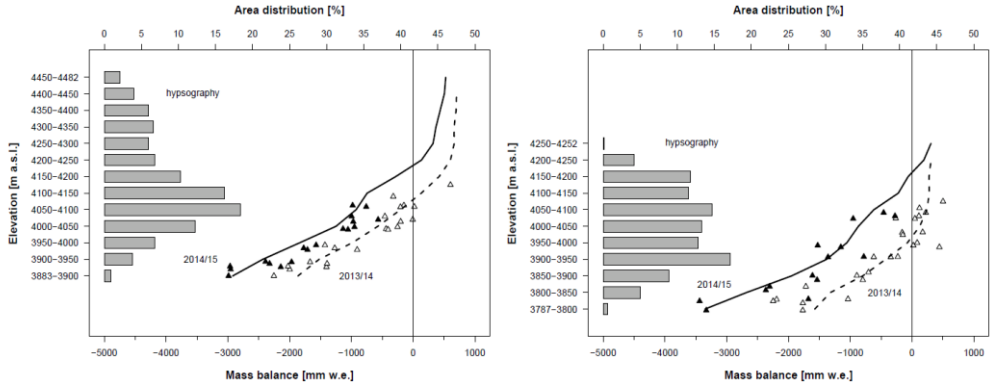



**Figure 60 :** area distribution per elevation bands (i.e. hypsometry or hypsography) of Urumqui Glacier W (left) and Urumqi Glacier E (right) as well as their balance profiles for the years 2013/2014 (dotted) and 2014/2015 (solid) (*WGMS, 2017*).

Their different evolution could be explained by effects of dissimilar geometries. The very different trend in the evolution of $db/dz_{acc}$ between the two glaciers could have been caused by the fact that in warmer years (here 2014/2015), $db/dz_{acc}$ gets much steeper on Urumqi Glacier E because more

[39] They were formerly part of the same glacier (Urumqi S. No 1) before their retreat separated them into two branches (*WGMS, 2017*)

melt is observed at higher elevations than on Urumqi Glacier W. This effect can be due to the important area coverage at these elevations.

In addition, *Kuhn et al.* (*1985*) found that Kesselwandferner and Hintereisferner, two adjacent glaciers selected in the present study, also show different mass balance responses to climatic variations. They attribute this observation to the two different glacier hypsometry, to topography effects and different dynamic response times. Kesselwandferner has a relatively large, plateau-like accumulation area allowing much snow accumulation and a steep tongue. Therefore, it also has steeper gradients than Hintereisferner which has a smaller mass turnover. The present study showed that these two adjacent glaciers indeed showed very different gradient evolution patterns through their common period of analysis (1967-2017) (see chapters 4.1.1.1 and 4.1.1.2). Hintereisferner shows a strong steepening phase of its $db/dz_{abl}$ and $db/dz_{gw}$ starting in the mid-1980s like many analyzed glaciers while Kesselwandferner has no reaction during this period. On the opposite, Kesselwandferner shows a pronounced steepening phase in all gradient since the mid-2000s until present for $db/dz_{acc}$, probably due to the important size at high altitude of its accumulation area.

The present study also analyzed other adjacent glaciers like Schwarzberg and Allalin, Maliy Aktru and Vodopadniy, Rabots Glaciaer and Storglaciaeren as well as Midre Lovenbreen and Austre Broeggerbreen. The present study found that the gradient evolution is particularly different for Schwarzberg and Allalin but less for the other adjacent glaciers (see Annex 18). Further analysis on their hypsometry and the interaction between climate variations and mass balance gradient changes could be interesting.

### The High Sensitivity of Short Glaciers

It has been observed that short glaciers show a $db/dz_{abl}$ and $db/dz_{gw}$ amplified evolution pattern as compared to the glaciers with longer lengths (i.e, the gradients are very high at the beginning of the period, very low in the 1980s and increase very sharply since the mid-1980s, are relatively high then and again lower in recent years). What is more, $db/dz_{acc}$ are particularly high from the late 1970s until the mid/late-1980s, a period of positive mass balances (e.g. *Huss et al., 2008*). In fact, it is known that short glaciers have shorter response times and reach equilibrium after a mass balance forcing in only a few years (*Kirkbride and Winkler, 2012*). Mass balance gradients changes are therefore quicker and respond well to inter-annual meteorological changes on short glaciers. Apparently this sensitivity is also well present over multi-decadal time scale, relating climate changes. What is more, their $db/dz_{gw}$ seems better correlated to the accelerating worldwide glacier decline as they are decreasing since the early 2000s already.

### The Strong Effect of Slope

The geometric parameter creating the biggest evolution differences amongst glaciers is the slope, where the effect is particularly strong for $db/dz_{abl}$ (it is also well marked for $db/dz_{gw}$ and present for $db/dz_{acc}$). In fact, small slope glaciers do not share particular increasing or decreasing trends of $db/dz_{abl}$ during the period, whereas steep slope glaciers show an amplified evolution as compared to the reference evolution curve. It is known that steeper glaciers typically have shorter response times (*Haeberli, 1995*). Therefore, flatter glaciers do not seem to translate changes in long-term climatic condition through their mass balance gradients. It is probably due to the fact that *i)* a minimum glacier steepness (creating a certain altitudinal difference) is needed to detect mass balance change with elevation and *ii)* steep glaciers are in general more sensitive to change in air temperature and precipitation than flatter glaciers (*Haeberli, 1995*). Therefore, small slope glaciers are not very well suited for studying the interaction between mass balance gradients and climate change because changes in mass balance occur too slowly with distance (*Bahr et al., 1998*).

### High Length/Area Ratio and Ablation Gradients

Interestingly, glaciers with high length/area ratio (i.e. "longer" glaciers for a given area) poorly showed any clear $db/dz_{abl}$ evolution trend during the analyzed period. In fact, the results are in opposition with the expectation that "longer" glaciers theoretically extend further down (like valley-type glaciers) and thus are more subject to glacier melt because they are exposed to warmer air temperatures.

## 5.2.4 Comparison with B, AAR and ELA Evolution

In order to better understand the link between the mass balance gradients evolution with other climatically-related glacier variables and potentially explaining some unresolved evolution patterns, the three relative gradient evolution curves are compared to the evolution of the annual glacier-wide balance *B*, Accumulation-Area ratio (*AAR*)[40] and *ELA* evolution. The data used for this analysis cover the same years and glaciers taken into account for the gradient evolution curves (see Annexes 7.1, 7.2 and 7.3) and are the annual averages of the three parameters are found in Annexes 19. They are downloaded from the WGMS database (*2017*). Note that *ELA* is expressed here as the altitude difference between the *ELA* and the $ELA_0$ for each glacier in order to allow comparison between glaciers[41].

[40] The ratio, or percentage, of the accumulation area to the glacier-wide area (*Cogley et al., 2011*).
[41] Positive *ELA* numbers indicate that the *ELA* is higher than the $ELA_0$ and negative number indicate that the *ELA* is lower than the $ELA_0$.

*B*, *AAR* and *ELA* are usually proxies from one another. Indeed, the likelihood that *B* will be positive increases with higher *AAR* (*Cogley et al., 2011*), and logically, the bigger the accumulation area is, the lower the *ELA* should be. The observed correlation *r* is -0.85 between the calculated *B* and *ELA*, 0.92 between *B* and *AAR* and -0.93 between *ELA* and *AAR*. Figure 61 shows the evolution of these parameters in comparison with the relative evolution curves of the three gradients.

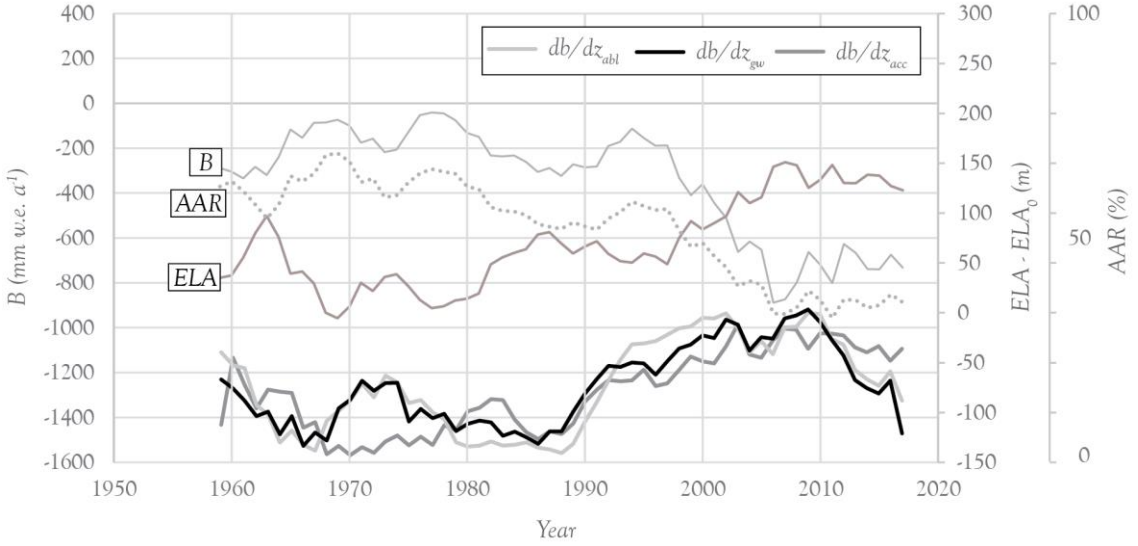



**Figure 61:** evolution of *B*, *AAR* and *ELA* (data from *WGMS, 2017*) in comparison with the relative evolution curves of the three gradients. The annual parameters values are taken only for the same glaciers and years from which the annual relative mass balance gradients have been calculated.

Similar to the results of *Dyurgerov and Meier* (*2005*) for numerous glaciers worldwide, *B* and *AAR* undergo a marked decrease at the end of the 1970s and another stronger decrease in the early/mid-1990s corresponding to a clear shift towards an acceleration in mass loss related to unusually high mean temperature during these years. *Huss et al.* (*2008*) also found a pronounced trend of mass balance decrease starting in the late-1980s for four Swiss glaciers (that part of the studied 49 glaciers). In addition, the *AAR*, and therefore *B*, increase for a short period in the late-1980s and early-1990s according to the present study.

Interestingly the timing of *db/dz* steepening phase in the mid-1980s until the late-1990s do not corresponds to a period of marked changes in *B*, *AAR* or *ELA* as calculated here. Nevertheless, *Dyurgerov and Meier* (*2005*), observed a glacier global volume shift towards accelerating wastage starting exactly in the mid-1980s, similar to the *db/dz* shift. Starting at the same time, *Meier et al.* (*2003*) also observed a global pronounced increase in global annual net balance and glacier mass turnover, reflected in the increase of both winter balance and summer balance. The observed results raise the hypothesis that mass balance gradients of glaciers could start steepening in the mid-1980s

not only as a result of solar radiation increase combined with increasing air temperature, but also due to an increase in solid precipitation, as witnessed by increasing winter balance.

If there is a link between *db/dz* and *B*, *ELA* and *AAR*, it could be shifted in time. Then, the observed steepening in gradients could result either from the decreasing negative *B* and *AAR* trend at the end of the 1970s until 1990 or could precede the subsequent strong negative *B* and drop in *AAR* starting around the early/mid-1990s. It is also possible that the observed different shifting timings are related to feedback mechanisms due to area and shape changes and different response time linked to ice dynamic processes amongst glaciers. It is known that all glaciers do not respond synchronously and identically to a climate forcing (e.g. *Oerlemans, 2001*) and this could explain the observed temporal shifts.

Another interesting point is that since approx. 2010, *B*, *AAR*, *ELA* and $db/dz_{acc}$ are rather stable but $db/dz_{gw}$ and $db/dz_{abl}$ undergo a clear decrease. A trend towards less negative ablation rates in the lower part of the glaciers could be the cause of decreasing $db/dz_{gw}$ and $db/dz_{abl}$. Nevertheless, this result remains quite enigmatic as global air temperature are known to be rising.

Concerning more methodological considerations, the evolution of *ELA* is significantly correlated to the one of $db/dz_{acc}$ ($r$ = 0.44) meaning that when the *ELA* rises, then $db/dz_{acc}$ steepens. This is probably due to the fact that a larger part of the lower $db/dz_{acc}$ profile lies in the accumulation zone and thus the mass balance values are more negative. Nevertheless, the evolution results from $db/dz_{gw}$ (methodologically independent from the *ELA* position) argue that the evolution of $db/dz_{acc}$ is not only an artefact relating for the evolution of the *ELA* (see chapter 5.1.1.4).

# 6 Conclusion

## 6.1 Summary and Perspectives

In the context of glacier-climate interactions, the present work analyzed the evolution of the mass balance gradients of 49 different glaciers during the last decades (1954-2017). The annual ablation $db/dz_{abl}$, glacier-wide $db/dz_{gw}$ and accumulation $db/dz_{acc}$ gradients of these glaciers were first calculated in absolute values (m w.e. $(100m)^{-1}$). With these data, the first research question motivating the analysis was:

> **What is the individual evolution of the annual absolute mass balance gradients for each of the 49 selected glaciers over the period 1954-2017?**

For the three gradients, the evolution curves and linear evolution trends were analyzed for each of the 49 glacier individually. The glaciers showed a rather high degree of heterogeneity of their individual evolutions. The biggest total change over the period for the 30 glaciers with the longest data coverage could be quantified to +25% for the last 50 years and concerns $db/dz_{acc}$. $db/dz_{abl}$ and $db/dz_{gw}$ are also getting steeper with an increase of +10% and +14% respectively. The observed steepening in gradients are the result of a consensus between glaciers for $db/dz_{abl}$ (73% of the 30 glaciers) and $db/dz_{gw}$ (77%) but relates more for the central tendency of a variable dataset for $db/dz_{acc}$ (60%). The analysis of the correlation between the gradients showed that $db/dz_{gw}$ is significantly correlated with the two other gradients most of the time whereas $db/dz_{abl}$ and $db/dz_{acc}$ do not evolve similarly, confirming that they are controlled by different processes (i.e. glacier melt and snowfall respectively).

From these absolute gradients, the annual mass balance gradients of each glacier were also expressed relatively to the standard deviation of their observed mean $db/dz$ value over the period to smooth their inter-annual variability. This procedure allowed a synthetic evolution as well as a comparison of glaciers classified according to different climatic, geometric and gradient-related parameters. The research question driving the second part of the present work was:

**What is the mean evolution curve of the annual relative mass balance gradients for the 49 selected glaciers and for classified glaciers over the period 1954-2017?**

The three mass balance gradients showed rather similar evolution patterns over the period. The observed non-linear evolution clearly captures smaller gradients at the beginning of the period and steeper gradients in recent years. These two periods are separated by a strong steepening phase starting in the mid-1980s and ending in the mid-1990s which mainly concerns maritime and transitional glaciers. This increase is simultaneous to the beginning of the enhanced solar radiation in the Alps and Scandinavia (i.e. the so-called global brightening phase (*Wild et al., 2005*)). This increase is combined but not triggered by increasing air temperature. It also coincides with the beginning of an accelerating mass loss of glaciers worldwide (*WGMS, 2017*). This observation confirmed that decadal changes in solar radiation can significantly alter the relationship between glacier melt and air temperature (*Huss et al., 2009*).

The $db/dz_{gw}$ steepening of continental glaciers started earlier and is quasi-linear since the late-1970s until recent years. This observation corresponds well with the two other gradient evolution and seems to be triggered by increasing global air temperature and precipitation. A similar evolution in $db/dz_{gw}$ and $db/dz_{acc}$ was observed for high latitude glaciers since as soon as the early/mid-1970s, synchronously to rising air temperature in the Arctic. This earlier steepening in gradients is probably due to the Arctic Amplification phenomenon and might have a link with a decrease in sea-ice extend. These results support the hypothesis that for continental (particularly *Asian* glaciers) and Arctic glaciers, a long-term warming induced increase in accumulation rates could participate to the observed mass balance gradient steepening. In addition, the high magnitude and continuous signal of the increase in $db/dz_{gw}$ clearly hints for a climate regime shift towards more maritime conditions in the continental and Arctic environments of glaciers.

The relatively high gradient situation since approximatively two decades are well related to the warm air temperature. Glaciers from high latitude and from *Asia* show a steepening in their gradients in line with the air temperature and solar radiation increase but maritime and particularly Scandinavian glaciers at low Elevations show decreasing gradients. Since 2012, maritime glaciers have an enigmatic marked decrease in $db/dz_{gw}$ and $db/dz_{abl}$ whereas high latitude glaciers show increasing gradients in line with the current warming. Therefore, it was observed that the mass balance gradient response to climatic signals differs according to the climatic environments of glaciers.

Small slope glaciers and short glaciers showed the most different evolution patterns in their gradients. Differences in hypsometry can also cause completely different mass balance gradient

evolutions as witnessed by Urumqi Glacier E and Urumqi Glacier W as well as Hintereisferner and Kesselwandferner (as already detected by *Kuhn et al., 1985*). These adjacent glaciers undergoing the same climatic signals showed a divergent short, middle and long-term evolution of their mass balance gradients. Therefore, individual geometric glacier characteristics can also significantly alter the relationship between mass balance gradient evolution and climate change.

These results explain the observed high heterogeneity of gradient evolution between individual glaciers and underline the fact that a great number of glaciers must be considered when the interaction between mass balance gradients and climate change is studied. It is was also observed that small slope glaciers are not very suited for studying this interaction.

Overall, the present work clearly confirmed the premise that mass balance gradients change when environmental parameters change (*Oerlemans and Hoogendoorn, 1989*). The gradients showed important inter-annual variability but also clear evolution trends that could be linked to variations in global radiation, air temperature or precipitation. This result is somehow contradictory with certain studies (e.g. *Rasmussen and Andreassen, 2005*) postulating that *db/dz* varies little from year to year in Norway but are more in line with studies from *Oerlemans and Hoogendoorn* (*1989*) or *Dyurgerov and Dwyer* (*2000*) who found steeper gradients in warm years.

Glacier-climate interactions are complex and therefore the interpretation of this work are subject to debate and should be complemented by further analysis. What is more, the glacier sample is particularly biased towards European and Scandinavian glaciers (Northern Hemisphere glaciers in general). In addition, the observed evolution differences between classified glaciers may be well influenced by the small number of glaciers in the classes. Considering the high heterogeneity in the gradient evolution of individual glaciers, the conclusions of this work (particularly about classified glaciers) might not always be accurate or even true. It would be interesting to consider a greater number of glaciers to further analyze the differences in the evolution of mass balance gradients for glaciers with different climatic or geometric parameters.

What is more, the observed high sensitivity of mass balance gradients to environmental parameters changes reminds that a better understanding of this relationship is important, particularly in the current context of climate change and given the implications of mass balance gradients for glacier dynamics and climate sensitivity. In consequence, the quality of future glacier melt scenarios, essential for climate change adaptation, can be improved. This task seems quite urgent given the ongoing accelerating negative mass balances, associated ice loss situation and the positive feedback mechanisms. Future works should study if mass balance gradients will continue steepening in the future, at which rate and with which consequences for the glaciers.

## 6.2 Key Findings

*i.* The observed mass balance gradients show important inter-annual variability and also pronounced decadal and multi-decadal variations, witnessing both annual meteorological conditions and climate change signals.

*ii.* The selected glaciers witness a median increasing trend of their ablation (+10%), glacier-wide (+14%) and accumulation gradients (+25%) over the analysed period.

*iii.* The observed steepening is marked by a clear and rapid shift from lower to higher gradients between the mid-1980s and the mid-1990s for maritime and transitional glaciers. It seems to be triggered by increasing solar radiation and is combined with rising air temperatures.

*iv.* Continental, high latitude (Arctic) and *Asian* glaciers have an earlier starting (in the 1970s), longer and continuous steepening in glacier-wide and accumulation gradients that seems to be triggered by warming air temperatures. Therefore, a long-term warming induced increase in accumulation rates could participate to their glacier-wide gradient steepening.

*v.* A climate regime shift in continental environments towards more maritime conditions is witnessed by much steeper gradients since two decades.

*vi.* The observed important evolution differences between continental and maritime glaciers suggests that the evolution of mass balance gradient is dependent on the climatic environment of glaciers.

*vii.* Glaciers with different geometric parameters, particularly glaciers with different hypsometry and slope showed contrasted evolutions of their mass balance gradients.

# 7 References


Arendt, A., et al. (2012). Randolph Glacier Inventory: A Dataset of Global Glacier Outlines, version 2.0, digital media, http://www.glims.org/RGI/RGI_Tech_Report_V2.0.pdf, Global Land Ice Measure from Space, Boulder, Colorado.

Abermann, J., Kuhn, M and Fischer, A. (2011). Climatic controls of glacier distribution and glacier changes in Austria, Ann. Glaciol., 52, 83–90.

Anderson, B., Mackintosh, A., Stumm, D., George, L., Kerr, T., Winter-Billington, A., and Fitzsimons, S. (2010). Climate sensitivity of a high precipitation glacier in New Zealand, J. Glaciology, 56, 114–128, doi:10.3189/002214310791190929.

Bahr, D.B., Pfeffer, W.T., Sassolas, C. and Meier, M.F. (1998). Response time of glaciers as a function of size and mass balance: 1. Theory. Journal of Geophysical Research: Solid Earth 103, 9777-9782.

Barnett, T.P., Adam, J.C. and Lettenmaier, D.P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. Nature, 438(17), 303–309.

Beniston, M. (2005). Climate change and its possible impacts in the Alpine region. In Global change impacts in mountain biosphere reserves. UNESCO.

Benn, D. I. and Evans, D. J. A. (2010). Glaciers and glaciation. Hodder Education, London.

Bojinski, S., Verstraete, M., Peterson, T.C., Richter, C., Simmons, A. and Zemp, M. (2014). The concept of Essential Climate Variables in support of climate research, applications, and policy. Bull. Am. Meteorol. Soc., 95(9), 1431–1443 (doi: 10.1175/BAMS-D-13-00047.

Bolch, T; Peters, J; Yegorov, A; Pradhan, B; Buchroithner, M; Blagoveshchensky, V. (2011). Identification of potentially dangerous glacial lakes in the northern Tien Shan. Natural Hazard, 59(3):1691-1714. DOI: https://doi.org/10.1007/s11069-011-9860-2.

Braithwaite, R.J. (2005). Mass-balance characteristics of arctic glaciers. Annals of Glaciology 42, 225-229, ISSN 0260-3055.

Braithwaite, R.J. (2011). Why Do We Expect Glacier Melting to Increase Under Global Warming?, Climate Change - Geophysical Foundations and Ecological Effects, Dr Juan Blanco (Ed.), InTech, DOI: 10.5772/25278.

Braithwaite, R.J. (1981). On glacier energy balance, ablation and air temperature. Journal of Glaciology 27, 381–91.

Braithwaite, R. J., and Olesen, O. B. (1989). Calculations of glacier ablation from air temperature, West Greenland. In Oerlemans, J. (ed.), Glacier Fluctuations and Climatic Change. Dordrecht: Kluwer Academic Publishers, pp. 219–233.

Braun, L. N. and Hagg, W. (2009). Present and future impact of snow cover and glaciers on runoff from mountain regions - comparison between Alps and Tien Shan. Assess. Snow Glacier Water Resources Asia 8, 36–43.

Clague J.J. and Evans S.G. (2000). A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quat Sci Rev 19:1763–1783.

Cogley, J. (2012). The future of the world's glaciers, in The Future of the World's Climate, edited by A. Henderson-Sellers and K. McGuffie, pp. 197–222, Elsevier, Waltham, Mass.

Cogley J.G. and 10 others. (2011). Glossary of glacier mass balance and related terms. UNESCO–International Hydrological Programme, Paris (IHP-VII Technical Documents in Hydrology 86).

Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther (2013): Introduction. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cuffey, K.M. and W.S.B. Paterson (2010). The Physics of Glaciers, Fourth Edition. Elsevier, 693 pp.

Cullen, N., Anderson, B., Sirguey, P., Stumm, D., Mackintosh, A., Conway, J. P., Horgan, H. J., Dadic, R., Fitzsimons, S. J., and Lorrey, A. (2016). An eleven-year record of mass balance of Brewster Glacier, New Zealand, determined using a geostatistical approach, J. Glaciology.

Dobhal, D.P. (2011) Glacier, in *Encyclopedia of Snow, Ice and Glaciers.* Springer, The Netherlands, Vijay P. S., Pratap S. and Umesh K. H.: 376.

Dyurgerov, M. B.. and Meier, M. F. (2005). Glaciers and the changing earth system: a 2004 snapshot. INSTAAR 15 Occasional Paper, 58: 117 pp.

Forel, F.A. (1895). Les variations périodiques des glaciers. Discours préliminaire. Arch. Sci. Phys. Nature, 34, 209–229

Førland E.J., Hanssen-Bauer I. (2001). Changes in Temperature and Precipitation in the Norwegian Arctic during the 20th Century. In: India M.B., Bonillo D.L. (eds) Detecting and Modelling Regional Climate Change. Springer, Berlin, Heidelberg.

Gardner, A. S., et al. (2013) A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. Science, 340, 852–857.

GISTEMP Team (2018). GISS Surface Temperature Analysis (GISTEMP). NASA Goddard Institute for Space Studies. Dataset accessed 20YY-MM-DD at data.giss.nasa.gov/gistemp/.

Grenfell, T.C. (2011). Albedo, in *Encyclopedia of Snow, Ice and Glaciers.* Springer, The Netherlands, Vijay P. S., Pratap S. and Umesh K. H.: 23.

Harris, C. and Murton, J. B. (eds) (2005). Cryospheric Systems: Glaciers and Permafrost. Geological Society, London, Special Publications, 242, 1-9.

Haeberli, W. (1995). Glacier fluctuations and climate change detection. Geogr. Fis. Dinam. Quat 18, 191-199.

Haeberli, W. (1998). Historical evolution and operational aspects of worldwide glacier monitoring. Into the second century of world glacier monitoring: prospects and strategies. UNESCO, Paris, 56: p. 35–51.

Haeberli, W., Cihlar, J. and Barry R.G. (2000). Glacier monitoring within the Global Climate Observing System. Ann. Glaciol., 31, 241–246.

Hansen, J., R. Ruedy, M. Sato, and K. Lo (2010). Global surface temperature change, Rev. Geophys., 48, RG4004, doi:10.1029/2010RG000345.

Hoelzle, M, Azisov, E., Barandun, M., Huss, M,, Farinotti, D., Gafurov, A., Hagg, W., Kenzhebaev, R., Kronenberg, M., Machguth, H., Merkushkin, A., Moldobekov, B., Petrov, M., Saks, T., Salzmann, N., Schöne, T., Tarasov, Y., Usubaliev, R., Vorogushyn, S., Yakovlev, A. and Zemp, M. (2017). Re-establishing glacier monitoring in Kyrgyzstan and Uzbekistan, Central Asia. Geosci. Instrum. Method. Data Syst., 6, 397–418.

Holmlund, P., and T. Schneider (1996), The effect of continentality on glacier response and mass balance, Ann. Glaciol., 24, 272–276.

Hooke, R. L. (2005). Principles of glacier mechanics. Cambridge university press.

Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R. S., Clague, J. J., ... and Mark, B. G. (2017). Toward mountains without permanent snow and ice. Earth's Future, 5(5), 418-435.

Huss, M., and Farinotti, D. (2012), Distributed ice thickness and volume of all glaciers around the globe, J. Geophys. Res., 117, F04010. https://doi.org/10.1029/2012JF002523.

Huss, M., M. Funk, and A. Ohmura. (2009). Strong Alpine glacier melt in the 1940s due to enhanced solar radiation, Geophys. Res. Lett., 36, L23501, doi:10.1029/2009GL040789.

Huss, M., and Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. Nature Climate Change, 8, 135-140.

Huss, M., Stöckli, R., Kappenberger, G. and Blatter, H. (2008). Temporal and spatial changes of Laika Glacier, Canadian Arctic, since 1959, inferred from satellite remote sensing and mass-balance modelling. Journal of Glaciology, 54 (188), 857-865.

IPCC (2014a). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

IPCC (2014b). Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

Jones, P. D. and Moberg, A.: 2003, 'Hemispheric and large scale surface air temperature variations:an extensive revision and an update to 2001', J. Climate 16, 206–223.

Kirkbride, M.P. and Winkler, S. (2012). Correlation of Late Quaternary moraines: impact of climate variability, glacier response, and chronological resolution. Quaternary Science Reviews 46, 1-29.

Klok, E.J. and Oerlemansm J. (2004). Modelled Climate Sensitivity of the mass balance of Morteratschgletscher and its dependence on albedo parametrization. Int. J. Climatol. 24, 231-245.

Krenke, A. N., and V. G. Khodakov. (1966). O svyazi poverkhnostnogc tayaniya lednikov s temperaturoy vozdukha (On the relationship of surface melt of glaciers with air temperature.) Materialy glyatsiologicheskikh issledovaniy (Data of glaciological studies), Khoronika obsuzhdeniya (Chronicle Discussions), No. 12, 153– 164.

Kuhn, M. (1981). Climate and glaciers. In Sea level, ice and climatic change (Proceedings of the Canberra Symposium, December 1979), volume 131 of IAHS Publ., 3–20

Kuhn, M., Markl, G., Kaser, G., Nickus, U. and Obleitner, F. (1985). Fluctuations of climate and mass balance. Different responses of two adjacent glaciers. Zeitschrift für Gletscherkunde und Glazialgeologie 2: p. 409–416.

Machguth, H. (2008). On the Use of RCM Data and Gridded Climatologies for Regional Scale Glacier Mass Balance Modeling in High Mountain Topography; The Example of the Swiss Alps. University of Zurich, Faculty of Science.

Machguth H., Cohen, D. (2016). Estimating the surface mass balance gradient of the Rhine Glacier at the Last Glacial Maximum. Aktennotiz AN 16-475, Nagra, Wettingen.

Machguth, H., Thomsen, H., Weidick, A., Ahlstrøm, A. P., Abermann, J., Andersen, M. L., Andersen, S., Bjørk, A. A., Box, J. E., Braithwaite, R. J., Bøggild, C. E., Citterio, M., Clement, P., Colgan, W., Fausto, R. S., Gleie, K., Gubler, S., Hasholt, B., Hynek, B., Knudsen, N., Larsen, S., Mernild, S., Oerlemans, J., Oerter, H., Olesen, O., Smeets, C., Steen, K., Stober, M., Sugiyama, S., van As, D., van den Broeke, M. & van de Wal, R. S. (2016). Greenland surface mass balance observations from the ice sheet ablation area and local glaciers, Journal of Glaciology.

Meier, M. F. (1965). Glaciers and climate. In: The Quaternary of the United States (ed. by H. E. Wright & D. G. Frey), 795-805. Princeton University Press, Princeton, New Jersey.

Meier M.F. (1984). Contribution of small glaciers to global sea-level. Science 226, 1418–1421.

Meier, M. F., Dyurgerov, M and Mccabe, G. (2003). The Health of Glaciers: Recent Changes in Glacier Regime. Climatic Change 59 (1-2).

Meier, M. F. & Post, A. S. (1962). Recent variations in mass net budgets of glaciers in western North America. In: Symposium of Obergurgl (on Variations of the Regime of Existing Glaciers), 63-77. IAHS Publ. no. 58.

Mitchell, T.D., T.R. Carter, P.D. Jones, M. Hulme, and M. New (2003). A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: The observed record (1901-2000) and 16 scenarios (2001-2100). J. Climate, submitted.

Naegeli, K. (2017): State, changes and impact of glacier surface albedo in the Swiss Alps. PhD Thesis, Department of Geosciences, University of Fribourg, Switzerland, 160pp.

Nesje, A. and Dahl, S. O. (2000). Glaciers and Environmental Change, Arnold, London, 2000, p. 347.

Oerlemans J. (2001). Glaciers and Climate Change. A.A. Balkema Publishers, 148 pp. ISBN 9026518137.

Oerlemans J. (2008). Minimal Glacier Models. Igitur, Utrecht University, 90 pp. ISBN 978-90-6701-022-1.

Oerlemans J. (2010). The Microclimate of Valley Glaciers. Institute for Marine and Atmospheric Research Utrecht, Utrecht University, The Netherlands.

Oerlemans J. and J.P.F. Fortuin (1992): Sensitivity of glaciers and small ice caps to greenhouse warming. Science 258, 115-117.

Oerlemans J. and N.C. Hoogendoorn (1989). Mass balance gradients and climatic change. Journal of Glaciology 35, 399-405.

Østrem, G. (1959). Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges.Geografiska Annaler,51, 228–230.

Ohmura, A. and Lang, H. (1989). Secular variations of global radiation in Europe, IRS '88: Current Problems in Atmospheric Radiation, Lille, France

Ohmura, A., Bauder, A., Müller, H. and Kappenberger, G. (2007). Long-term change of mass balance and the role of radiation. Annals of Glaciology, 46, 367-374.

Rasmussen, L.A. and L.M. Andreassen. (2005). Seasonal mass balance gradients in Norway. Journal of Glaciology. vol. 51, no. 175, p. 601-606Shumskiy, P. A. , 1947: Energiya oledeneniya i zhisn' lednikov (Energy of glaciation and life of glaciers). Moscow: Geographgiz, 60 pp. (Russian)

Reeh, N. (1991). Parameterization of melt rate and surfaee temperature on the Greenland lee Sheet. Polarforschung, 59(3), 113-128, hdl:10013/epic.29636.d001.

Serreze, M. C., and J. A. Francis. (2006). The arctic amplification debate. Climatic Change 76(3-4): 241-264. doi:1007/s10584-005-9017-y.

Sicart, J. E., R. Hock, and D. Six (2008), Glacier melt, air temperature, and energy balance in different climates: The Bolivian Tropics, the French Alps, and northern Sweden, J. Geophys. Res., 113, D24113, doi:10.1029/ 2008JD010406.

Sorg, A., Bolch, T., Stoffel, M., Solomina, O., and Beniston, M. (2012). Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). Nature Climate Change, 2: 725–731.

Stanhill, G. and Cohen, S. (2001). Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences, Agr. Forest Meteorol., 107, 255–278.

Stumm, D. (2011). The Mass Balance of Selected Glaciers of the Southern Alps in New Zealand (Thesis, Doctor of Philosophy). University of Otago. Retrieved from http://hdl.handle.net/10523/1672.

UNEP (2007). Global outlook for ice and snow. UNEP: United Nations Environment Programme. Nairobi (Kenya), Birkeland Trykkerri, Birkeland, Norway, 2007, 235 p.

Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen and T. Zhang. (2013). Observations: Cryosphere. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C. N., Dutton, E. G., Forgan, B., Kallis, A., Russak, V., and Tsvetkov, A. (2005). From dimming to brightening: Decadal changes in solar radiation at Earth's surface, Science, 308, 847–850, https://doi.org/10.1126/science.1103215

Wild, M., Ohmura, A., Schär, C., Müller, G., Folini, D., Schwarz, M., Hakuba, M.Z., Sanchez-Lorenzo, A. (2017). The Global Energy Balance Archive (GEBA) version 2017: a database for worldwide measured surface energy fluxes. Earth System Science Data 9, 601–613. https://doi.org/10.5194/essd-9-601-2017

WGMS (2008). Global Glacier Changes: facts and figures. Zemp, M., Roer, I., Kääb, A., Hoelzle, M., Paul, F. and Haeberli, W. (eds.), UNEP, World Glacier Monitoring Service, Zurich, Switzerland: 88 pp.

WGMS (2013). Glacier Mass Balance Bulletin No. 12 (2010–2011). Zemp, M., Nussbaumer, S. U., Naegeli, K., Gärtner-Roer, I., Paul, F., Hoelzle, M., and Haeberli, W. (eds.), ICSU(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, 106 pp., publication based on database version: doi:10.5904/wgms-fog-2013-11.

WGMS (2017). Global Glacier Change Bulletin No. 2 (2014–2015). Zemp, M., Nussbaumer, S. U., Gärtner-Roer, I., Huber, J., Machguth, H., Paul, F., and Hoelzle, M. (eds.), ICSU(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, 244 pp., publication based on database version: doi:10.5904/wgms-fog-2017-10.

WMO (2016). The Global Observing System for Climate: Implementation Needs (GCOS – No. 200), 235 p. Available at: https://library.wmo.int/opac/doc_num.php?explnum_id=3417.

Zemp, M., Armstrong, R., Haeberli, W., Hoelzle, M., Kääb, A., Kargel, J., Paul, F and Raup, R.H. (2007). Worldwide Glacier Monitoring – Present State and Current Challenges. Ice and Climate News, 9.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstroem, A.P., Anderson, B., Bajracharya S., Baroni, C., Braun, L.N., Caceres, B.E., Casassa, G., Cobos, G., Davila, L.R., Delgado Granados, H., Demuth, M.N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J.O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V.V., Portocarrero, C.A., Prinz, R., Sangewar, C.V., Severskiy, I., Sigurdsson, O., Soruco, A., Usubaliev, R. & C. Vincent (2015). Historically unprecedented global glacier decline in the early 21st century. Journal of Glaciology, 61(228), 745–762.

Zemp, M. and Haeberli, W. (2007). Glaciers and Ice Caps in Global outlook for ice and snow. UNEP/GRID-Arendal, Norway: 235 pp.

Zemp, M., M. Hoelzle, and W. Haeberli (2009). Six decades of glacier mass-balance observations: a review of the worldwide monitoring network. Annals of Glaciology, 50(50), 101–111.

# Annexes

All Annexes can be found in the attached CD as numeric tables in *Excel* files except Annex 18 as it only countains Figures.

## Annex 1

| Nr. | Political unit | Glacier name | Region | Coordinates | | Elevation (m a.s.l.) | | | Lenght (km) | Area ($km^2$) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | °N | °E | Max. | Med. | Min. | | |
| 1 | AT | Hintereisferner* | CEU | 46.80 | 10.77 | 3715 | 3064 | 2450 | 6.6 | 6.7 |
| 2 | AT | Jamtalferner | CEU | 46.86 | 10.16 | 3120 | 2780 | 2400 | 2.8 | 3.1 |
| 3 | AT | Kesselwandferner* | CEU | 46.84 | 10.79 | 3493 | 3190 | 2850 | 3.6 | 3.6 |
| 4 | AT | Vernagtferner* | CEU | 46.88 | 10.82 | 3619 | 3143 | 2800 | 2.6 | 7.3 |
| 5 | BO | Zongo | TRP | -16.28 | -68.14 | 6109 | 5420 | 4939 | 2.7 | 1.9 |
| 6 | CA | Devon Ice Cap NW* | ACN | 75.42 | -83.25 | 1820 | 1200 | 0 | 50 | 1668 |
| 7 | CA | Helm* | WNA | 49.96 | -122.99 | 2150 | 1900 | 1700 | 2.4 | 0.8 |
| 8 | CA | Peyto* | WNA | 51.66 | -116.56 | 3190 | 2640 | 2100 | 5.3 | 11.4 |
| 9 | CA | Place* | WNA | 50.43 | -122.60 | 2601 | 2089 | 1800 | 4.2 | 3.2 |
| 10 | CA | White* | ACN | 79.45 | -90.70 | 1780 | 1160 | 80 | 15.4 | 38.5 |
| 11 | CH | Allalin* | CEU | 46.05 | 7.93 | 4179 | 3323 | 2600 | 6.8 | 9.7 |
| 12 | CH | Basodino | CEU | 46.42 | 8.48 | 3180 | 2886 | 2566 | 1.5 | 1.8 |
| 13 | CH | Gietro* | CEU | 46.00 | 7.38 | 3810 | 3229 | 2700 | 4.4 | 5.3 |
| 14 | CH | Gries* | CEU | 46.44 | 8.34 | 3305 | 2945 | 2444 | 5.5 | 4.4 |
| 15 | CH | Grosser Aletsch | CEU | 46.50 | 8.03 | 4126 | 3153 | 1649 | 23.6 | 78.2 |
| 16 | CH | Rhone | CEU | 46.62 | 8.40 | 3596 | 2958 | 2252 | 10.1 | 15.6 |
| 17 | CH | Schwarzberg | CEU | 46.02 | 7.93 | 3551 | 3044 | 2600 | 4.1 | 5.1 |
| 18 | CH | Silvretta* | CEU | 46.85 | 10.08 | 3075 | 2782 | 2475 | 3.3 | 2.7 |
| 19 | CN | Urumqi Glacier E | ASC | 43.12 | 86.81 | 4552 | 4021 | 3787 | 2.1 | 1 |
| 20 | CN | Urumqi Glacier W | ASC | 43.12 | 86.81 | 4482 | 4121 | 3883 | 1.8 | 0.6 |
| 21 | KG | Abramov | ASC | 39.62 | 71.56 | 4918 | 4231 | 3659 | 7.8 | 24 |
| 22 | KG | Golubin | ASC | 42.46 | 74.50 | 4350 | 3825 | 3325 | 4.7 | 5.4 |
| 23 | KZ | Shumskiy | ASC | 45.08 | 80.23 | 4464 | 3663 | 3156 | 3.5 | 2.8 |
| 24 | KZ | Tuyuksuyskiy* | ASC | 43.05 | 77.08 | 4219 | 3822 | 3486 | 2.6 | 2.3 |
| 25 | NO | Aalfotbreen* | SCA | 61.75 | 5.65 | 1368 | 1230 | 890 | 2.9 | 4 |
| 26 | NO | Austdalsbreen | SCA | 61.82 | 7.35 | 1747 | 1495 | 1200 | 5.7 | 10.6 |
| 27 | NO | Engabreen* | SCA | 66.65 | 13.85 | 1544 | 1220 | 111 | 11.5 | 36.8 |
| 28 | NO | Graasubreen* | SCA | 61.66 | 8.60 | 2284 | 2085 | 1833 | 2.3 | 2.1 |
| 29 | NO | Hansebreen | SCA | 61.75 | 5.68 | 1310 | 1150 | 927 | 2.5 | 2.8 |
| 30 | NO | Hellstugubreen* | SCA | 61.56 | 8.44 | 2229 | 1900 | 1482 | 3.4 | 2.9 |
| 31 | NO | Langfordjoekelen | SCA | 70.13 | 21.74 | 1050 | 850 | 302 | 4.2 | 3.2 |
| 32 | NO | Nigardsbreen* | SCA | 61.72 | 7.13 | 1952 | 1627 | 330 | 9.6 | 46.6 |
| 33 | NO | Rembesdalskaaka* | SCA | 60.54 | 7.37 | 1854 | 1735 | 1066 | 8.1 | 17.3 |
| 34 | NO | Storbreen* | SCA | 61.57 | 8.13 | 2102 | 1775 | 1400 | 2.9 | 5.1 |
| 35 | RU | Djankuat* | CAU | 43.19 | 42.76 | 3729 | 3280 | 2722 | 3.4 | 2.7 |
| 36 | RU | Garabashi | CAU | 43.30 | 42.47 | 5000 | 3880 | 3300 | 5.8 | 4.4 |
| 37 | RU | Maliy Aktru* | ASN | 50.05 | 87.75 | 3714 | 3200 | 2246 | 4.2 | 2.7 |
| 38 | RU | Vodopadniy | ASN | 50.05 | 87.78 | 3552 | 3230 | 3038 | 1.4 | 0.8 |
| 39 | SE | Marmaglaciaeren | SCA | 68.08 | 18.68 | 1740 | NA | 1320 | 3.3 | 4 |
| 40 | SE | Rabots Glaciaer | SCA | 67.91 | 18.50 | 1930 | NA | 1080 | 3.7 | 3.7 |
| 41 | SE | Riukojietna | SCA | 68.08 | 18.05 | 1440 | NA | 1160 | 2.3 | 2.8 |
| 42 | SE | Storglaciaeren* | SCA | 67.90 | 18.57 | 1720 | NA | 1140 | 3.4 | 2.9 |
| 43 | SJ | Austre Broeggerbreen* | SJM | 78.89 | 11.83 | 600 | 260 | 50 | 6 | 6.1 |
| 44 | SJ | Midtre Lovenbreen* | SJM | 78.88 | 12.05 | 650 | 330 | 50 | 4.8 | 5.4 |
| 45 | SJ | Waldemarbreen | SJM | 78.68 | 12.07 | 570 | 320 | 150 | 3.3 | 2.4 |
| 46 | US | Gulkana* | ALA | 63.28 | -145.43 | 2459 | 1840 | 1217 | 7.5 | 16.3 |
| 47 | US | Lemon Creek* | ALA | 58.39 | -134.35 | 1400 | 1100 | 750 | 5.9 | 10.3 |
| 48 | US | South Cascade* | WNA | 48.35 | -121.06 | 2135 | 1920 | 1626 | 3 | 1.6 |
| 49 | US | Wolverine* | ALA | 60.42 | -148.90 | 1672 | 1310 | 436 | 8 | 15.9 |

**Annex 1 :** Glacier's characteristics with information collected from the files *General Information* and *State* of the WGMS database (WGMS, 2017) and the WGMS Glacier App for the selected glaciers. Glacier's name with a * are classified as reference glaciers by the WGMS.

# Annex 2

| Nr. | Glacier name | Total time coverage | | Missing years | # of years with data | Selected Data type |
|---|---|---|---|---|---|---|
| | | first-last year | # of years | | | |
| 1 | Hintereisferner | 1964-2017 | 54 | x | 54 | Elevation bands |
| 2 | Jamtalferner | 1989-2016 | 28 | 1998-99, 2010 | 25 | Elevation bands |
| 3 | Kesselwandferner | 1967-2017 | 51 | 2010 | 50 | Elevation bands |
| 4 | Vergtferner | 1965-2015 | 51 | x | 51 | Elevation bands |
| 5 | Zongo | 1992-2015 | 24 | 1998-99 | 22 | Elevation bands |
| 6 | Devon Ice Cap NW | 1961-2000 | 40 | 1968 | 39 | Elevation bands |
| 7 | Helm | 1982-2005 | 24 | 1990-2003 | 10 | Elevation bands |
| 8 | Peyto | 1966-2005 | 40 | 1975, 1990-91 | 37 | Elevation bands |
| 9 | Place | 1965-2005 | 41 | 1975-80, 1990-93, 1996-2003 | 23 | Elevation bands |
| 10 | White | 1960-2016 | 57 | 1980-82, 2012-3 | 52 | Elevation bands |
| 11 | Allalin | 1956-2016 | 61 | x | 56 | Elevation bands |
| 12 | Basodino | 1993-2016 | 24 | 2008-09, 2011 | 21 | Elevation bands |
| 13 | Gietro | 1967-2016 | 50 | x | 50 | Elevation bands |
| 14 | Gries | 1962-2016 | 55 | 2008-11 | 51 | Elevation bands |
| 15 | Grosser Aletsch | 1954-1985 | 32 | x | 32 | Points |
| 16 | Rhone | 1980-2015 | 36 | 1983-2012 | **6** | Elevation bands |
| 17 | Schwarzberg | 1956-2016 | 61 | x | **61** | Elevation bands |
| 18 | Silvretta | 1954-2016 | **63** | 2008-09, 2011 | 60 | Elevation bands |
| 19 | Urumqi Glacier E | 1989-2016 | 28 | 2001-03 | 25 | Elevation bands |
| 20 | Urumqi Glacier W | 1989-2016 | 28 | 2001-02 | 26 | Elevation bands |
| 21 | Abramov | 1968-2016 | 49 | 1969-70, 1999-2011 | 34 | Elevation bands |
| 22 | Golubin | 1981-2016 | 36 | 1991-2010 | 16 | Elevation bands |
| 23 | Shumskiy | 1968-1984 | 17 | x | 17 | Elevation bands |
| 24 | Tuyuksuyskiy | 1965-2016 | 52 | x | 52 | Elevation bands |
| 25 | Aalfotbreen | 1963-2015 | 53 | x | 53 | Elevation bands |
| 26 | Austdalsbreen | 1988-2016 | 29 | x | 29 | Elevation bands |
| 27 | Engabreen | 1970-2016 | 47 | x | 47 | Elevation bands |
| 28 | Graasubreen | 1963-2016 | 54 | x | 54 | Elevation bands |
| 29 | Hansebreen | 1986-2016 | 31 | x | 31 | Elevation bands |
| 30 | Hellstugubreen | 1962-2016 | 55 | x | 55 | Elevation bands |
| 31 | Langfordjoekelen | 1989-2016 | 28 | 1994-95 | 26 | Elevation bands |
| 32 | Nigardsbreen | 1962-2016 | 55 | x | 55 | Elevation bands |
| 33 | Rembesdalskaaka | 1963-2016 | 54 | 1978-84 | 47 | Elevation bands |
| 34 | Storbreen | 1990-2016 | 27 | x | 27 | Elevation bands |
| 35 | Djankuat | 1968-2009 | 42 | x | 42 | Elevation bands |
| 36 | Garabashi | 1984-2014 | 31 | x | 31 | Elevation bands |
| 37 | Maliy Aktru | 1970-2012 | 43 | 1981-90, 2002-03, 2010 | 30 | Elevation bands |
| 38 | Vodopadniy | 1988-2000 | 13 | 1990 | 12 | Elevation bands |
| 39 | Marmaglaciaeren | 1995-2016 | 22 | 2012 | 21 | Elevation bands |
| 40 | Rabots Glaciaer | 1986-2015 | 30 | 1993, 1996-2001, 2003-04, 2007, 2013-14 | 18 | Elevation bands |
| 41 | Riukojietna | 1996-2015 | 20 | 1998, 2004, 2013-14 | 16 | Elevation bands |
| 42 | Storglaciaeren | 1971-2016 | 46 | 1976-1980 | 46 | Elevation bands |
| 43 | Austre Broeggerbreen | 1990-2009 | 20 | 1992, 1998 | 18 | Elevation bands |
| 44 | Midtre Lovenbreen | 1996-2009 | 14 | 1998 | 13 | Elevation bands |
| 45 | Waldemarbreen | 2000-2017 | 18 | 2006-07 | 16 | Elevation bands |
| 46 | Gulkana | 2008-2017 | 10 | x | 10 | Points |
| 47 | Lemon Creek | 2008-2016 | **9** | 2012 | 8 | Elevation bands |
| 48 | South Cascade | 1965-2015 | 51 | 1981-2007, 2010-12 | 21 | Elevation bands |
| 49 | Wolverine | 2008-2017 | 10 | x | 10 | Points |
| | | **Mean** | **37** | **Mean** | **33** | |
| | | **Median** | **36** | **Median** | **30** | |

**Annex 2 :** Total time coverage, missing years, number of years with data and selected mass balance data type of the mass balance data from the 49 selected glacier. Note that when both elevation bands data and point data where available for a period, elevation bands data are taken in priority unless the time coverage of point data is larger. Extracted point mass balance data concern the glaciers Grosser Aletsch, Gulkana and Wolverine only.

## Annex 3

Due to its size, Annex 3 is only available in numerical format in the CD attached to this work.

## Annex 4

| Nr. | Glacier name | $ELA_0$ (m a.s.l.) | $R^2$ |
|---|---|---|---|
| 1 | Hintereisferner | 2934 | 0.90 |
| 2 | Jamtalferner | 2829 | 0.70 |
| 3 | Kesselwandferner | 3120 | 0.82 |
| 4 | Vernagtferner | 3081 | 0.80 |
| 5 | Zongo | 5259 | 0.68 |
| 6 | Devon Ice Cap NW | 992* | 0.84 |
| 7 | Helm | 2010 | 0.73 |
| 8 | Peyto | 2593 | 0.72 |
| 9 | Place | 2083 | 0.85 |
| 10 | White | 925 | 0.76 |
| 11 | Allalin | 3251 | 0.90 |
| 12 | Basodino | 2872 | 0.86 |
| 13 | Gietro | 3158* | 0.93 |
| 14 | Gries | 2827 | 0.88 |
| 15 | Grosser Aletsch | 2914 | 0.84 |
| 16 | Rhone | 2878 | 0.83 |
| 17 | Schwarzberg | 3020 | 0.92 |
| 18 | Silvretta | 2742 | 0.91 |
| 19 | Urumqi Glacier E | 3948 | 0.81 |
| 20 | Urumqi Glacier W | 4041 | 0.43 |
| 21 | Abramov | 4159 | 0.92 |
| 22 | Golubin | 3804 | 0.67 |
| 23 | Shumskiy | 3568 | 0.70 |
| 24 | Tuyuksuyskiy | 3765 | 0.80 |
| 25 | Aalfotbreen | 1185 | 0.82 |
| 26 | Austdalsbreen | 1448 | 0.88 |
| 27 | Engabreen | 1174 | 0.86 |
| 28 | Graasubreen | 2072 | 0.74 |
| 29 | Hansebreen | 1148 | 0.77 |
| 30 | Hellstugubreen | 1851 | 0.92 |
| 31 | Langfordjoekelen | 809 | 0.69 |
| 32 | Nigardsbreen | 1563 | 0.81 |
| 33 | Rembesdalskaaka | 1677 | 0.88 |
| 34 | Storbreen | 1737 | 0.94 |
| 35 | Djankuat | 3189 | 0.89 |
| 36 | Garabashi | 3789 | 0.86 |
| 37 | Maliy Aktru | 3162 | 0.78 |
| 38 | Vodopadniy | 3203 | 0.90 |
| 39 | Marmaglaciaeren | 1618 | 0.23 |
| 40 | Rabots Glaciaer | 1376 | 0.81 |
| 41 | Riukojietna | 1377 | 0.51 |
| 42 | Storglaciaeren | 1469 | 0.84 |
| 43 | Austre Broeggerbreen | 298 | 0.93 |
| 44 | Midtre Lovenbreen | 323 | 0.91 |
| 45 | Waldemarbreen | 310 | 0.88 |
| 46 | Gulkana | 1696 | 0.75 |
| 47 | Lemon Creek | 1020 | 0.93 |
| 48 | South Cascade | 1903* | 0.72 |
| 49 | Wolverine | 1138 | 0.94 |
| | | **Mean $R^2$** | **0.80** |

**Annex 4 :** $ELA_0$ and corresponding $R^2$ of each glaciers alongside with the mean $R^2$ value of all glaciers. Glaciers identified with a * had a slighly different value taken as the $ELA_0$ to calculate the gradients for logical reasons related to elevation bands assignation to ablation or accumulation areas. These values are 950 m a.s.l for Devon Ice Cap NW, 3150 m a.s.l. for Gietro and 1900 m a.s.l. for South Cascade.

## Annex 5.1

The table from Annex 5.1 it splitted on three pages due to its size.

| Nr. | GlacierNAme | 1954 | 1955 | 1956 | 1957 | 1958 | 1959 | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.018 | 0.993 | 1.111 | 1.059 | 1.191 | 1.247 | 0.916 | 1.106 | 0.952 | 1.016 |
| 2 | Jamtalferner | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 3 | Kesselwandferner | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.169 | 0.895 | 1.127 | 0.799 | 1.578 | 1.416 | 1.144 |
| 4 | Vernagtferner | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.994 | NA | 1.000 | 1.111 | 1.026 | 1.111 | 1.119 | 0.968 | 0.807 | 0.875 |
| 5 | Zongo | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 6 | Devon Ice Cap NW | NA | NA | NA | NA | NA | NA | NA | 0.095 | 0.105 | 0.159 | 0.072 | 0.110 | 0.103 | 0.064 | NA | 0.186 | 0.093 | 0.067 | 0.062 | 0.124 |
| 7 | Helm | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 8 | Peyto | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.413 | 0.504 | 0.408 | 0.486 | 0.566 | 0.658 | 0.580 | 0.772 |
| 9 | Place | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.920 | 0.910 | 0.845 | 1.280 | 0.717 | 0.935 | 1.080 | 0.820 | 0.895 |
| 10 | White | NA | NA | NA | NA | NA | NA | 0.205 | 0.166 | 0.231 | 0.272 | 0.160 | 0.225 | 0.200 | 0.188 | 0.215 | 0.238 | 0.172 | 0.200 | 0.229 | 0.192 |
| 11 | Allalin | NA | NA | 0.334 | 0.331 | 0.322 | 0.316 | 0.365 | 0.346 | 0.155 | 0.355 | 0.214 | 0.364 | 0.314 | 0.220 | 0.423 | 0.403 | 0.344 | 0.385 | 0.295 | 0.502 |
| 12 | Basodino | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 13 | Gietro | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.681 | 0.670 | 0.673 | 0.528 | 0.661 | 0.668 | 0.702 |
| 14 | Gries | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.777 | 0.729 | 0.509 | 0.669 | 0.950 | 0.815 | 0.604 | 0.812 |
| 15 | Grosser Aletsch | 1.142 | 0.824 | 0.840 | 0.848 | 0.881 | 0.506 | 0.799 | 0.897 | 0.840 | 0.486 | 0.870 | 0.714 | 0.792 | 0.654 | 0.865 | 0.774 | 0.874 | 0.806 | 0.854 | 0.722 |
| 16 | Rhone | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 17 | Schwarzberg | NA | NA | 0.986 | 0.949 | 0.971 | 0.791 | 0.839 | 0.732 | 0.410 | 0.869 | 0.680 | 0.641 | 0.847 | 0.647 | 0.686 | 0.644 | 0.633 | 0.717 | 0.543 | 0.765 |
| 18 | Silvretta | 0.886 | 0.747 | 0.752 | 0.741 | 0.830 | 0.688 | 1.449 | 0.648 | 0.495 | 0.544 | 0.876 | 0.542 | 1.179 | 0.824 | 0.992 | 1.321 | 0.887 | 1.457 | 0.902 | 1.031 |
| 19 | Urumqi Glacier E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 20 | Urumqi Glacier W | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 21 | Abramov | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.599 | NA | NA | 0.675 | 0.625 | 0.596 |
| 22 | Golubin | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 23 | Shumskiy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.239 | 0.367 | 0.383 | 0.279 | 0.262 | 0.325 |
| 24 | Tuyuksuyskiy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.365 | 0.503 | 0.529 | NA | 0.557 | 0.546 | 0.281 | 0.479 | 0.505 |
| 25 | Aalfotbreen | NA | NA | NA | NA | NA | NA | NA | NA | 0.964 | NA | 1.257 | 0.531 | 0.864 | 0.570 | 0.948 | 0.500 | 0.495 | 0.660 | 0.795 | 0.397 |
| 26 | Austdalsbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 27 | Engabreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.832 | 0.887 | 1.022 | 1.286 |
| 28 | Graasubreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 29 | Hansebreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 30 | Helstugubreen | NA | NA | NA | NA | NA | NA | NA | NA | 0.590 | 0.658 | 0.527 | 0.724 | 0.582 | 0.638 | 0.644 | 0.483 | 0.601 | 0.671 | 0.676 | 0.684 |
| 31 | Langfjordjokelen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 32 | Nigardsbreen | NA | NA | NA | NA | NA | NA | NA | NA | 0.865 | 1.089 | 0.875 | 0.890 | 0.747 | 0.773 | 0.852 | 0.892 | 0.736 | 0.947 | 0.973 | 1.075 |
| 33 | Rembesdalskaaka | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.875 | 0.774 | 0.875 | 1.095 | 1.095 | 1.028 | 0.989 | 0.973 | 1.003 | 1.000 | 1.050 |
| 34 | Storbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 35 | Djankuat | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.124 | 0.913 | 1.185 | 1.031 | 0.914 | 1.138 |
| 36 | Garabashi | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 37 | Maliy Aktru | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.440 | 0.447 | 0.330 | 0.381 |
| 38 | Vodopadniy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 39 | Marmaglaciaeren | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 40 | Rabots Glaciaer | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 41 | Riukojietna | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 42 | Storglaciaeren | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.637 | 0.812 | 0.549 |
| 43 | Austre Broggerbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 44 | Midtre Lovenbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 45 | Waldemarbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 46 | Gulkana | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 47 | Lemon Creek | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 48 | South Cascade | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 2.000 | 1.700 | 1.500 | 3.000 | 3.182 | 1.794 | 2.852 | 0.902 | 2.066 |
| 49 | Wolverine | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |

| Nr. | Glacier NAme | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | 0.969 | 1.025 | 1.052 | 1.074 | 0.908 | 0.841 | 0.903 | 0.950 | 0.857 | 0.877 | 0.731 | 0.995 | 0.928 | 0.877 | 1.061 | 1.075 | 1.019 | 1.079 | 1.180 | 1.211 | 1.289 | 1.054 |
| 2 | Jamtalferner | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.961 | 0.778 | 0.683 | 0.675 | 0.769 | 0.817 | 0.607 |
| 3 | Kesselwandferner | 0.712 | 0.774 | 1.003 | 1.274 | 0.922 | 1.238 | 1.230 | 1.079 | 1.118 | 0.846 | 1.170 | 1.094 | 1.282 | 1.298 | 1.202 | 1.161 | 1.236 | 1.042 | 1.191 | 1.452 | 1.494 | 1.206 |
| 4 | Vernagtferner | 0.769 | 1.000 | 0.840 | 0.636 | 0.623 | 0.769 | 0.363 | 0.958 | 0.714 | 0.550 | 0.604 | 0.492 | 0.810 | 0.772 | 0.782 | 1.004 | 0.870 | 1.138 | 0.927 | 0.747 | 1.141 | 0.594 |
| 5 | Zongo | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.468 | 1.812 | 2.632 | 1.180 |
| 6 | Devon Ice Cap NW | 0.113 | 0.128 | 0.064 | 0.142 | 0.105 | 0.077 | 0.074 | 0.048 | 0.153 | 0.159 | 0.091 | 0.132 | 0.141 | 0.095 | 0.099 | 0.085 | 0.090 | 0.115 | 0.108 | 0.081 | 0.142 | 0.108 |
| 7 | Helm | NA | NA | NA | NA | NA | NA | NA | NA | 0.060 | 0.765 | 0.345 | 0.840 | 0.477 | 1.377 | 0.910 | 0.280 | NA | NA | NA | NA | NA | NA |
| 8 | Peyto | 0.644 | NA | 0.719 | 0.768 | 0.652 | 0.691 | 0.729 | 0.206 | 0.248 | 0.259 | 0.237 | 0.608 | 0.577 | 0.795 | 0.685 | 0.147 | 0.713 | NA | NA | 0.593 | 1.123 | 0.732 |
| 9 | Place | 0.685 | NA | NA | NA | NA | NA | NA | 1.080 | 1.680 | 0.740 | 0.770 | 1.090 | 1.239 | 1.065 | 0.598 | 1.500 | NA | NA | NA | NA | 0.265 | 0.671 |
| 10 | White | 0.177 | 0.236 | 0.186 | 0.235 | 0.208 | 0.160 | NA | NA | NA | 0.229 | 0.242 | 0.271 | 0.338 | 0.402 | 0.204 | 0.180 | 0.221 | 0.257 | 0.149 | 0.235 | 0.280 | 0.254 |
| 11 | Allalin | 0.366 | 0.421 | 0.507 | 0.335 | 0.416 | 0.371 | 0.365 | 0.368 | 0.482 | 0.238 | 0.284 | 0.286 | 0.327 | 0.319 | 0.293 | 0.399 | 0.354 | 0.328 | 0.554 | 0.434 | 0.391 | 0.220 |
| 12 | Basodino | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.225 | 0.875 | 1.100 |
| 13 | Gietro | 0.604 | 0.571 | 0.577 | 0.802 | 0.691 | 0.726 | 0.571 | 0.744 | 0.928 | 0.690 | 0.718 | 0.800 | 0.839 | 0.825 | 0.836 | 0.812 | 0.614 | 1.025 | 0.810 | 0.899 | 0.751 | 1.080 |
| 14 | Gries | 0.659 | 0.651 | 0.931 | 0.481 | 0.869 | 0.901 | 0.726 | 1.077 | 1.044 | 0.758 | 0.799 | 0.428 | 0.616 | 0.597 | 0.715 | 0.816 | 0.949 | 0.952 | 0.845 | 0.469 | 1.004 | 0.677 |
| 15 | Grosser Aletsch | 0.889 | 0.497 | 0.741 | 0.806 | 0.796 | 0.760 | 0.806 | 0.946 | 0.478 | 0.377 | 0.609 | 0.623 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 16 | Rhone | NA | NA | NA | NA | NA | NA | 0.944 | 0.881 | 0.911 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 17 | Schwarzberg | 0.673 | 0.400 | 0.727 | 0.579 | 0.524 | 0.695 | 0.512 | 0.619 | 0.807 | 0.592 | 0.533 | 0.599 | 0.648 | 0.580 | 0.677 | 0.696 | 0.597 | 0.629 | 0.461 | 0.498 | 0.353 | 0.410 |
| 18 | Silvretta | 0.916 | 1.111 | 1.519 | 1.034 | 0.963 | 1.051 | 1.073 | 0.928 | 0.807 | 1.446 | 0.831 | 0.786 | 0.820 | 0.621 | 0.739 | 0.980 | 1.123 | 1.112 | 1.259 | 1.417 | 1.487 | 0.984 |
| 19 | Urumqi Glacier E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.912 | 1.337 | 1.292 | 1.302 | 1.452 | 1.430 | 1.109 |
| 20 | Urumqi Glacier W | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.780 | 0.882 | 0.944 | 0.979 | 1.244 | 1.094 | 0.768 |
| 21 | Abramov | 0.771 | 0.503 | 0.665 | 0.652 | 0.590 | 0.593 | 0.622 | 0.537 | 0.897 | 0.715 | 0.671 | 0.759 | 0.601 | 0.772 | 0.691 | 0.580 | 0.791 | 0.654 | 0.690 | 0.829 | 0.728 | 0.907 |
| 22 | Golubin | NA | NA | NA | NA | NA | NA | NA | 0.344 | 0.495 | 0.595 | 0.453 | 0.523 | 0.471 | 0.603 | 0.558 | 0.368 | 0.627 | NA | NA | NA | NA | NA |
| 23 | Shumskiy | 0.347 | 0.255 | 0.302 | 0.356 | 0.207 | 0.247 | 0.319 | 0.415 | 0.415 | 0.305 | 0.294 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 24 | Tuyuksuyskiy | 0.248 | 0.472 | 0.312 | 0.342 | 0.301 | 0.329 | 0.441 | 0.509 | 0.395 | 0.364 | 0.072 | 0.447 | 0.358 | 0.196 | 0.444 | 0.348 | 0.680 | 0.372 | 0.487 | 0.695 | 0.382 | 0.559 |
| 25 | Aalfotbreen | 0.485 | 0.515 | 0.620 | 0.305 | 0.585 | 0.384 | 1.010 | 0.385 | 0.175 | 0.609 | 0.715 | 0.745 | 0.405 | 0.770 | 0.755 | 1.438 | 1.067 | 0.747 | 1.424 | NA | 0.314 | 0.701 |
| 26 | Austdalsbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.211 | 0.881 | 1.050 | 1.130 | 1.980 | 1.340 | 1.550 | 1.400 |
| 27 | Engabreen | 1.131 | 0.848 | 0.819 | 1.089 | 0.861 | 1.135 | 1.355 | 1.000 | 1.078 | 0.848 | 1.284 | 1.080 | 0.876 | 1.052 | 1.202 | 1.310 | 1.213 | 1.096 | 1.232 | 0.966 | 0.912 | 0.863 |
| 28 | Graasubreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 29 | Hansebreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.780 | 0.718 | 0.818 | 0.705 | 0.563 | 0.651 | 0.782 | 1.100 | 1.280 | 0.675 |
| 30 | Hellstugubreen | 0.804 | 0.637 | 0.750 | 0.516 | 0.761 | 0.705 | 0.429 | 0.753 | 0.687 | 0.643 | 0.775 | 0.730 | 0.547 | 0.605 | 0.521 | 0.821 | 0.988 | 0.535 | 0.524 | 0.820 | 0.690 | 0.673 |
| 31 | Langfordjoekelen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.730 | 0.799 | 0.799 | 1.016 | 0.704 | NA | NA |
| 32 | Nigardsbreen | 1.023 | 0.968 | 0.805 | 0.752 | 0.656 | 0.644 | 0.804 | 0.666 | 0.810 | 0.932 | 0.919 | 0.566 | 0.780 | 0.699 | 0.939 | 0.886 | 0.869 | 0.819 | 0.842 | 0.865 | 0.757 | 0.954 |
| 33 | Rembesdalskaaka | 0.985 | 1.005 | 0.962 | 0.897 | NA | NA | NA | NA | NA | NA | NA | 0.754 | 0.905 | 0.714 | 1.016 | 0.829 | 0.885 | 1.056 | 1.039 | 0.772 | 1.094 | 1.149 |
| 34 | Storbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.682 | 1.148 | 0.704 | 0.834 | 0.701 | 0.762 |
| 35 | Djankuat | 0.971 | 0.737 | 0.679 | 0.645 | 0.779 | 0.696 | 0.677 | 0.983 | 0.837 | 1.004 | 0.823 | 0.844 | 0.809 | 1.028 | 1.019 | 0.858 | 0.642 | 0.978 | 0.837 | 1.196 | 0.916 | 0.836 |
| 36 | Garabashi | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.426 | 0.435 | 0.527 | 0.324 | 0.327 | 0.476 | 0.413 | 0.431 | 0.295 | 0.604 | 0.385 | 0.293 |
| 37 | Maliy Aktru | 0.398 | 0.623 | 0.629 | 0.975 | 0.512 | 0.389 | 0.578 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.329 | 0.435 | 0.433 | 0.410 | 0.442 |
| 38 | Vodopadniy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.660 | 0.690 | NA | 0.220 | 0.500 | 0.470 | 0.340 | 0.140 |
| 39 | Marmaglaciaeren | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.481 |
| 40 | Rabots Glaciaer | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.605 | 0.500 | 0.584 | 0.708 | 0.875 | 1.026 | 1.358 | 0.416 | 0.603 | 0.817 |
| 41 | Riukojietna | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 42 | Storglaciaeren | 0.753 | 0.792 | NA | NA | NA | NA | NA | 0.520 | 0.644 | 0.845 | 0.724 | 0.668 | 0.642 | 0.631 | 0.837 | 1.274 | 0.906 | 0.929 | 1.030 | 0.699 | 0.484 | 0.964 |
| 43 | Austre Broeggerbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.490 | 0.568 | NA | 0.990 | 0.774 | 0.954 |
| 44 | Midtre Lovenbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 45 | Waldemarbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 46 | Gulkana | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 47 | Lemon Creek | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 48 | South Cascade | 3.000 | 2.318 | 3.724 | 1.682 | 1.636 | 1.254 | 2.162 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 49 | Wolverine | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |

| Nr. | Glacier NAme | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | 1.174 | 1.278 | 1.042 | 1.308 | 1.252 | 1.073 | 1.171 | 1.287 | 1.045 | 1.212 | 1.047 | 1.182 | 1.041 | 0.866 | 1.232 | 1.210 | 1.229 | 1.276 | 1.152 | 1.077 | 1.315 | 1.059 |
| 2 | Jamtalferner | 0.745 | 0.829 | NA | NA | 0.746 | 0.555 | 0.658 | 1.009 | 0.615 | 0.939 | 0.881 | 0.923 | 0.757 | 0.813 | NA | 0.743 | 0.740 | 0.708 | 0.717 | 0.886 | 0.781 | NA |
| 3 | Kesselwandferner | 1.060 | 1.219 | 1.328 | 1.204 | 1.665 | 1.182 | 1.272 | 1.198 | 0.858 | 1.061 | 0.847 | 1.618 | 1.582 | 1.244 | NA | 1.974 | 1.336 | 1.116 | 1.386 | 1.365 | 0.381 | 0.369 |
| 4 | Vernagtferner | 0.980 | 0.845 | 0.807 | 1.074 | 1.198 | 0.918 | 1.160 | 0.862 | 0.906 | 1.057 | 0.796 | 0.869 | 0.870 | 0.843 | 0.794 | 0.938 | 0.969 | 0.959 | 0.569 | 0.943 | NA | NA |
| 5 | Zongo | 2.295 | 2.030 | NA | NA | 1.939 | 1.608 | 1.637 | 1.872 | 1.097 | 1.448 | 1.887 | 2.234 | 1.559 | 2.490 | 2.581 | 1.059 | 1.722 | 1.934 | 1.558 | 0.449 | NA | NA |
| 6 | Devon Ice Cap NW | 0.063 | 0.081 | 0.141 | 0.120 | 0.106 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 7 | Helm | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 8 | Peyto | 0.767 | 0.940 | 0.733 | 0.768 | 0.756 | 0.607 | 0.592 | 0.765 | 0.553 | 0.700 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 9 | Place | NA | NA | NA | NA | NA | NA | NA | NA | 0.730 | 1.600 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 10 | White | 0.142 | 0.167 | 0.321 | 0.136 | 0.179 | 0.134 | 0.243 | 0.117 | 0.214 | 0.233 | 0.208 | 0.248 | 0.143 | 0.188 | 0.243 | 0.262 | NA | NA | 0.184 | 0.197 | 0.264 | NA |
| 11 | Allalin | 0.314 | 0.327 | 0.315 | 0.388 | 0.523 | 0.536 | 0.477 | 0.619 | 0.282 | 0.521 | 0.440 | 0.634 | 0.429 | 0.232 | 0.218 | 0.281 | 0.368 | 0.247 | 0.394 | 0.605 | 0.186 | NA |
| 12 | Basodino | 0.850 | 0.950 | 0.575 | 0.810 | 0.950 | 0.840 | 0.900 | 0.800 | 0.370 | 0.450 | 0.650 | 0.560 | NA | NA | 0.350 | NA | 0.470 | 0.139 | 0.350 | NA | NA | NA |
| 13 | Gietro | 0.545 | 0.671 | 0.775 | 0.700 | 0.615 | 0.972 | 0.732 | 0.971 | 0.990 | 0.983 | 0.899 | 1.085 | 1.080 | 0.684 | 0.932 | 1.079 | 1.018 | 1.164 | 1.023 | 1.128 | 1.194 | NA |
| 14 | Gries | 0.830 | 0.782 | 0.658 | 0.887 | 0.906 | 0.477 | 0.993 | 0.551 | 0.761 | 0.830 | 0.851 | 0.714 | NA | NA | NA | NA | 0.608 | 0.916 | 0.484 | 0.752 | 0.768 | NA |
| 15 | Grosser Aletsch | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 16 | Rhone | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.877 | 0.667 | 0.742 | NA | NA |
| 17 | Schwarzberg | 0.375 | 0.532 | 0.421 | 0.524 | 1.085 | 1.260 | 1.138 | 1.115 | 0.696 | 0.996 | 0.819 | 1.319 | 1.050 | 0.817 | 0.698 | 0.766 | 0.805 | 0.710 | 0.958 | 0.858 | 0.589 | NA |
| 18 | Silvretta | 1.032 | 1.410 | 1.147 | 1.329 | 1.515 | 1.222 | 1.418 | 0.990 | 0.981 | 1.114 | 1.246 | 1.186 | NA | NA | 0.800 | NA | 0.427 | 0.789 | 0.474 | 0.436 | 0.823 | NA |
| 19 | Urumqi Glacier E | 1.196 | 1.129 | 1.351 | 1.623 | 1.464 | NA | NA | NA | 0.910 | 1.470 | 1.488 | 1.488 | 1.425 | 1.414 | 1.131 | 1.396 | 0.835 | 1.171 | 0.792 | 1.483 | 1.340 | NA |
| 20 | Urumqi Glacier W | 0.872 | 1.464 | 1.598 | 1.201 | 0.998 | 1.265 | NA | NA | 0.943 | 1.121 | 1.328 | 1.345 | 1.143 | 1.529 | 1.036 | 1.474 | 0.952 | 1.152 | 0.884 | 1.232 | 1.034 | NA |
| 21 | Abramov | 0.850 | 0.978 | 0.916 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.797 | 0.797 | 0.882 | 1.057 | 0.546 | NA |
| 22 | Golubin | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.493 | 0.719 | 0.587 | 0.798 | 0.637 | 1.113 | NA |
| 23 | Shumskiy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 24 | Tuyuksuyskiy | 0.570 | 0.599 | 0.607 | 0.505 | 0.692 | 0.332 | 0.449 | 0.261 | 0.372 | 0.590 | 0.500 | 0.635 | 0.635 | 0.650 | 0.575 | 0.604 | 0.461 | 0.489 | 0.378 | 0.383 | 0.559 | NA |
| 25 | Aaifonfreen | 1.114 | 0.527 | 1.723 | 0.494 | 0.979 | 0.880 | 0.950 | 0.860 | 0.922 | 0.508 | 0.432 | 0.560 | 0.920 | 0.548 | 0.616 | 0.948 | 0.772 | 1.021 | 1.413 | 1.267 | NA | NA |
| 26 | Austdalsbreen | 1.326 | 1.760 | 1.436 | 1.730 | 2.010 | 1.790 | 1.780 | 1.060 | 1.680 | 1.490 | 1.210 | 1.450 | 1.800 | 1.580 | 0.870 | 0.880 | 1.380 | 1.600 | 1.420 | 1.260 | 1.276 | NA |
| 27 | Engabreen | 1.181 | 1.187 | 1.011 | 0.834 | 1.282 | 0.940 | 1.415 | 1.027 | 1.103 | 1.123 | 1.180 | 1.179 | 1.085 | 1.284 | 0.915 | 1.089 | 1.012 | 0.941 | 1.087 | 0.926 | 0.980 | NA |
| 28 | Graasbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 29 | Hansebreen | 1.233 | 0.416 | 0.823 | 0.385 | 0.938 | 0.568 | 0.982 | 0.482 | 0.768 | 0.806 | 0.275 | 0.835 | 0.915 | 0.900 | 0.383 | 0.620 | 0.925 | 0.633 | 0.550 | 0.800 | 1.150 | NA |
| 30 | Hellstugubreen | 0.629 | 0.857 | 0.612 | 0.780 | 0.703 | 0.827 | 0.985 | 0.735 | 0.937 | 0.957 | 0.766 | 0.774 | 0.762 | 0.725 | 0.527 | 0.977 | 0.749 | 0.615 | 0.643 | 0.769 | 0.536 | NA |
| 31 | Langfjordjoekelen | 1.149 | 0.793 | 0.754 | 0.779 | 0.733 | 0.609 | 0.606 | 0.617 | 0.937 | 1.006 | 0.757 | 0.884 | 0.686 | 0.857 | 0.627 | 0.622 | 0.538 | 0.644 | 0.592 | 0.697 | 0.679 | NA |
| 32 | Nigardbreen | 0.882 | 1.024 | 1.037 | 0.947 | 1.153 | 0.892 | 0.727 | 0.768 | 0.912 | 0.946 | 0.911 | 0.882 | 1.093 | 1.012 | 0.668 | 0.812 | 0.778 | 0.828 | 1.049 | 0.739 | 0.863 | NA |
| 33 | Rembesdalskaaka | 0.856 | 1.137 | 0.955 | 0.500 | 1.163 | 1.000 | 0.924 | 1.039 | 1.033 | 1.150 | 0.929 | 0.981 | 1.248 | 1.103 | 0.730 | 0.739 | 0.831 | 1.024 | 1.104 | 0.929 | 1.235 | NA |
| 34 | Storbreen | 0.695 | 0.509 | 0.843 | 0.600 | 1.066 | 0.353 | 0.464 | 0.541 | 0.634 | 0.659 | 0.559 | 0.293 | 0.712 | 0.589 | 0.654 | 0.713 | 0.796 | 0.501 | 0.860 | 0.709 | 0.628 | NA |
| 35 | Djankuat | 0.839 | 0.897 | 0.866 | 0.757 | 0.644 | 0.703 | 0.806 | 0.813 | 0.877 | 0.947 | 0.734 | 1.053 | 0.601 | 0.820 | NA | NA | NA | NA | NA | NA | NA | NA |
| 36 | Ganbashi | 0.262 | 0.288 | 0.536 | 0.519 | 0.599 | 0.517 | 0.342 | 0.318 | 0.429 | 0.461 | 0.541 | 0.528 | 0.495 | 0.438 | 0.531 | 0.440 | NA | 0.386 | 0.543 | NA | NA | NA |
| 37 | Maliy Aktru | 0.453 | 0.396 | 0.417 | 0.456 | 0.412 | 0.423 | NA | NA | 0.439 | 0.409 | 0.435 | 0.411 | 0.385 | 0.448 | NA | 0.418 | 0.414 | NA | NA | NA | NA | NA |
| 38 | Vodopadniy | 0.500 | 0.520 | 0.480 | NA | 0.460 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 39 | Marmaglaciaeren | 0.382 | 0.276 | 0.584 | 0.354 | 0.296 | 0.383 | 0.359 | 0.342 | 0.259 | 0.443 | 0.668 | NA | 0.496 | 0.864 | 0.316 | 0.339 | 0.449 | NA | NA | NA | 0.648 | NA |
| 40 | Rabots Glaciaer | NA | NA | NA | NA | NA | 0.520 | 0.875 | 0.541 | NA | 0.933 | 0.838 | NA | 0.701 | 0.612 | 0.309 | 0.081 | 0.616 | NA | NA | 0.299 | NA | NA |
| 41 | Riukojietna | 0.423 | 0.280 | NA | 0.845 | 0.665 | 0.458 | 0.583 | 0.134 | NA | 0.257 | 0.466 | 0.602 | 0.266 | 0.330 | NA | 0.197 | 0.308 | NA | NA | 0.184 | NA | NA |
| 42 | Storglaciaeren | 1.261 | 0.952 | 0.720 | 1.032 | 0.720 | 0.768 | 1.489 | 0.938 | 0.715 | 1.090 | 0.773 | 0.776 | 0.824 | 0.981 | 0.430 | 0.705 | 1.051 | 0.897 | 1.008 | 0.579 | 0.915 | NA |
| 43 | Austre Broeggerbreen | 0.748 | 0.816 | NA | 0.766 | 0.304 | 0.375 | 0.391 | 0.418 | 0.334 | 0.427 | 0.508 | 0.403 | 0.505 | 0.339 | NA | NA | NA | NA | NA | NA | NA | NA |
| 44 | Midtre Lovenbreen | 0.714 | 0.476 | NA | 0.840 | 0.308 | 0.430 | 0.493 | 0.437 | 0.414 | 0.537 | 0.555 | 0.531 | 0.435 | 0.372 | NA | NA | NA | NA | NA | NA | NA | NA |
| 45 | Waldemarbreen | NA | NA | NA | NA | 0.428 | 0.291 | 0.554 | 0.494 | 0.597 | 0.878 | NA | NA | 0.862 | 1.327 | 0.655 | 0.480 | 0.415 | 0.508 | 0.710 | 0.705 | NA | NA |
| 46 | Gulkana | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.961 | 1.053 | 1.285 | 0.768 | 0.864 | 1.209 | 0.853 | 0.830 | 0.843 | 0.683 |
| 47 | Lemon Creek | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.245 | 1.166 | 1.300 | 1.240 | NA | 1.196 | 1.196 | 0.957 | 1.120 | NA |
| 48 | South Cascale | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 3.273 | NA | 2.314 | NA | NA | NA | 1.011 | 2.992 | 3.983 | NA | NA |
| 49 | Wolverine | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.368 | 0.633 | 1.085 | 0.981 | 0.984 | 0.816 | 1.398 | 1.280 | 1.309 | 1.150 |

**Annex 5.1 :** calculated annual absolute ablation gradients $db/dz_{abl}$ in m w.e. $(100m)^{-1}$ for the 49 selected glaciers in the period of analysis 1954-2017

## Annex 5.2

The table from Annex 5.2 it splitted on three pages due to its size.

| Nr. | Glacier NAme | 1954 | 1955 | 1956 | 1957 | 1958 | 1959 | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisfemer | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.793 | 0.838 | 0.722 | 0.716 | 0.732 | 1.008 | 0.665 | 0.736 | 0.678 | 0.760 |
| 2 | Jamtalfemer | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 3 | Kesselwandfemer | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.230 | 1.056 | 1.227 | 1.054 | 1.295 | 0.976 | 1.031 | |
| 4 | Vernagtfemer | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.818 | 0.812 | 0.746 | 0.675 | 0.815 | 0.832 | 0.785 | 0.620 | 0.756 |
| 5 | Zongo | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 6 | Devon Ice Cap NW | NA | NA | NA | NA | NA | NA | NA | 0.089 | 0.112 | 0.091 | 0.039 | 0.072 | 0.099 | 0.063 | NA | 0.126 | 0.095 | 0.088 | 0.061 | 0.110 |
| 7 | Hdin | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 8 | Peyto | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.483 | 0.546 | 0.449 | 0.520 | 0.551 | 0.681 | 0.586 | 0.752 |
| 9 | Place | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.437 | 0.609 | 0.651 | 0.649 | 0.670 | 0.605 | 0.502 | 0.510 |
| 10 | White | NA | NA | NA | NA | NA | NA | 0.207 | 0.145 | 0.243 | 0.167 | 0.081 | 0.167 | 0.152 | 0.143 | 0.193 | 0.194 | 0.149 | 0.179 | 0.095 | 0.152 |
| 11 | Allalin | NA | NA | 0.378 | 0.282 | 0.313 | 0.230 | 0.300 | 0.288 | 0.256 | 0.283 | 0.275 | 0.299 | 0.226 | 0.274 | 0.325 | 0.326 | 0.293 | 0.322 | 0.240 | 0.427 |
| 12 | Basodino | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 13 | Gietro | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.972 | 0.940 | 0.794 | 0.666 | 1.114 | 0.897 | 0.899 | |
| 14 | Gries | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.507 | 0.310 | 0.324 | 0.296 | 0.544 | 0.432 | 0.429 | 0.268 | 0.471 |
| 15 | Grosser Aletsch | 0.963 | 0.705 | 0.771 | 0.620 | 0.769 | 0.672 | 0.756 | 0.714 | 0.748 | 0.625 | 0.792 | 0.695 | 0.717 | 0.711 | 0.667 | 0.644 | 0.811 | 0.707 | 0.737 | 0.625 |
| 16 | Rhone | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 17 | Schwarzberg | NA | NA | 0.619 | 0.604 | 0.581 | 0.481 | 0.544 | 0.468 | 0.671 | 0.546 | 0.529 | 0.518 | 0.491 | 0.482 | 0.450 | 0.431 | 0.486 | 0.504 | 0.373 | 0.551 |
| 18 | Silvretta | 0.541 | 0.448 | 0.428 | 0.462 | 0.523 | 0.461 | 0.618 | 0.367 | 0.362 | 0.472 | 0.457 | 0.276 | 0.701 | 0.456 | 0.509 | 0.629 | 0.408 | 0.634 | 0.411 | 0.567 |
| 19 | Urumqi Glacier E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 20 | Urumqi Glacier W | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 21 | Abramov | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 22 | Golubin | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 23 | Shumskiy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 24 | Tuyuksuyskiy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 25 | Aalfotbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 26 | Austdalsbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 27 | Engabreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 28 | Grasubreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 29 | Hansebreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 30 | Hellstugubreen | NA | NA | NA | NA | NA | NA | NA | NA | 0.422 | 0.683 | 0.481 | 0.541 | 0.670 | 0.641 | 0.453 | 0.523 | 0.593 | 0.580 | 0.597 | 0.491 |
| 31 | Langfjordjoekelen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 32 | Nigardsbreen | NA | NA | NA | NA | NA | NA | NA | NA | 0.837 | 0.944 | 0.826 | 0.780 | 0.730 | 0.760 | 0.850 | 0.776 | 0.721 | 0.866 | 0.888 | 0.931 |
| 33 | Rembesdalskaaka | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.775 | 0.768 | 0.866 | 1.009 | 1.066 | 1.014 | 0.956 | 0.878 | 0.990 | 0.960 | 1.016 |
| 34 | Storbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 35 | Djankuat | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.774 | 0.836 | 0.811 | 0.928 | 0.863 | 0.976 |
| 36 | Garabashi | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 37 | Maliy Aktru | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.373 | NA | NA | 0.329 | 0.238 |
| 38 | Vodopadniy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 39 | Marmaglaciaren | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 40 | Rabots Glaciaer | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 41 | Riukojietna | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 42 | Storglaciaeren | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.651 | 0.969 |
| 43 | Austre Broeggerbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.867 |
| 44 | Midtre Lovenbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 45 | Waldemarbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 46 | Gulkana | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 47 | Lemon Creek | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 48 | South Cascade | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.490 | 1.460 | 1.350 | 1.915 | 1.289 | NA | 1.091 | 1.015 | |
| 49 | Wolverine | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.831 | NA | NA | NA | NA | NA | NA | NA |

| Nr. | Glacier NAme | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | 0.680 | 0.779 | 0.791 | 0.887 | 0.666 | 0.700 | 0.751 | 0.806 | 0.709 | 0.693 | 0.642 | 0.810 | 0.816 | 0.755 | 0.863 | 0.655 | 0.874 | 0.795 | 0.935 | 0.960 | 0.887 | 0.776 |
| 2 | Jamtalferner | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.661 | 0.543 | 0.494 | 0.471 | 0.620 | 0.531 | 0.386 |
| 3 | Kesselwandferner | 0.793 | 0.920 | 1.031 | 1.099 | 0.848 | 1.018 | 1.048 | 0.979 | 0.989 | 0.782 | 1.050 | 0.900 | 1.089 | 1.063 | 0.960 | 0.931 | 0.968 | 0.924 | 0.980 | 1.094 | 1.230 | 0.916 |
| 4 | Vernagtferner | 0.650 | 0.869 | 0.561 | 0.520 | 0.519 | 0.575 | 0.363 | 0.820 | 0.653 | 0.472 | 0.458 | 0.487 | 0.727 | 0.642 | 0.681 | 0.723 | 0.646 | 0.968 | 0.770 | 0.619 | 0.920 | 0.537 |
| 5 | Zongo | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.435 | 0.285 | 0.397 | 0.411 |
| 6 | Devon Ice Cap NW | 0.093 | 0.119 | NA | 0.093 | 0.085 | 0.105 | 0.106 | 0.071 | 0.105 | 0.099 | 0.081 | 0.119 | 0.124 | 0.104 | 0.123 | 0.102 | 0.109 | 0.105 | 0.109 | 0.094 | 0.142 | 0.141 |
| 7 | Helm | NA | NA | NA | NA | NA | NA | NA | NA | 0.145 | 0.655 | 0.406 | 0.681 | 0.698 | 1.042 | 0.878 | 0.867 | NA | NA | NA | NA | NA | NA |
| 8 | Peyto | 0.628 | NA | 0.619 | 0.573 | 0.641 | 0.668 | 0.616 | 0.539 | 0.523 | 0.454 | 0.532 | 0.620 | 0.580 | 0.678 | 0.724 | 0.156 | 0.690 | NA | NA | 0.527 | 0.817 | 0.585 |
| 9 | Place | 0.527 | NA | NA | NA | NA | NA | NA | 0.569 | 0.585 | 0.507 | 0.434 | 0.441 | 0.502 | 0.600 | 0.508 | 0.776 | NA | NA | NA | NA | 0.480 | 0.458 |
| 10 | White | 0.132 | 0.147 | 0.157 | 0.285 | 0.224 | 0.160 | NA | NA | NA | 0.226 | 0.181 | 0.137 | 0.305 | 0.243 | NA | NA | 0.162 | 0.148 | 0.108 | 0.172 | 0.168 | 0.220 |
| 11 | Allalin | 0.309 | 0.336 | 0.421 | 0.288 | 0.336 | 0.322 | 0.317 | 0.299 | 0.454 | 0.210 | 0.228 | 0.275 | 0.295 | 0.318 | 0.275 | 0.327 | 0.301 | 0.309 | 0.441 | 0.361 | 0.370 | 0.208 |
| 12 | Basodino | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.951 | 0.743 | 0.750 |
| 13 | Gietro | NA | 0.791 | 0.959 | 0.945 | 0.830 | 1.031 | 0.788 | 0.991 | 1.263 | 0.827 | 1.125 | 0.905 | 0.598 | 0.756 | 0.718 | 0.543 | 0.431 | 0.633 | 0.730 | 0.808 | 0.716 | 0.996 |
| 14 | Gries | 0.386 | 0.314 | 0.521 | 0.376 | 0.403 | 0.431 | 0.458 | 0.655 | 0.564 | 0.376 | 0.455 | 0.279 | 0.396 | 0.412 | 0.442 | 0.473 | 0.552 | 0.596 | 0.526 | 0.405 | 0.659 | 0.415 |
| 15 | Grosser Aletsch | 0.770 | 0.574 | 0.753 | 0.736 | 0.714 | 0.637 | 0.717 | 0.833 | 0.619 | 0.489 | 0.596 | 0.629 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 16 | Rhone | NA | NA | NA | NA | NA | NA | 0.697 | 0.674 | 0.740 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 17 | Schwarzberg | 0.428 | 0.263 | 0.490 | 0.377 | 0.354 | 0.516 | 0.351 | 0.430 | 0.610 | 0.477 | 0.372 | 0.444 | 0.531 | 0.504 | 0.512 | 0.471 | 0.569 | 0.335 | 0.306 | 0.323 | 0.245 | 0.332 |
| 18 | Silvretta | 0.540 | 0.645 | 0.670 | 0.711 | 0.642 | 0.489 | 0.628 | 0.581 | 0.639 | 0.679 | 0.699 | 0.455 | 0.475 | 0.326 | 0.426 | 0.688 | 0.548 | 0.642 | 0.722 | 0.730 | 0.821 | 0.537 |
| 19 | Urumqi Glacier E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.429 | 0.557 | 0.786 | 0.674 | 0.594 | 0.744 | 0.655 |
| 20 | Urumqi Glacier W | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.526 | 0.661 | 0.935 | 0.677 | 0.943 | 1.035 | 0.698 |
| 21 | Abramov | 0.620 | 0.505 | 0.592 | 0.536 | 0.607 | 0.555 | 0.422 | 0.501 | 0.757 | 0.591 | 0.567 | 0.700 | 0.575 | 0.630 | 0.636 | 0.394 | 0.704 | 0.470 | 0.581 | 0.667 | 0.659 | 0.809 |
| 22 | Golubin | NA | NA | NA | NA | NA | NA | NA | 0.466 | 0.460 | 0.590 | 0.641 | 0.602 | 0.459 | 0.694 | 0.669 | 0.503 | 0.775 | NA | NA | NA | NA | NA |
| 23 | Shumskiy | 0.361 | 0.259 | 0.288 | 0.376 | 0.240 | 0.264 | 0.338 | 0.385 | 0.406 | 0.323 | 0.305 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 24 | Tuyuksuyskiy | 0.450 | 0.430 | 0.459 | 0.475 | 0.537 | 0.421 | NA | 0.384 | 0.485 | 0.265 | 0.301 | 0.335 | 0.431 | NA | 0.407 | 0.351 | 0.604 | 0.528 | 0.491 | NA | 0.473 | 0.745 |
| 25 | Aalfotbreen | 0.585 | 0.391 | 0.524 | 0.605 | 0.548 | 0.474 | 0.926 | 0.577 | 0.396 | 0.702 | 0.755 | 0.668 | 0.543 | 0.911 | 0.718 | 1.298 | 0.793 | 0.566 | 1.327 | NA | 0.348 | 0.894 |
| 26 | Austdalsbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.096 | 0.983 | 0.786 | 0.807 | 1.188 | 0.819 | 0.899 | 0.744 |
| 27 | Engabreen | 1.028 | 0.842 | 0.856 | 0.958 | 0.848 | 1.039 | 1.122 | 0.945 | 0.974 | 0.811 | 1.181 | 0.897 | 0.856 | 0.961 | 1.064 | 1.233 | 1.172 | 0.988 | 1.155 | 0.882 | 0.844 | 0.842 |
| 28 | Graasubreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 29 | Hansebreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.911 | 1.291 | 1.008 | 1.017 | 1.000 | 0.856 | 1.567 | 0.844 | 1.337 | 1.280 |
| 30 | Hellstugubreen | 0.604 | 0.485 | 0.613 | 0.427 | 0.680 | 0.531 | 0.536 | 0.442 | 0.449 | 0.562 | 0.552 | 0.601 | 0.578 | 0.440 | 0.701 | 0.714 | 0.773 | 0.487 | 0.553 | 0.630 | 0.614 | 0.692 |
| 31 | Langfordjoekelen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.713 | 0.687 | 0.620 | 0.834 | 0.625 | NA | NA |
| 32 | Nigardsbreen | 0.975 | 0.826 | 0.801 | 0.746 | 0.687 | 0.701 | 0.784 | 0.686 | 0.805 | 0.865 | 0.826 | 0.600 | 0.768 | 0.673 | 0.909 | 0.882 | 0.869 | 0.753 | 0.790 | 0.849 | 0.686 | 0.821 |
| 33 | Rembesdalskaaka | 0.964 | 0.965 | 0.939 | 0.830 | NA | NA | NA | NA | NA | NA | NA | 0.757 | 0.891 | 0.702 | 0.983 | 0.808 | 0.875 | 1.016 | 1.051 | 0.773 | 1.020 | 1.007 |
| 34 | Storbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.517 | 0.773 | 0.508 | 0.572 | 0.453 | 0.580 |
| 35 | Djankuat | 0.725 | 0.752 | 0.799 | 0.766 | 0.705 | 0.734 | 0.746 | 0.698 | 0.821 | 0.820 | 0.709 | 0.740 | 0.707 | 0.811 | 0.775 | 0.750 | 0.669 | 0.758 | 0.676 | 0.766 | 0.877 | 0.799 |
| 36 | Garabashi | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.489 | 0.583 | 0.495 | 0.463 | 0.354 | 0.611 | 0.460 | 0.515 | 0.363 | 0.515 | 0.513 | 0.418 |
| 37 | Maliy Aktru | 0.381 | 0.433 | 0.400 | 0.454 | 0.376 | 0.357 | 0.490 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.356 | 0.435 | 0.452 | 0.455 | 0.467 |
| 38 | Vodopadniy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.319 | 0.253 | NA | 0.667 | 0.540 |
| 39 | Marmaglaciaeren | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.663 |
| 40 | Rabots Glaciaer | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.592 | 0.426 | 0.648 | 0.617 | 0.922 | NA | 0.561 | 0.613 | 0.417 | 0.766 |
| 41 | Riukojietna | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 42 | Storglaciaeren | 0.689 | 0.901 | NA | NA | NA | NA | NA | 0.721 | 0.808 | 0.923 | 1.104 | 0.869 | 1.008 | 0.687 | 0.855 | 1.195 | 1.230 | 1.172 | 1.247 | 1.009 | 0.736 | 1.145 |
| 43 | Austre Broeggerbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.363 | 0.309 | NA | 0.432 | 0.317 | 0.563 |
| 44 | Midtre Lovenbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 45 | Waldemarbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 46 | Gulkana | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 47 | Lemon Creek | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 48 | South Cascade | 1.863 | 1.398 | 2.074 | 1.173 | 1.595 | 1.568 | 1.607 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 49 | Wolverine | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |

| Nr. | Glacier NAme | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | 0.929 | 0.732 | 0.778 | 0.835 | 0.848 | 0.796 | 0.792 | 1.102 | 0.691 | 0.780 | 0.755 | 0.701 | 0.764 | 0.726 | 0.778 | 0.861 | 0.707 | 0.972 | 0.784 | 0.721 | 0.746 | 0.595 |
| 2 | Jamtalferner | 0.529 | 0.564 | NA | NA | 0.551 | 0.469 | 0.536 | 0.695 | 0.366 | 0.518 | 0.752 | 0.593 | 0.570 | 0.488 | NA | 0.484 | 0.423 | 0.511 | 0.472 | 0.476 | 0.490 | NA |
| 3 | Kesselwandferner | 0.784 | 0.790 | 1.023 | 0.859 | 1.026 | 0.841 | 0.877 | 1.303 | 0.787 | 0.886 | 0.945 | 1.361 | 1.349 | 1.315 | NA | 1.486 | 1.243 | 1.170 | 1.042 | 1.346 | 0.663 | 0.803 |
| 4 | Vernagtferner | 0.667 | 0.621 | 0.793 | 0.801 | 0.901 | 0.717 | 0.790 | 0.723 | 0.715 | 0.833 | 0.811 | 0.806 | 0.607 | 0.612 | 0.742 | 0.921 | 0.665 | 0.588 | 0.507 | 0.689 | NA | NA |
| 5 | Zongo | 0.584 | 0.298 | NA | NA | 0.533 | 0.841 | 0.666 | 0.405 | 0.458 | 0.799 | 0.468 | 0.771 | 0.353 | 0.881 | 1.303 | 0.453 | 0.749 | 0.576 | 0.488 | 0.419 | NA | NA |
| 6 | Devon Ice Cap NW | 0.053 | 0.081 | 0.125 | 0.114 | 0.107 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 7 | Helm | NA | NA | NA | NA | NA | NA | NA | NA | 1.026 | 1.030 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 8 | Peyto | 0.572 | 0.706 | 0.694 | 0.362 | 0.595 | 0.725 | 0.352 | 0.413 | 0.508 | 0.469 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 9 | Place | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.435 | 0.612 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 10 | White | 0.067 | 0.140 | 0.257 | 0.190 | 0.186 | 0.114 | NA | NA | 0.175 | 0.249 | 0.147 | 0.276 | NA | 0.205 | 0.182 | 0.251 | NA | NA | 0.158 | 0.215 | 0.172 | NA |
| 11 | Allalin | 0.302 | 0.324 | 0.332 | 0.322 | 0.377 | 0.316 | 0.298 | 0.415 | 0.281 | 0.382 | 0.338 | 0.392 | 0.400 | 0.246 | 0.276 | 0.313 | 0.361 | 0.193 | 0.323 | 0.657 | 0.170 | NA |
| 12 | Basodino | 0.655 | 0.720 | NA | 0.422 | 0.790 | 0.656 | 0.670 | 0.700 | 0.415 | 0.550 | 0.590 | 0.476 | NA | NA | NA | NA | 0.430 | NA | 0.380 | NA | NA | NA |
| 13 | Gietro | 0.310 | 0.542 | 0.578 | 0.530 | 0.719 | 0.832 | 0.752 | 0.951 | 0.532 | 0.515 | 0.515 | 0.599 | 0.519 | 0.456 | 0.403 | 0.525 | 0.570 | 0.470 | 0.516 | 0.608 | 0.455 | NA |
| 14 | Gries | 0.369 | 0.434 | 0.441 | 0.541 | 0.498 | 0.472 | 0.495 | 0.461 | 0.390 | 0.491 | 0.622 | 0.498 | NA | NA | NA | NA | 0.332 | 0.635 | 0.472 | 0.576 | 0.521 | NA |
| 15 | Grosser Aletsch | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 16 | Rhone | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.697 | 0.591 | 0.764 | NA | NA |
| 17 | Schwarzberg | 0.337 | 0.469 | 0.438 | 0.492 | 0.756 | 0.709 | 0.712 | 0.883 | 0.555 | 0.770 | 0.714 | 0.916 | 0.795 | 0.610 | 0.593 | 0.605 | 0.808 | 0.512 | 0.711 | 0.694 | 0.469 | NA |
| 18 | Silvretta | 0.584 | 0.738 | 0.593 | 0.739 | 0.675 | 0.995 | 1.200 | 0.595 | 0.614 | 0.905 | 0.838 | 0.793 | NA | NA | 0.574 | NA | 0.485 | 0.636 | 0.466 | 0.606 | 0.666 | NA |
| 19 | Urumqi Glacier E | NA | 0.783 | 0.836 | 0.933 | 0.715 | NA | NA | NA | 0.520 | 0.780 | 0.860 | 0.795 | 0.746 | 0.554 | 0.542 | 0.595 | 0.641 | 0.575 | 0.463 | 0.754 | 0.876 | NA |
| 20 | Urumqi Glacier W | 0.625 | 1.093 | 1.158 | 0.807 | 0.575 | 0.986 | NA | NA | 0.681 | 0.739 | 0.974 | 0.928 | 0.826 | 0.768 | 0.451 | 0.540 | 0.734 | 0.546 | 0.480 | 0.588 | 0.643 | NA |
| 21 | Abramov | 0.803 | 0.826 | 0.744 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.702 | 0.632 | 0.799 | 0.902 | 0.446 | NA |
| 22 | Golubin | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.434 | 0.601 | 0.469 | 0.600 | 0.525 | 0.829 | NA |
| 23 | Shumskiy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 24 | Tuyuksuyskiy | 0.575 | 0.652 | 0.752 | 0.541 | 0.695 | 0.600 | 0.631 | 0.586 | 0.452 | 0.724 | 0.478 | 0.648 | 0.600 | 0.485 | 0.687 | 0.644 | 0.648 | 0.660 | 0.618 | 0.552 | 0.774 | NA |
| 25 | Adlfobreen | 0.946 | 0.601 | 1.370 | 0.735 | 0.984 | 0.717 | 0.764 | 0.611 | 0.862 | 0.579 | 0.587 | 0.510 | 0.863 | 0.572 | 0.572 | 0.820 | 0.711 | 0.940 | 1.186 | 0.828 | NA | NA |
| 26 | Austdalsbreen | 0.841 | 0.967 | 1.151 | 1.111 | 1.363 | 1.260 | 1.473 | 1.105 | 1.401 | 1.083 | 0.765 | 1.012 | 1.423 | 1.150 | 0.902 | 0.930 | 1.158 | 0.906 | 1.190 | 1.000 | 1.149 | NA |
| 27 | Engabreen | 1.032 | 1.103 | 0.949 | 0.792 | 1.145 | 0.855 | 1.305 | 0.968 | 1.036 | 1.069 | 1.115 | 1.061 | 0.993 | 1.165 | 0.839 | 1.069 | 0.952 | 0.906 | 1.069 | 0.869 | 0.973 | NA |
| 28 | Grasubreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 29 | Hansebreen | 1.193 | 0.573 | NA | 0.871 | 1.010 | 0.748 | 1.058 | 0.606 | 0.754 | 0.855 | 0.460 | 0.817 | 0.959 | 0.834 | 0.466 | 0.781 | 0.793 | 0.927 | 0.645 | 0.840 | 0.970 | NA |
| 30 | Helstugubreen | 0.616 | 0.838 | 0.590 | 0.607 | 0.566 | 0.590 | 0.783 | 0.603 | 0.689 | 0.788 | 0.682 | 0.684 | 0.669 | 0.638 | 0.535 | 0.845 | 0.687 | 0.634 | 0.659 | 0.524 | 0.497 | NA |
| 31 | Langfjordjoekelen | 0.882 | 0.666 | 0.673 | 0.768 | 0.628 | 0.490 | 0.529 | 0.540 | 0.783 | 0.855 | 0.707 | 0.755 | 0.575 | 0.721 | 0.517 | 0.520 | 0.523 | 0.585 | 0.531 | 0.565 | 0.581 | NA |
| 32 | Nigardsbreen | 0.764 | 0.836 | 0.913 | 0.790 | 1.009 | 0.762 | 0.665 | 0.646 | 0.843 | 0.878 | 0.810 | 0.768 | 0.885 | 0.869 | 0.580 | 0.743 | 0.694 | 0.738 | 0.860 | 0.694 | 0.706 | NA |
| 33 | Rembesdalskaaka | 0.855 | 1.110 | 0.925 | 0.553 | 1.080 | 0.966 | 0.935 | 0.997 | 0.992 | 1.105 | 0.949 | 0.983 | 1.218 | 1.085 | 0.731 | 0.767 | 0.860 | 0.990 | 1.118 | 0.929 | 1.131 | NA |
| 34 | Storbreen | 0.662 | 0.698 | 0.713 | 0.634 | 0.951 | 0.550 | 0.595 | 0.558 | 0.605 | 0.647 | 0.480 | 0.431 | 0.734 | 0.924 | 0.675 | 0.625 | 0.653 | 0.616 | 0.778 | 0.581 | 0.721 | NA |
| 35 | Djankuat | 0.622 | 0.740 | 0.783 | 0.672 | 0.619 | 0.691 | 0.679 | 0.778 | 0.713 | 0.665 | 0.612 | 0.849 | 0.568 | 0.633 | NA | NA | NA | NA | NA | NA | NA | NA |
| 36 | Garabashi | 0.420 | 0.444 | 0.762 | 0.617 | 0.619 | 0.634 | 0.469 | 0.492 | 0.504 | 0.553 | 0.726 | 0.615 | 0.684 | 0.546 | 0.811 | 0.581 | NA | 0.500 | 0.690 | NA | NA | NA |
| 37 | Maliy Aktru | 0.461 | 0.454 | 0.469 | 0.459 | 0.441 | 0.454 | NA | NA | 0.457 | 0.414 | 0.448 | 0.440 | 0.429 | 0.417 | NA | 0.443 | 0.461 | NA | NA | NA | NA | NA |
| 38 | Vodopadniy | 0.472 | 0.642 | 0.516 | NA | 0.651 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 39 | Marmaglaciaeren | 0.969 | 1.200 | 0.691 | 0.618 | 0.806 | 0.671 | 0.938 | 0.918 | 0.869 | 0.562 | 1.157 | 1.970 | 0.902 | 1.698 | 0.480 | 0.773 | 0.600 | NA | NA | NA | 1.073 | NA |
| 40 | Rabots Glaciaer | NA | NA | NA | NA | NA | 0.500 | 0.787 | 0.439 | NA | 0.766 | 1.045 | NA | 1.232 | 0.954 | 0.462 | 0.368 | 0.831 | NA | NA | 0.331 | NA | NA |
| 41 | Riukojietna | 0.363 | 0.339 | NA | 0.836 | 0.679 | 0.446 | 0.617 | 0.186 | NA | 0.258 | 0.467 | 0.597 | 0.269 | 0.372 | 0.175 | NA | 0.319 | NA | NA | 0.205 | NA | NA |
| 42 | Storglaciaeren | 1.173 | 0.879 | 0.794 | 0.985 | 0.974 | 0.927 | 1.508 | 1.017 | 0.779 | 1.324 | 1.081 | 0.940 | 1.112 | 1.090 | 0.862 | 1.064 | 1.302 | 1.057 | 1.191 | 0.620 | 0.949 | NA |
| 43 | Austre Broeggerbreen | 0.427 | 0.457 | NA | 0.490 | 0.307 | 0.376 | 0.391 | 0.418 | 0.334 | 0.428 | 0.509 | 0.403 | 0.505 | 0.340 | NA | NA | NA | NA | NA | NA | NA | NA |
| 44 | Midtre Lovenbreen | 0.484 | 0.484 | NA | 0.533 | 0.312 | 0.430 | 0.493 | 0.437 | 0.414 | 0.537 | 0.554 | 0.531 | 0.435 | 0.372 | NA | NA | NA | NA | NA | NA | NA | NA |
| 45 | Waldemarbreen | NA | NA | NA | NA | 0.407 | 0.371 | 0.487 | 0.455 | 0.660 | 0.599 | NA | NA | 0.517 | 0.725 | 0.546 | 0.622 | 0.584 | 0.480 | 0.596 | 0.645 | NA | NA |
| 46 | Gulkana | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 47 | Lemon Creek | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.776 | 1.004 | 1.237 | 1.210 | NA | 1.209 | 1.447 | 1.298 | 0.976 | NA |
| 48 | South Cascade | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.851 | 1.585 | NA | NA | NA | 1.229 | 1.825 | 2.244 | NA | NA |
| 49 | Wolverine | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |

**Annex 5.2 :** calculated annual absolute glacier-wide gradients $db/dz_{gw}$ in m w.e. $(100m)^{-1}$ for the 49 selected glaciers in the period of analysis 1954-2017

## Annex 5.3

The table from Annex 5.3 it splitted on three pages due to its size.

| Nr. | Glacier NAme | 1954 | 1955 | 1956 | 1957 | 1958 | 1959 | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.341 | 0.546 | 0.215 | 0.262 | 0.222 | 0.298 | 0.230 | 0.270 | 0.200 | 0.355 |
| 2 | Jamtalferner | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 3 | Kesselwandferner | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.260 | 0.348 | 0.398 | 0.443 | NA | 0.442 | 0.390 |
| 4 | Vernagtferner | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.132 | 0.234 | 0.113 | 0.098 | 0.190 | 0.153 | 0.168 | 0.261 | 0.222 |
| 5 | Zongo | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 6 | Devon Ice Cap NW | NA | NA | NA | NA | NA | NA | 0.073 | 0.076 | 0.029 | 0.018 | 0.009 | 0.087 | 0.039 | NA | 0.124 | 0.021 | 0.117 | 0.054 | 0.101 | |
| 7 | Helm | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | |
| 8 | Peyto | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.259 | 0.329 | 0.158 | 0.320 | 0.370 | 0.696 | 0.535 | 0.500 | |
| 9 | Place | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.438 | 0.473 | 0.583 | 0.607 | 0.419 | 0.446 | |
| 10 | White | NA | NA | NA | NA | NA | NA | 0.193 | 0.069 | 0.249 | 0.104 | 0.044 | 0.051 | 0.070 | 0.052 | 0.105 | 0.091 | 0.071 | 0.096 | 0.011 | 0.051 |
| 11 | Allalin | NA | NA | 0.732 | 0.130 | 0.201 | 0.151 | 0.264 | 0.298 | 0.869 | 0.244 | 0.376 | 0.222 | 0.290 | 0.524 | 0.173 | 0.318 | 0.114 | 0.145 | 0.177 | 0.203 |
| 12 | Basodino | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 13 | Gietro | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.398 | 0.303 | 0.196 | 0.189 | 0.828 | 0.451 | 0.260 |
| 14 | Gries | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.399 | 0.382 | 0.126 | 0.118 | 0.167 | 0.201 | 0.233 | 0.212 | 0.106 | 0.282 |
| 15 | Grosser Aletsch | 0.281 | 0.596 | 0.866 | 0.447 | 0.461 | 0.695 | 0.569 | 0.482 | 0.460 | 0.484 | 0.554 | 0.406 | 0.448 | 0.626 | 0.334 | 0.507 | 0.483 | 0.447 | 0.344 | 0.526 |
| 16 | Rhone | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 17 | Schwarzberg | NA | NA | 0.423 | 0.336 | 0.434 | 0.232 | 0.330 | 0.263 | 0.744 | 0.403 | 0.387 | 0.413 | 0.404 | 0.279 | 0.270 | 0.279 | 0.337 | 0.306 | 0.239 | 0.354 |
| 18 | Silvretta | 0.311 | 0.294 | 0.196 | 0.242 | 0.318 | 0.341 | 0.419 | 0.200 | 0.285 | 0.417 | 0.310 | 0.217 | 0.322 | 0.266 | 0.299 | 0.316 | 0.166 | 0.153 | 0.209 | 0.441 |
| 19 | Urumqi Glacier E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 20 | Urumqi Glacier W | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 21 | Abramov | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.051 | NA | NA | NA | 0.146 | 0.100 | 0.225 |
| 22 | Golubin | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 23 | Shumskiy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.150 | 1.200 | NA | 0.465 | 2.050 | 0.075 | 2.000 |
| 24 | Tuyuksuyskiy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.340 | 0.250 | 0.070 | NA | NA | 0.500 | 0.500 | 0.215 | 0.370 | 0.580 |
| 25 | Aalfotbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.622 | 0.654 | 0.725 | 0.450 | 0.948 | 0.776 | 1.065 | 0.801 | 0.771 | |
| 26 | Austdalsbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 27 | Engabreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.500 | 0.650 | 0.350 | 1.650 | |
| 28 | Graasubreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.380 | 0.430 | 0.056 | 0.472 | 0.660 | 0.501 | 0.381 | 0.505 | 0.347 | |
| 29 | Hansebreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 30 | Hellstugubreen | NA | NA | NA | NA | NA | NA | NA | NA | 0.366 | 0.650 | 0.606 | 0.460 | 0.696 | 0.619 | 0.309 | 0.362 | 0.547 | 0.414 | 0.624 | 0.344 |
| 31 | Langfjordjoekelen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 32 | Nigardsbreen | NA | NA | NA | NA | NA | NA | NA | NA | 0.288 | 0.275 | 0.315 | 0.375 | 0.619 | 0.450 | 0.692 | 0.344 | 0.585 | 0.288 | 0.450 | 0.423 |
| 33 | Rembesdalskaaka | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.204 | 0.400 | 0.330 | 0.410 | 0.560 | 0.180 | 0.460 | 0.250 | 0.460 | 0.360 | 0.360 |
| 34 | Storbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 35 | Djankuat | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.578 | 0.468 | 0.515 | 0.263 | 0.448 | 0.600 | |
| 36 | Garabashi | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 37 | Maliy Aktru | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.015 | NA | 0.050 | 0.098 | |
| 38 | Vodopadniy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 39 | Marmagdaciaeren | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 40 | Rabots Glaciar | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 41 | Riukojietna | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 42 | Storglaciaeren | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 43 | Austre Broggerbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.378 | 0.587 | 0.721 |
| 44 | Midtre Lovenbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 45 | Waldemarbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 46 | Gulkana | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 47 | Lemon Creek | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 48 | South Cascade | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.750 | 0.300 | 0.550 | 0.250 | 0.394 | 0.438 | NA | 0.880 | 0.137 |
| 49 | Wolverine | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |

| Nr. | Glacier NAme | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | 0.275 | 0.340 | 0.352 | 0.648 | 0.290 | 0.268 | 0.398 | 0.422 | 0.388 | 0.290 | 0.562 | 0.232 | 0.440 | 0.448 | 0.438 | 0.241 | 0.454 | 0.372 | 0.675 | 0.440 | 0.347 | 0.479 |
| 2 | Jamtalferner | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.300 | 0.290 | 0.251 | 0.360 | 0.550 | 0.215 | 0.180 |
| 3 | Kesselwandferner | 0.260 | 0.428 | 0.188 | 0.364 | 0.186 | 0.280 | 0.178 | 0.070 | 0.452 | 0.286 | 0.480 | 0.278 | 0.248 | 0.214 | 0.386 | 0.316 | 0.246 | 0.436 | 0.362 | 0.322 | 0.542 | 0.260 |
| 4 | Vernagtferner | 0.098 | 0.126 | 0.084 | 0.036 | 0.162 | 0.112 | 0.108 | 0.264 | 0.318 | 0.232 | 0.129 | 0.145 | 0.348 | 0.121 | 0.184 | 0.147 | 0.219 | 0.389 | 0.404 | 0.295 | 0.435 | 0.161 |
| 5 | Zongo | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.306 | 0.117 | 0.130 | 0.300 |
| 6 | Devon Ice Cap NW | 0.080 | 0.091 | NA | 0.040 | 0.058 | 0.065 | 0.068 | 0.066 | 0.050 | 0.005 | 0.052 | 0.091 | 0.023 | 0.049 | 0.113 | 0.087 | 0.078 | 0.080 | 0.060 | 0.097 | 0.140 | 0.161 |
| 7 | Helm | NA | NA | NA | NA | NA | NA | NA | NA | 0.060 | 0.500 | 0.250 | 0.470 | 0.508 | 0.804 | 0.978 | 1.170 | NA | NA | NA | NA | NA | NA |
| 8 | Peyto | 0.506 | NA | 0.391 | 0.217 | 0.637 | 0.590 | 0.374 | 0.585 | 0.530 | 0.329 | 0.610 | 0.627 | 0.412 | 0.216 | 0.424 | 0.142 | 0.423 | NA | NA | 0.476 | 0.550 | 0.394 |
| 9 | Place | 0.421 | NA | NA | NA | NA | NA | NA | 0.298 | 0.134 | 0.505 | 0.278 | 0.347 | 0.250 | 0.441 | 0.412 | 0.580 | NA | NA | NA | NA | 0.530 | 0.621 |
| 10 | White | 0.056 | 0.044 | 0.067 | 0.230 | 0.159 | 0.097 | NA | NA | NA | 0.138 | 0.089 | 0.041 | 0.182 | 0.097 | NA | NA | 0.099 | 0.075 | 0.097 | 0.140 | 0.108 | 0.133 |
| 11 | Allalin | 0.180 | 0.153 | 0.223 | 0.178 | 0.204 | 0.182 | 0.361 | 0.170 | 0.273 | 0.129 | 0.097 | 0.216 | 0.176 | 0.288 | 0.189 | 0.171 | 0.185 | 0.289 | 0.249 | 0.200 | 0.238 | 0.165 |
| 12 | Basodino | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.380 | 0.290 | 0.000 |
| 13 | Gietro | NA | 0.247 | 0.612 | 0.321 | 0.266 | 0.466 | 0.197 | 0.325 | 0.504 | 0.237 | 0.532 | 0.299 | 0.264 | 0.274 | 0.389 | 0.250 | 0.183 | 0.367 | 0.344 | 0.377 | 0.401 | 0.530 |
| 14 | Gries | 0.208 | 0.140 | 0.239 | 0.292 | 0.202 | 0.244 | 0.287 | 0.363 | 0.366 | 0.210 | 0.257 | 0.218 | 0.268 | 0.341 | 0.301 | 0.287 | 0.374 | 0.454 | 0.334 | 0.252 | 0.457 | 0.201 |
| 15 | Grosser Aletsch | 0.549 | 0.598 | 0.562 | 0.571 | 0.578 | 0.434 | 0.420 | 0.563 | 0.507 | 0.412 | 0.503 | 0.501 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 16 | Rhone | NA | NA | NA | NA | NA | NA | 0.685 | 0.641 | 0.701 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 17 | Schwarzberg | 0.255 | 0.165 | 0.296 | 0.220 | 0.211 | 0.354 | 0.235 | 0.312 | 0.427 | 0.366 | 0.243 | 0.292 | 0.400 | 0.391 | 0.337 | 0.288 | 0.519 | 0.249 | 0.244 | 0.210 | 0.180 | 0.212 |
| 18 | Silvretta | 0.237 | 0.295 | 0.227 | 0.341 | 0.557 | 0.211 | 0.228 | 0.282 | 0.362 | 0.145 | 0.548 | 0.222 | 0.200 | 0.150 | 0.197 | 0.366 | 0.209 | 0.365 | 0.497 | 0.448 | 0.454 | 0.331 |
| 19 | Urumqi Glacier E | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.167 | 0.251 | 0.345 | 0.281 | 0.152 | 0.357 | 0.203 |
| 20 | Urumqi Glacier W | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.282 | 0.611 | 1.050 | 0.482 | 0.498 | 0.940 | 0.246 |
| 21 | Abramov | 0.088 | 0.330 | 0.167 | 0.176 | 0.278 | 0.209 | 0.130 | 0.144 | 0.201 | 0.229 | 0.156 | 0.231 | 0.270 | 0.171 | 0.111 | 0.088 | 0.176 | 0.137 | 0.158 | 0.188 | 0.211 | 0.275 |
| 22 | Golubin | NA | NA | NA | NA | NA | NA | NA | 0.862 | 0.274 | 0.551 | 0.367 | 0.288 | 0.258 | 0.663 | 1.178 | 0.973 | 1.843 | NA | NA | NA | NA | NA |
| 23 | Shumskiy | 1.300 | 1.400 | 0.850 | 1.400 | 2.000 | 1.300 | 1.500 | 0.300 | 0.650 | 0.525 | 0.475 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 24 | Tuyuksuyskiy | 0.335 | 0.390 | 0.490 | 0.228 | 0.295 | 0.529 | NA | 0.020 | 0.090 | 0.123 | 0.328 | 0.258 | 0.080 | NA | 0.098 | 0.110 | 0.260 | 0.670 | 0.360 | NA | 0.979 | 0.858 |
| 25 | Aalfotbreen | 0.581 | 0.410 | 0.568 | 0.625 | 0.450 | 0.501 | 0.776 | 0.572 | 0.694 | 0.633 | 0.250 | 0.526 | 0.450 | 1.008 | 0.645 | 0.800 | 0.150 | 0.464 | 0.925 | NA | 0.175 | 1.075 |
| 26 | Austdalsbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.778 | 0.960 | 0.360 | 0.400 | 0.693 | 0.471 | 0.320 | 0.174 |
| 27 | Engabreen | 0.325 | 0.600 | 1.700 | 0.275 | 0.500 | 0.400 | 0.522 | 0.550 | 0.400 | 0.410 | 0.350 | 0.167 | 0.575 | 0.550 | 0.325 | 0.475 | 0.242 | 0.225 | 0.575 | 0.300 | 0.250 | 0.450 |
| 28 | Graasubreen | *0.178* | NA | *0.094* | *0.320* | *0.610* | *0.120* | *0.656* | *0.290* | *0.362* | *0.468* | *0.340* | *0.279* | *0.494* | NA | *0.433* | NA | NA | *0.488* | *0.395* | *0.284* | *0.600* | *0.449* |
| 29 | Hansebreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.690 | 1.680 | 0.828 | 0.356 | 0.653 | 0.100 | 1.600 | 0.273 | 0.800 | 1.502 |
| 30 | Hellstugubreen | 0.537 | 0.451 | 0.750 | 0.246 | 0.391 | 0.339 | 0.769 | 0.210 | 0.261 | 0.499 | 0.436 | 0.377 | 0.565 | 0.399 | 0.803 | 0.902 | 0.768 | 0.314 | 0.468 | 0.360 | 0.351 | 1.010 |
| 31 | Langfordjoekelen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.820 | 0.510 | 0.240 | 0.230 | 0.410 | NA | NA |
| 32 | Nigardsbreen | 0.675 | 0.251 | 0.613 | 0.459 | 0.619 | 0.668 | 0.471 | 0.617 | 0.642 | 0.489 | 0.534 | 0.662 | 0.584 | 0.363 | 0.605 | 0.863 | 0.988 | 0.288 | 0.564 | 0.913 | 0.494 | 0.294 |
| 33 | Rembesdalskaaka | 0.500 | 0.400 | 0.400 | 0.280 | NA | NA | NA | NA | NA | NA | NA | 0.320 | 0.200 | 0.760 | 0.400 | 0.300 | 0.600 | 0.300 | 0.600 | 0.300 | 0.300 | 0.250 |
| 34 | Storbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.361 | 0.406 | 0.389 | 0.325 | 0.282 | 0.606 |
| 35 | Djankuat | 0.408 | 0.558 | 0.763 | 0.527 | 0.585 | 0.638 | 0.701 | 0.354 | 0.624 | 0.514 | 0.347 | 0.453 | 0.476 | 0.472 | 0.431 | 0.442 | 0.651 | 0.511 | 0.490 | 0.416 | 0.661 | 0.592 |
| 36 | Garabashi | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.710 | 1.020 | 0.695 | 1.100 | 0.235 | 0.560 | 0.570 | 1.060 | 0.465 | 1.050 | 1.020 | 1.050 |
| 37 | Maliy Aktru | 0.495 | 0.595 | 0.365 | 0.275 | 0.275 | 0.473 | 0.315 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.430 | 0.245 | 0.400 | 0.380 | 0.530 |
| 38 | Vodopadniy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.085 | 0.010 | NA | 0.070 | 0.300 |
| 39 | Marmaglaciaeren | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.048 |
| 40 | Rabots Glaciaer | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.533 | 0.357 | 0.636 | 0.518 | 0.992 | NA | 0.169 | 0.438 | 0.380 | 0.763 |
| 41 | Riukojietna | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 42 | Storglaciaeren | 0.375 | 0.634 | NA | NA | NA | NA | NA | 0.910 | 0.766 | 0.828 | 1.041 | 1.069 | 1.515 | 0.791 | 0.875 | 1.339 | 1.476 | 1.509 | 1.336 | 1.377 | 0.979 | 1.489 |
| 43 | Austre Broeggerbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.303 | 0.177 | NA | 0.156 | 0.086 | 0.307 |
| 44 | Midtre Lovenbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 45 | Waldemarbreen | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 46 | Gulkana | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 47 | Lemon Creek | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 48 | South Cascade | 0.260 | 0.372 | 0.070 | 0.311 | 0.954 | 0.828 | 0.874 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 49 | Wolverine | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |

| Nr. | Glacier NAme | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | 0.466 | 0.190 | 0.428 | 0.369 | 0.331 | 0.256 | 0.299 | 0.572 | 0.327 | 0.340 | 0.442 | 0.360 | 0.454 | 0.414 | 0.433 | 0.465 | 0.337 | 0.481 | 0.439 | 0.410 | 0.412 | 0.293 |
| 2 | Jamtalferner | 0.260 | 0.240 | NA | NA | 0.280 | 0.310 | 0.360 | 0.439 | 0.125 | 0.166 | 0.610 | 0.260 | 0.498 | 0.164 | NA | 0.247 | 0.192 | 0.243 | 0.291 | 0.135 | 0.162 | NA |
| 3 | Kesselwandferner | 0.487 | 0.256 | 0.684 | 0.320 | 0.352 | 0.422 | 0.272 | 0.618 | 0.365 | 0.398 | 0.679 | 0.528 | 0.354 | 0.815 | NA | 0.646 | 0.851 | 0.761 | 0.621 | 0.876 | 0.972 | 1.048 |
| 4 | Vernagtferner | 0.167 | 0.175 | 0.412 | 0.271 | 0.310 | 0.339 | 0.196 | 0.498 | 0.225 | 0.257 | 0.475 | 0.397 | 0.187 | 0.251 | 0.394 | 0.543 | 0.366 | 0.295 | 0.213 | 0.252 | NA | NA |
| 5 | Zongo | 0.297 | 0.061 | NA | NA | 0.152 | 0.410 | 0.222 | 0.104 | 0.182 | 0.412 | 0.053 | 0.209 | 0.047 | 0.140 | 0.352 | 0.210 | 0.397 | 0.189 | 0.209 | 0.369 | NA | NA |
| 6 | Devon Ice Cap NW | 0.069 | 0.049 | 0.088 | 0.092 | 0.107 | NA | 0.049 | 0.125 | 0.071 | 0.179 | 0.074 | 0.218 | 0.229 | 0.162 | 0.090 | 0.275 | NA | 0.355 | 0.270 | 0.376 | NA | NA |
| 7 | Helm | NA | NA | NA | NA | NA | NA | NA | NA | 0.180 | 0.220 | NA | NA | NA | NA | 0.272 | NA | NA | NA | NA | NA | NA | NA |
| 8 | Peyto | 0.299 | 0.423 | 0.330 | 0.051 | 0.328 | 0.499 | 0.159 | 0.121 | 0.202 | 0.245 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 9 | Place | NA | NA | NA | NA | NA | NA | NA | NA | 0.314 | 0.419 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 10 | White | 0.024 | 0.072 | 0.104 | 0.128 | 0.137 | 0.063 | 0.049 | 0.125 | 0.071 | 0.179 | 0.074 | 0.218 | 0.229 | 0.162 | 0.090 | 0.275 | NA | 0.106 | 0.201 | 0.078 | NA | NA |
| 11 | Allalin | 0.184 | 0.169 | 0.343 | 0.173 | 0.214 | 0.131 | 0.133 | 0.279 | 0.211 | 0.233 | 0.214 | 0.196 | 0.353 | 0.166 | 0.272 | 0.217 | 0.303 | 0.114 | 0.210 | 0.644 | 0.152 | NA |
| 12 | Basodino | 0.150 | 0.150 | NA | 0.100 | 0.600 | 0.420 | 0.200 | 0.400 | 0.290 | 0.700 | 0.600 | 0.420 | NA | NA | NA | NA | 0.480 | NA | 0.200 | 0.033 | 0.277 | NA |
| 13 | Gietro | 0.125 | 0.266 | 0.350 | 0.431 | 0.382 | 0.489 | 0.258 | 0.793 | 0.248 | 0.175 | 0.216 | 0.246 | 0.290 | 0.362 | 0.206 | 0.287 | 0.355 | 0.211 | 0.255 | 0.274 | 0.166 | NA |
| 14 | Gries | 0.157 | 0.287 | 0.389 | 0.369 | 0.291 | 0.579 | 0.279 | 0.395 | 0.258 | 0.352 | 0.518 | 0.415 | NA | NA | NA | NA | 0.182 | 0.541 | 0.466 | 0.410 | 0.292 | NA |
| 15 | Grosser Aletsch | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 16 | Rhone | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.355 | 0.270 | 0.376 | NA | NA |
| 17 | Schwarzberg | 0.253 | 0.318 | 0.418 | 0.352 | 0.379 | 0.365 | 0.377 | 0.601 | 0.342 | 0.410 | 0.479 | 0.507 | 0.399 | 0.399 | 0.437 | 0.403 | 0.628 | 0.342 | 0.458 | 0.408 | 0.302 | NA |
| 18 | Silvretta | 0.339 | 0.400 | 0.212 | 0.454 | 0.249 | 0.785 | 0.777 | 0.474 | 0.371 | 0.661 | 0.455 | 0.537 | NA | NA | 0.405 | NA | 0.319 | 0.396 | 0.484 | 0.575 | 0.482 | NA |
| 19 | Urumqi Glacier E | NA | 0.494 | 0.544 | 0.503 | 0.271 | NA | NA | NA | 0.471 | 0.485 | 0.438 | 0.334 | 0.454 | 0.271 | 0.315 | 0.244 | 0.377 | 0.328 | 0.150 | 0.517 | 0.632 | NA |
| 20 | Urumqi Glacier W | 0.205 | 0.506 | 0.430 | 0.370 | 0.196 | 0.826 | NA | NA | 0.293 | 0.054 | 0.402 | 0.572 | 0.538 | 0.146 | 0.186 | 0.201 | 0.401 | 0.371 | 0.237 | 0.381 | 0.428 | NA |
| 21 | Abramov | 0.470 | 0.517 | 0.269 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.266 | 0.207 | 0.270 | 0.325 | 0.093 | NA |
| 22 | Golubin | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.203 | 0.302 | 0.249 | 0.382 | 0.276 | 0.332 | NA |
| 23 | Shumskiy | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 24 | Tuyuksuyskiy | 0.476 | 0.328 | 0.717 | 0.596 | 1.000 | 1.047 | 2.013 | 0.565 | 0.307 | 0.530 | 0.535 | 0.650 | 0.511 | 0.376 | 1.407 | 0.609 | 0.983 | 0.817 | 0.932 | 0.747 | 0.739 | NA |
| 25 | Aalfotbreen | 0.570 | 0.339 | 1.039 | 1.023 | 0.839 | 0.200 | 0.458 | 0.256 | 0.810 | 0.950 | 0.598 | 0.380 | 0.654 | 0.515 | 0.545 | 0.496 | 0.471 | 0.429 | 0.400 | 0.157 | NA | NA |
| 26 | Austdalsbreen | 0.464 | 0.140 | 0.340 | 0.352 | 0.750 | 0.350 | 0.450 | 0.650 | 0.470 | 0.300 | 0.100 | 0.380 | 0.550 | 0.230 | 0.438 | 0.450 | 0.550 | 0.250 | 0.400 | 0.300 | 0.500 | NA |
| 27 | Engabreen | 0.275 | 0.600 | 0.400 | 0.775 | 0.375 | 0.400 | 0.375 | 0.375 | 0.600 | 0.650 | 0.500 | 0.450 | 0.300 | 0.450 | 0.250 | 0.800 | 0.325 | 0.550 | 0.500 | 0.450 | 0.600 | NA |
| 28 | Graastubreen | 0.413 | 0.740 | 0.297 | 0.499 | 0.298 | 0.370 | 0.720 | 0.445 | 0.373 | 0.385 | NA | 0.456 | 0.521 | 0.364 | 0.778 | 0.764 | 0.528 | 0.790 | 0.339 | 0.410 | 0.308 | NA |
| 29 | Hansebreen | 0.423 | 0.344 | NA | 1.500 | 0.650 | 1.000 | 0.900 | 0.519 | 0.474 | 0.528 | 0.300 | 0.400 | 0.305 | 0.356 | 0.307 | 0.550 | 0.235 | 0.900 | 0.400 | 0.550 | 0.550 | NA |
| 30 | Hellstugubreen | 0.354 | 0.842 | 0.712 | 0.414 | 0.463 | 0.362 | 0.608 | 0.540 | 0.428 | 0.946 | 0.562 | 0.786 | 0.530 | 0.688 | 0.608 | 0.615 | 0.854 | 0.641 | 0.634 | 0.313 | 0.422 | NA |
| 31 | Langfjordjoekelen | 0.480 | 0.055 | 0.215 | 0.645 | 0.365 | 0.250 | 0.415 | 0.420 | 0.490 | 0.535 | 0.605 | 0.415 | 0.345 | 0.470 | 0.235 | 0.320 | 0.300 | 0.300 | 0.170 | 0.170 | 0.175 | NA |
| 32 | Nigardsbreen | 0.387 | 0.524 | 0.524 | 0.415 | 0.363 | 0.304 | 0.332 | 0.215 | 0.438 | 0.538 | 0.323 | 0.506 | 0.287 | 0.325 | 0.218 | 0.405 | 0.225 | 0.386 | 0.176 | 0.552 | 0.249 | NA |
| 33 | Rembesdalskaaka | 0.590 | 0.260 | 0.600 | 1.200 | 0.060 | 0.480 | 0.550 | 0.900 | 0.300 | 0.500 | 0.310 | 0.500 | 0.400 | 0.800 | 0.350 | 0.350 | 0.640 | 0.400 | 0.397 | 0.800 | 0.300 | NA |
| 34 | Storbreen | 0.661 | 0.888 | 0.644 | 0.735 | 1.143 | 0.817 | 0.569 | 0.652 | 0.596 | 0.626 | 0.489 | 0.312 | 0.723 | 0.860 | 0.735 | 0.509 | 0.669 | 0.805 | 0.807 | 0.436 | 0.782 | NA |
| 35 | Djankuat | 0.398 | 0.706 | 0.573 | 0.475 | 0.462 | 0.555 | 0.397 | 0.613 | 0.480 | 0.378 | 0.266 | 0.684 | 0.411 | 0.354 | NA | NA | NA | NA | NA | NA | NA | NA |
| 36 | Garabashi | 0.880 | 0.800 | 1.100 | 0.725 | 0.670 | 0.835 | 0.960 | 1.510 | 0.830 | 0.870 | 0.955 | 0.685 | 0.735 | 0.575 | 1.310 | 0.837 | NA | 0.633 | 0.946 | NA | NA | NA |
| 37 | Maliy Aktru | 0.305 | 0.790 | 0.770 | 0.310 | 0.365 | 0.360 | NA | NA | 0.360 | 0.295 | 0.345 | 0.880 | 0.730 | 0.235 | NA | 0.515 | 0.745 | NA | NA | NA | NA | NA |
| 38 | Vodopadniy | 0.100 | 0.220 | 0.200 | 0.038 | 0.150 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 39 | Marmaglaciaeren | 1.729 | 1.842 | 0.934 | 0.967 | 1.333 | 0.991 | 2.261 | 1.693 | 1.555 | 1.750 | 1.788 | 1.970 | 0.971 | 3.335 | 0.482 | 1.500 | 0.632 | NA | 0.655 | 0.530 | 1.273 | NA |
| 40 | Rabots Glaciar | NA | NA | NA | NA | NA | 0.467 | 0.813 | 0.378 | NA | 0.660 | 1.176 | NA | 2.144 | 1.433 | 0.710 | 0.433 | 1.240 | NA | NA | 0.317 | NA | NA |
| 41 | Riukojietna | 0.025 | 0.350 | NA | 0.629 | 0.470 | 0.350 | 0.365 | 0.125 | NA | 0.150 | 0.405 | 0.475 | 0.235 | 0.460 | 0.175 | NA | 0.350 | NA | NA | 0.200 | NA | NA |
| 42 | Storglaciaeren | 1.216 | 0.844 | 0.949 | 1.186 | 1.139 | 1.136 | 1.403 | 1.098 | 1.098 | 1.373 | 1.731 | 1.230 | 1.170 | 0.986 | 1.256 | 1.399 | 1.628 | 1.162 | 1.443 | 0.524 | 0.646 | NA |
| 43 | Austre Broggerbreen | 0.248 | 0.317 | NA | 0.415 | 0.306 | 0.376 | 0.391 | 0.418 | 0.335 | 0.428 | 0.508 | 0.403 | 0.505 | 0.340 | NA | NA | NA | NA | NA | NA | NA | NA |
| 44 | Midtre Lovenbreen | 0.412 | 0.444 | NA | 0.543 | 0.312 | 0.430 | 0.493 | 0.437 | 0.414 | 0.537 | 0.554 | 0.531 | 0.435 | 0.372 | NA | NA | NA | NA | NA | NA | NA | NA |
| 45 | Waldemarbreen | NA | NA | NA | NA | 0.279 | 0.372 | 0.511 | 0.705 | 0.581 | 0.359 | NA | NA | 0.395 | 0.658 | 0.512 | 0.730 | 0.520 | 0.498 | 0.560 | 0.706 | NA | NA |
| 46 | Gulkana | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 47 | Lemon Creek | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.425 | 0.513 | 0.760 | 0.820 | NA | 0.800 | 1.260 | 1.200 | 0.500 | NA |
| 48 | South Cascale | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 1.425 | 1.389 | NA | NA | NA | 2.774 | 0.579 | 3.269 | NA | NA |
| 49 | Wolverine | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |

**Annex 5.3 :** calculated annual absolute accumulation gradients $db/dz_{acc}$ in m w.e. $(100m)^{-1}$ for the 49 selected glaciers in the period of analysis 1954-2017

# Annex 6.1

| Nr. | Glacier name | $\sigma$ | Interval limit values (m w.e. (100 m)$^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | (m w.e. (100 m)$^{-1}$) | $x - 2\sigma$ | $x - \sigma$ | $x - 1/2\sigma$ | **x** (mean *db/dz*) | $x + 1/2\sigma$ | $x + \sigma$ | $x + 2\sigma$ |
| 1 | Hintereisferner | **0.138** | 0.799 | 0.937 | 1.007 | **1.076** | 1.145 | 1.214 | 1.352 |
| 2 | Jamtalferner | **0.112** | 0.549 | 0.661 | 0.717 | **0.773** | 0.829 | 0.885 | 0.998 |
| 3 | Kesselwandferner | **0.289** | 0.589 | 0.879 | 1.024 | **1.168** | 1.313 | 1.458 | 1.747 |
| 4 | Vergtferner | **0.183** | 0.506 | 0.689 | 0.781 | **0.872** | 0.963 | 1.055 | 1.238 |
| 5 | Zongo | **0.582** | 0.540 | 1.122 | 1.413 | **1.704** | 1.995 | 2.286 | 2.868 |
| 6 | Devon Ice Cap NW | **0.032** | 0.042 | 0.073 | 0.089 | **0.105** | 0.121 | 0.137 | 0.168 |
| 7 | Helm | **0.424** | -0.099 | 0.325 | 0.537 | **0.748** | 0.960 | 1.172 | 1.596 |
| 8 | Peyto | **0.203** | 0.207 | 0.410 | 0.512 | **0.613** | 0.715 | 0.817 | 1.020 |
| 9 | Place | **0.328** | 0.306 | 0.634 | 0.798 | **0.961** | 1.125 | 1.289 | 1.617 |
| 10 | White | **0.053** | 0.109 | 0.162 | 0.189 | **0.215** | 0.241 | 0.268 | 0.321 |
| 11 | Allalin | **0.105** | 0.157 | 0.262 | 0.314 | **0.367** | 0.419 | 0.472 | 0.577 |
| 12 | Basodino | **0.283** | 0.130 | 0.413 | 0.554 | **0.695** | 0.837 | 0.978 | 1.261 |
| 13 | Gietro | **0.180** | 0.455 | 0.635 | 0.725 | **0.815** | 0.905 | 0.995 | 1.174 |
| 14 | Gries | **0.169** | 0.402 | 0.571 | 0.655 | **0.740** | 0.825 | 0.909 | 1.079 |
| 15 | Grosser Aletsch | **0.158** | 0.443 | 0.602 | 0.681 | **0.760** | 0.839 | 0.918 | 1.076 |
| 16 | Rhone | **0.099** | 0.640 | 0.738 | 0.788 | **0.837** | 0.886 | 0.936 | 1.034 |
| 17 | Schwarzberg | **0.214** | 0.288 | 0.502 | 0.609 | **0.716** | 0.823 | 0.930 | 1.144 |
| 18 | Silvretta | **0.290** | 0.406 | 0.696 | 0.841 | **0.985** | 1.130 | 1.275 | 1.565 |
| 19 | Urumqi Glacier E | **0.222** | 0.834 | 1.056 | 1.167 | **1.278** | 1.389 | 1.500 | 1.722 |
| 20 | Urumqi Glacier W | **0.227** | 0.671 | 0.898 | 1.012 | **1.126** | 1.239 | 1.353 | 1.580 |
| 21 | Abramov | **0.134** | 0.454 | 0.588 | 0.655 | **0.722** | 0.789 | 0.855 | 0.989 |
| 22 | Golubin | **0.177** | 0.232 | 0.409 | 0.498 | **0.587** | 0.675 | 0.764 | 0.941 |
| 23 | Shumskiy | **0.060** | 0.194 | 0.253 | 0.283 | **0.313** | 0.342 | 0.372 | 0.432 |
| 24 | Tuyuksuyskiy | **0.135** | 0.189 | 0.324 | 0.391 | **0.458** | 0.525 | 0.593 | 0.727 |
| 25 | Aalfotbreen | **0.326** | 0.109 | 0.435 | 0.598 | **0.761** | 0.924 | 1.088 | 1.414 |
| 26 | Austdalsbreen | **0.312** | 0.802 | 1.113 | 1.269 | **1.425** | 1.581 | 1.737 | 2.049 |
| 27 | Engabreen | **0.156** | 0.754 | 0.909 | 0.987 | **1.065** | 1.143 | 1.221 | 1.376 |
| 28 | Graasubreen | ***NA*** | NA | NA | NA | ***NA*** | NA | NA | NA |
| 29 | Hansebreen | **0.243** | 0.272 | 0.514 | 0.636 | **0.757** | 0.878 | 0.999 | 1.242 |
| 30 | Hellstugubreen | **0.130** | 0.436 | 0.566 | 0.631 | **0.696** | 0.761 | 0.826 | 0.956 |
| 31 | Langfordjoekelen | **0.146** | 0.463 | 0.609 | 0.682 | **0.754** | 0.827 | 0.900 | 1.046 |
| 32 | Nigardsbreen | **0.125** | 0.615 | 0.740 | 0.803 | **0.865** | 0.928 | 0.991 | 1.116 |
| 33 | Rembesdalskaaka | **0.147** | 0.673 | 0.820 | 0.893 | **0.967** | 1.040 | 1.113 | 1.260 |
| 34 | Storbreen | **0.182** | 0.311 | 0.492 | 0.583 | **0.674** | 0.765 | 0.856 | 1.038 |
| 35 | Djankuat | **0.150** | 0.567 | 0.718 | 0.793 | **0.868** | 0.943 | 1.018 | 1.169 |
| 36 | Garabashi | **0.096** | 0.245 | 0.341 | 0.389 | **0.437** | 0.485 | 0.533 | 0.629 |
| 37 | Maliy Aktru | **0.118** | 0.220 | 0.338 | 0.397 | **0.455** | 0.514 | 0.573 | 0.691 |
| 38 | Vodopadniy | **0.158** | 0.137 | 0.295 | 0.374 | **0.453** | 0.532 | 0.611 | 0.768 |
| 39 | Marmaglaciaeren | **0.156** | 0.129 | 0.285 | 0.363 | **0.441** | 0.519 | 0.597 | 0.753 |
| 40 | Rabots Glaciaer | **0.274** | 0.111 | 0.384 | 0.521 | **0.658** | 0.795 | 0.931 | 1.205 |
| 41 | Riukojietna | **0.196** | 0.008 | 0.204 | 0.302 | **0.400** | 0.498 | 0.596 | 0.792 |
| 42 | Storglaciaeren | **0.217** | 0.394 | 0.611 | 0.720 | **0.828** | 0.937 | 1.045 | 1.262 |
| 43 | Austre Broeggerbreen | **0.215** | 0.132 | 0.347 | 0.454 | **0.562** | 0.669 | 0.777 | 0.991 |
| 44 | Midtre Lovenbreen | **0.136** | 0.231 | 0.367 | 0.435 | **0.503** | 0.571 | 0.639 | 0.775 |
| 45 | Waldemarbreen | **0.250** | 0.135 | 0.386 | 0.511 | **0.636** | 0.761 | 0.886 | 1.137 |
| 46 | Gulkana | **0.183** | 0.569 | 0.752 | 0.843 | **0.935** | 1.026 | 1.118 | 1.301 |
| 47 | Lemon Creek | **0.098** | 0.982 | 1.080 | 1.129 | **1.178** | 1.226 | 1.275 | 1.373 |
| 48 | South Cascade | **0.854** | 0.595 | 1.449 | 1.875 | **2.302** | 2.729 | 3.156 | 4.009 |
| 49 | Wolverine | **0.305** | 0.390 | 0.695 | 0.848 | **1.000** | 1.153 | 1.305 | 1.610 |

**Annex 6.1 :** Standard deviation and mean from the absolute ablation gradients used to calculate the interval limit values of the relative ablation gradients. All values are given in m w.e. (100m)$^{-1}$.

# Annex 6.2

| Nr. | Glacier name | $\sigma$ | Interval limit values (m w.e. (100 m)$^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | (m w.e. (100 m)$^{-1}$) | $x - 2\sigma$ | $x - \sigma$ | $x - 1/2\sigma$ | **x** (mean $db/dz$) | $x + 1/2\sigma$ | $x + \sigma$ | $x + 2\sigma$ |
| 1 | Hintereisferner | **0.097** | 0.589 | 0.686 | 0.734 | **0.783** | 0.831 | 0.880 | 0.977 |
| 2 | Jamtalferner | **0.087** | 0.354 | 0.441 | 0.484 | **0.528** | 0.571 | 0.615 | 0.702 |
| 3 | Kesselwandferner | **0.182** | 0.664 | 0.846 | 0.937 | **1.028** | 1.119 | 1.210 | 1.392 |
| 4 | Vergtferner | **0.132** | 0.432 | 0.565 | 0.631 | **0.697** | 0.763 | 0.829 | 0.962 |
| 5 | Zongo | **0.235** | 0.102 | 0.337 | 0.454 | **0.571** | 0.689 | 0.806 | 1.041 |
| 6 | Devon Ice Cap NW | **0.022** | 0.054 | 0.076 | 0.088 | **0.099** | 0.110 | 0.121 | 0.144 |
| 7 | Helm | **0.278** | 0.188 | 0.465 | 0.604 | **0.743** | 0.882 | 1.020 | 1.298 |
| 8 | Peyto | **0.126** | 0.319 | 0.445 | 0.508 | **0.571** | 0.634 | 0.697 | 0.823 |
| 9 | Place | **0.087** | 0.375 | 0.462 | 0.506 | **0.549** | 0.593 | 0.637 | 0.724 |
| 10 | White | **0.050** | 0.079 | 0.130 | 0.155 | **0.180** | 0.205 | 0.230 | 0.280 |
| 11 | Allalin | **0.074** | 0.170 | 0.244 | 0.280 | **0.317** | 0.354 | 0.391 | 0.464 |
| 12 | Basodino | **0.157** | 0.305 | 0.462 | 0.540 | **0.619** | 0.697 | 0.775 | 0.932 |
| 13 | Gietro | **0.216** | 0.294 | 0.510 | 0.618 | **0.726** | 0.834 | 0.941 | 1.157 |
| 14 | Gries | **0.099** | 0.259 | 0.358 | 0.408 | **0.457** | 0.507 | 0.556 | 0.655 |
| 15 | Grosser Aletsch | **0.087** | 0.529 | 0.616 | 0.660 | **0.704** | 0.747 | 0.791 | 0.878 |
| 16 | Rhone | **0.055** | 0.584 | 0.639 | 0.667 | **0.694** | 0.721 | 0.749 | 0.804 |
| 17 | Schwarzberg | **0.148** | 0.231 | 0.379 | 0.453 | **0.527** | 0.600 | 0.674 | 0.822 |
| 18 | Silvretta | **0.161** | 0.274 | 0.435 | 0.515 | **0.595** | 0.676 | 0.756 | 0.917 |
| 19 | Urumqi Glacier E | **0.134** | 0.415 | 0.549 | 0.616 | **0.684** | 0.751 | 0.818 | 0.952 |
| 20 | Urumqi Glacier W | **0.195** | 0.365 | 0.560 | 0.657 | **0.755** | 0.852 | 0.949 | 1.144 |
| 21 | Abramov | **0.134** | 0.340 | 0.474 | 0.541 | **0.608** | 0.676 | 0.743 | 0.877 |
| 22 | Golubin | **0.115** | 0.353 | 0.468 | 0.525 | **0.582** | 0.640 | 0.697 | 0.812 |
| 23 | Shumskiy | **0.051** | 0.219 | 0.270 | 0.295 | **0.321** | 0.347 | 0.372 | 0.424 |
| 24 | Tuyuksuyskiy | **0.122** | 0.294 | 0.416 | 0.477 | **0.538** | 0.599 | 0.659 | 0.781 |
| 25 | Aalfotbreen | **0.230** | 0.280 | 0.510 | 0.625 | **0.740** | 0.855 | 0.970 | 1.199 |
| 26 | Austdalsbreen | **0.201** | 0.656 | 0.857 | 0.957 | **1.057** | 1.158 | 1.258 | 1.459 |
| 27 | Engabreen | **0.131** | 0.730 | 0.861 | 0.926 | **0.991** | 1.057 | 1.122 | 1.253 |
| 28 | Graasubreen | ***NA*** | *NA* | *NA* | *NA* | ***NA*** | *NA* | *NA* | *NA* |
| 29 | Hansebreen | **0.247** | 0.415 | 0.662 | 0.785 | **0.909** | 1.033 | 1.156 | 1.403 |
| 30 | Hellstugubreen | **0.101** | 0.398 | 0.500 | 0.550 | **0.601** | 0.652 | 0.702 | 0.804 |
| 31 | Langfordjoekelen | **0.112** | 0.425 | 0.537 | 0.593 | **0.649** | 0.705 | 0.761 | 0.873 |
| 32 | Nigardsbreen | **0.091** | 0.612 | 0.703 | 0.749 | **0.794** | 0.839 | 0.885 | 0.976 |
| 33 | Rembesdalskaaka | **0.129** | 0.682 | 0.811 | 0.875 | **0.940** | 1.004 | 1.068 | 1.197 |
| 34 | Storbreen | **0.123** | 0.393 | 0.515 | 0.577 | **0.638** | 0.700 | 0.761 | 0.884 |
| 35 | Djankuat | **0.084** | 0.579 | 0.664 | 0.706 | **0.748** | 0.790 | 0.832 | 0.917 |
| 36 | Garabashi | **0.111** | 0.327 | 0.438 | 0.493 | **0.548** | 0.604 | 0.659 | 0.770 |
| 37 | Maliy Aktru | **0.052** | 0.317 | 0.370 | 0.396 | **0.422** | 0.448 | 0.474 | 0.527 |
| 38 | Vodopadniy | **0.144** | 0.219 | 0.363 | 0.435 | **0.508** | 0.580 | 0.652 | 0.796 |
| 39 | Marmaglaciaeren | **0.370** | 0.184 | 0.554 | 0.739 | **0.924** | 1.109 | 1.294 | 1.664 |
| 40 | Rabots Glaciaer | **0.239** | 0.187 | 0.425 | 0.545 | **0.664** | 0.783 | 0.902 | 1.141 |
| 41 | Riukojietna | **0.190** | 0.028 | 0.218 | 0.313 | **0.408** | 0.504 | 0.599 | 0.789 |
| 42 | Storglaciaeren | **0.199** | 0.589 | 0.787 | 0.886 | **0.986** | 1.085 | 1.184 | 1.383 |
| 43 | Austre Broeggerbreen | **0.073** | 0.263 | 0.336 | 0.373 | **0.409** | 0.446 | 0.482 | 0.555 |
| 44 | Midtre Lovenbreen | **0.068** | 0.326 | 0.394 | 0.429 | **0.463** | 0.497 | 0.531 | 0.600 |
| 45 | Waldemarbreen | **0.098** | 0.354 | 0.452 | 0.501 | **0.550** | 0.599 | 0.647 | 0.745 |
| 46 | Gulkana | ***NA*** | *NA* | *NA* | *NA* | ***NA*** | *NA* | *NA* | *NA* |
| 47 | Lemon Creek | **0.199** | 0.747 | 0.946 | 1.045 | **1.145** | 1.244 | 1.343 | 1.542 |
| 48 | South Cascade | **0.357** | 0.809 | 1.166 | 1.344 | **1.523** | 1.701 | 1.879 | 2.236 |
| 49 | Wolverine | ***NA*** | *NA* | *NA* | *NA* | *NA* | *NA* | *NA* | *NA* |

**Annex 6.2 :** Standard deviation and mean from the absolute glacier-wide gradients used to calculate the interval limit values of the relative glacier-wide gradients. All values are given in m w.e. (100m)$^{-1}$.

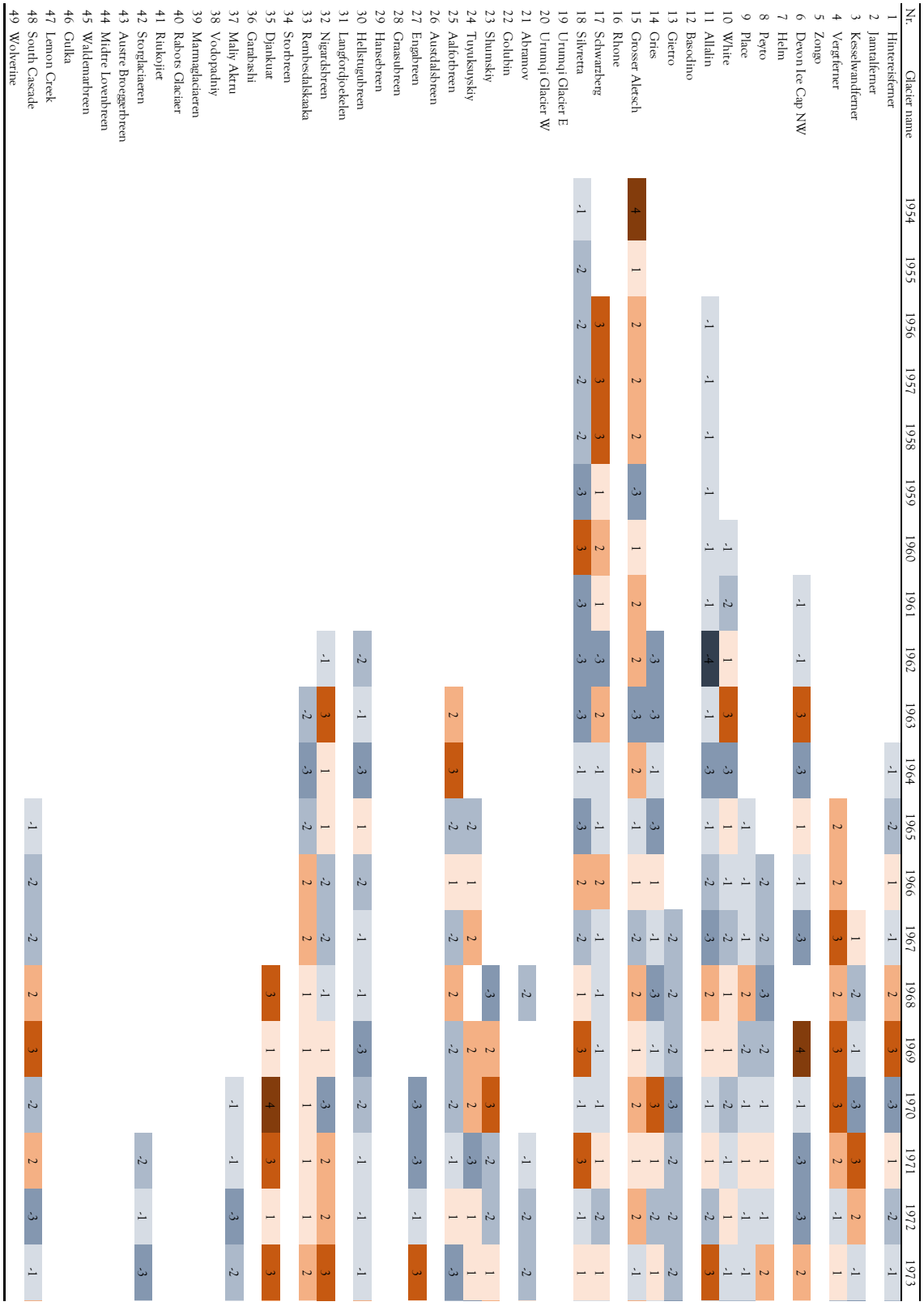
# Annex 6.3

| Nr. | Glacier name | $\sigma$ | Interval limit values (m w.e. (100 m)$^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | (m w.e. (100 m)$^{-1}$) | $x - 2\sigma$ | $x - \sigma$ | $x - 1/2\sigma$ | **x** (mean *db/dz*) | $x + 1/2\sigma$ | $x + \sigma$ | $x + 2\sigma$ |
| 1 | Hintereisferner | **0.108** | 0.158 | 0.267 | 0.321 | **0.375** | 0.429 | 0.484 | 0.592 |
| 2 | Jamtalferner | **0.124** | 0.038 | 0.162 | 0.223 | **0.285** | 0.347 | 0.409 | 0.532 |
| 3 | Kesselwandferner | **0.214** | 0.009 | 0.223 | 0.330 | **0.437** | 0.544 | 0.651 | 0.865 |
| 4 | Vergtferner | **0.118** | 0.006 | 0.124 | 0.183 | **0.241** | 0.300 | 0.359 | 0.477 |
| 5 | Zongo | **0.115** | -0.009 | 0.106 | 0.164 | **0.221** | 0.279 | 0.337 | 0.452 |
| 6 | Devon Ice Cap NW | **0.035** | 0.001 | 0.036 | 0.054 | **0.071** | 0.089 | 0.106 | 0.141 |
| 7 | Helm | **0.347** | -0.180 | 0.167 | 0.340 | **0.514** | 0.688 | 0.861 | 1.208 |
| 8 | Peyto | **0.162** | 0.061 | 0.223 | 0.304 | **0.385** | 0.466 | 0.547 | 0.709 |
| 9 | Place | **0.139** | 0.148 | 0.287 | 0.356 | **0.426** | 0.495 | 0.564 | 0.703 |
| 10 | White | **0.061** | -0.012 | 0.049 | 0.079 | **0.110** | 0.140 | 0.171 | 0.232 |
| 11 | Allalin | **0.138** | -0.033 | 0.105 | 0.174 | **0.244** | 0.313 | 0.382 | 0.520 |
| 12 | Basodino | **0.194** | -0.073 | 0.122 | 0.219 | **0.316** | 0.413 | 0.510 | 0.705 |
| 13 | Gietro | **0.145** | 0.045 | 0.190 | 0.262 | **0.335** | 0.407 | 0.480 | 0.625 |
| 14 | Gries | **0.110** | 0.076 | 0.186 | 0.241 | **0.296** | 0.351 | 0.407 | 0.517 |
| 15 | Grosser Aletsch | **0.108** | 0.290 | 0.399 | 0.453 | **0.507** | 0.561 | 0.615 | 0.723 |
| 16 | Rhone | **0.175** | 0.155 | 0.330 | 0.417 | **0.505** | 0.592 | 0.680 | 0.855 |
| 17 | Schwarzberg | **0.108** | 0.135 | 0.243 | 0.297 | **0.351** | 0.405 | 0.459 | 0.567 |
| 18 | Silvretta | **0.143** | 0.063 | 0.206 | 0.278 | **0.349** | 0.421 | 0.493 | 0.636 |
| 19 | Urumqi Glacier E | **0.132** | 0.095 | 0.226 | 0.292 | **0.358** | 0.423 | 0.489 | 0.621 |
| 20 | Urumqi Glacier W | **0.235** | -0.053 | 0.182 | 0.300 | **0.417** | 0.535 | 0.652 | 0.888 |
| 21 | Abramov | **0.099** | 0.009 | 0.108 | 0.158 | **0.208** | 0.257 | 0.307 | 0.406 |
| 22 | Golubin | **0.436** | -0.309 | 0.127 | 0.344 | **0.562** | 0.780 | 0.998 | 1.434 |
| 23 | Shumskiy | **0.596** | -0.095 | 0.501 | 0.799 | **1.096** | 1.394 | 1.692 | 2.288 |
| 24 | Tuyuksuyskiy | **0.374** | -0.222 | 0.152 | 0.339 | **0.526** | 0.713 | 0.899 | 1.273 |
| 25 | Aalfotbreen | **0.245** | 0.115 | 0.359 | 0.482 | **0.604** | 0.727 | 0.849 | 1.094 |
| 26 | Austdalsbreen | **0.192** | 0.050 | 0.242 | 0.338 | **0.433** | 0.529 | 0.625 | 0.817 |
| 27 | Engabreen | **0.286** | -0.075 | 0.210 | 0.353 | **0.496** | 0.639 | 0.782 | 1.067 |
| 28 | Graasubreen | **0.169** | 0.096 | 0.265 | 0.349 | **0.434** | 0.518 | 0.603 | 0.771 |
| 29 | Hansebreen | **0.417** | -0.179 | 0.238 | 0.447 | **0.656** | 0.864 | 1.073 | 1.491 |
| 30 | Hellstugubreen | **0.190** | 0.156 | 0.346 | 0.442 | **0.537** | 0.632 | 0.727 | 0.918 |
| 31 | Langfordjoekelen | **0.170** | 0.029 | 0.199 | 0.284 | **0.369** | 0.453 | 0.538 | 0.708 |
| 32 | Nigardsbreen | **0.178** | 0.107 | 0.285 | 0.374 | **0.463** | 0.551 | 0.640 | 0.818 |
| 33 | Rembesdalskaaka | **0.206** | 0.026 | 0.232 | 0.335 | **0.438** | 0.540 | 0.643 | 0.849 |
| 34 | Storbreen | **0.203** | 0.218 | 0.421 | 0.522 | **0.623** | 0.724 | 0.826 | 1.028 |
| 35 | Djankuat | **0.117** | 0.271 | 0.388 | 0.447 | **0.506** | 0.564 | 0.623 | 0.741 |
| 36 | Garabashi | **0.254** | 0.338 | 0.592 | 0.719 | **0.846** | 0.973 | 1.100 | 1.354 |
| 37 | Maliy Aktru | **0.213** | -0.014 | 0.199 | 0.305 | **0.412** | 0.518 | 0.625 | 0.838 |
| 38 | Vodopadniy | **0.089** | -0.048 | 0.041 | 0.086 | **0.130** | 0.175 | 0.220 | 0.309 |
| 39 | Marmaglaciaeren | **0.660** | 0.072 | 0.732 | 1.062 | **1.392** | 1.722 | 2.052 | 2.713 |
| 40 | Rabots Glaciaer | **0.460** | -0.193 | 0.267 | 0.498 | **0.728** | 0.958 | 1.188 | 1.649 |
| 41 | Riukojietna | **0.157** | 0.004 | 0.161 | 0.239 | **0.318** | 0.396 | 0.475 | 0.632 |
| 42 | Storglaciaeren | **0.336** | 0.415 | 0.752 | 0.920 | **1.088** | 1.256 | 1.424 | 1.761 |
| 43 | Austre Broeggerbreen | **0.111** | 0.113 | 0.224 | 0.279 | **0.334** | 0.390 | 0.445 | 0.556 |
| 44 | Midtre Lovenbreen | **0.070** | 0.315 | 0.385 | 0.420 | **0.455** | 0.490 | 0.525 | 0.595 |
| 45 | Waldemarbreen | **0.136** | 0.256 | 0.392 | 0.460 | **0.528** | 0.595 | 0.663 | 0.799 |
| 46 | Gulkana | ***NA*** | *NA* | *NA* | *NA* | ***NA*** | *NA* | *NA* | *NA* |
| 47 | Lemon Creek | **0.293** | 0.200 | 0.492 | 0.639 | **0.785** | 0.931 | 1.077 | 1.370 |
| 48 | South Cascade | **0.818** | -0.796 | 0.022 | 0.431 | **0.840** | 1.249 | 1.658 | 2.476 |
| 49 | Wolverine | ***NA*** | *NA* | *NA* | *NA* | ***NA*** | *NA* | *NA* | *NA* |

**Annex 6.3 :** Standard deviation and mean from the absolute accumulation gradients used to calculate the interval limit values of the relative accumulation gradients. All values are given in m w.e. (100m)$^{-1}$.

## Annex 7.1

The table from Annex 7.1 it splitted on three pages due to its size.



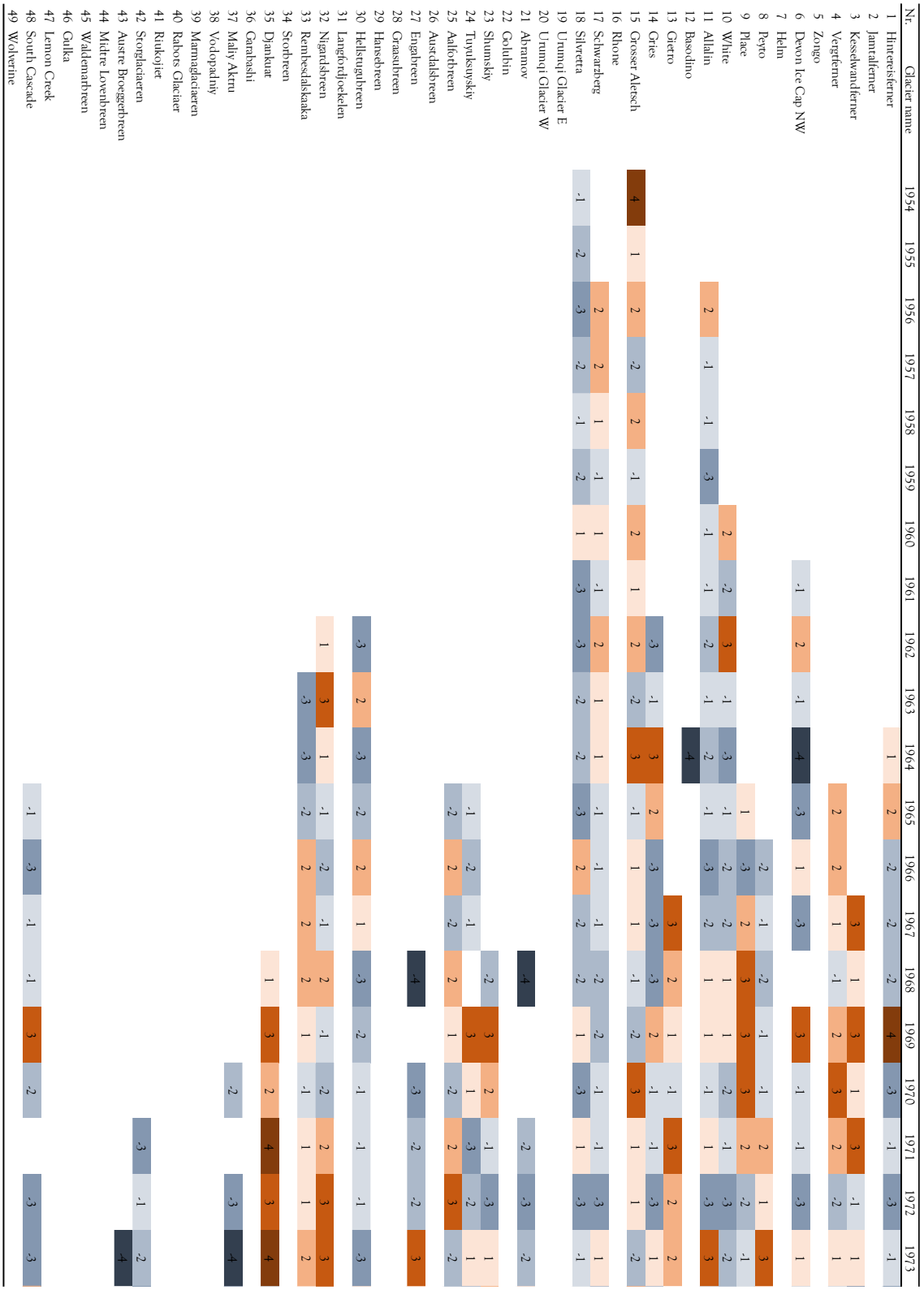
| Nr. | Glacier name | 1954 | 1955 | 1956 | 1957 | 1958 | 1959 | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | | | | | | | | | | | -1 | -2 | 1 | -1 | 2 | 3 | 3 | 1 | -2 | -1 |
| 2 | Jamtalferner | | | | | | | | | | | | | | | | | | | | |
| 3 | Kesselwandferner | | | | | | | | | | | | 2 | 2 | 3 | 2 | 3 | -3 | 3 | 2 | -1 |
| 4 | Vergaferner | | | | | | | | | | | | | | | -2 | -1 | -3 | 2 | -1 | 1 |
| 5 | Zongo | | | | | | | | | | | | | | 1 | 2 | 3 | 3 | 2 | 2 | |
| 6 | Devon Ice Cap NW | | | | | | | | -1 | -1 | 3 | -3 | 1 | -1 | -3 | | 4 | -1 | -3 | -3 | 2 |
| 7 | Helm | | | | | | | | | | | | | | | | | | | | |
| 8 | Peyto | | | | | | | | | | | | | | | | | | | | |
| 9 | Place | | | | | | | -1 | -2 | 1 | 3 | -3 | -1 | -2 | -2 | -3 | -2 | -1 | 1 | -1 | 2 |
| 10 | White | | | | | | | -1 | -2 | 1 | 3 | -3 | -1 | -1 | -2 | 2 | -2 | -2 | 1 | -1 | -1 |
| 11 | Allalin | | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -4 | -1 | -3 | -1 | -2 | -3 | 2 | 1 | -2 | -1 | -2 | 3 |
| 12 | Basodino | | | | | | | | | | | | | | | | | | | | |
| 13 | Gietro | | | | | | | | | | | | | | | | | | | | |
| 14 | Gries | | | | | | | | -3 | -3 | -3 | -1 | -3 | 1 | -1 | -3 | -2 | -3 | -2 | -2 | -2 |
| 15 | Grosser Aletsch | 4 | 1 | 2 | 2 | 2 | -3 | 1 | 2 | -3 | -3 | 2 | -1 | 1 | -2 | 2 | 1 | 2 | 1 | -2 | -1 |
| 16 | Rhone | | | 2 | 2 | 2 | | 1 | 2 | 2 | -3 | -1 | -3 | 1 | -2 | 2 | -1 | -3 | -2 | -2 | 1 |
| 17 | Schwarzberg | | 3 | 3 | 3 | 3 | 1 | 2 | -3 | -3 | 2 | -1 | -1 | 2 | -1 | -1 | -1 | -1 | 1 | -2 | 1 |
| 18 | Silvretta | -1 | -2 | -2 | -2 | -2 | -3 | 3 | -3 | -3 | -3 | -1 | -3 | 2 | -2 | 1 | 3 | -1 | 1 | -2 | 1 |
| 19 | Urumqi Glacier E | | | | | | | | | | | | | | | | | | | | |
| 20 | Urumqi Glacier W | | | | | | | | | | | | | | | | | | | | |
| 21 | Abramov | | | | | | | | | | | | | | -2 | | | | | | |
| 22 | Golubin | | | | | | | | | | | | | | | | | | | | |
| 23 | Shumskiy | | | | | | | | | | | | | | -3 | | 2 | | | | |
| 24 | Tuyuksuyskiy | | | | | | | | | | | | -2 | 1 | 2 | | 2 | | | | |
| 25 | Aalfotbreen | | | | | | | | | 2 | 3 | | -2 | 1 | -2 | 2 | -2 | -2 | -1 | -2 | -2 |
| 26 | Austdalsbreen | | | | | | | | | | | | | | | | | | | | |
| 27 | Engabreen | | | | | | | | | | | | | | | | | -3 | -3 | -1 | 3 |
| 28 | Graasubreen | | | | | | | | | | | | | | | | | | | | |
| 29 | Hansebreen | | | | | | | | | | | | | | | | | | | | |
| 30 | Hellstugubreen | | | | | | | | -2 | | | -3 | 1 | | -1 | -1 | -3 | -2 | -1 | -1 | -1 |
| 31 | Langfjordjoekelen | | | | | | | | | -1 | -1 | -3 | 1 | -2 | -1 | | | | | | |
| 32 | Nigardsbreen | | | | | | | | -1 | 3 | 1 | 1 | 1 | -2 | -2 | -1 | 1 | -3 | 2 | 2 | 3 |
| 33 | Rembesdalskaaka | | | | | | | | | -2 | -3 | -2 | 2 | 2 | -2 | 1 | 1 | 1 | 1 | 1 | 2 |
| 34 | Storbreen | | | | | | | | | | | | | | | | | | | | |
| 35 | Djankuat | | | | | | | | | | | | | | | 3 | 1 | 4 | 3 | 1 | 3 |
| 36 | Garabashi | | | | | | | | | | | | | | | | | | | | |
| 37 | Maliy Aktru | | | | | | | | | | | | | | | | | -1 | -1 | -3 | -2 |
| 38 | Vodopadniy | | | | | | | | | | | | | | | | | | | | |
| 39 | Marmaglaciaren | | | | | | | | | | | | | | | | | | | | |
| 40 | Rabots Glaciar | | | | | | | | | | | | | | | | | | | | |
| 41 | Riukojiet | | | | | | | | | | | | | | | | | | | | |
| 42 | Storglaciaren | | | | | | | | | | | | | | | | | | -2 | -1 | -3 |
| 43 | Austre Broeggerbreen | | | | | | | | | | | | | | | | | | | | |
| 44 | Midtre Lovenbreen | | | | | | | | | | | | | | | | | | | | |
| 45 | Waldemarbreen | | | | | | | | | | | | | | | | | | | | |
| 46 | Gulka | | | | | | | | | | | | | | | | | | | | |
| 47 | Lemon Creek | | | | | | | | | | | | | | | | | | | | |
| 48 | South Cascade | | | | | | | | | | | | -1 | -2 | -2 | 2 | 3 | -2 | 2 | -3 | -1 |
| 49 | Wolverine | | | | | | | | | | | | | | | | | | | | |

| Nr. | Glacier name | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | -2 | -1 | -1 | -1 | -3 | -3 | -3 | -2 | -3 | -3 | -4 | -2 | -3 | -3 | -1 | -1 | -1 | 1 | 2 | 2 | 3 | -1 |
| 2 | Jamtalferner | | | | | | | | | | | | | | | | 3 | 1 | -2 | -2 | -1 | 1 | -3 |
| 3 | Kesselwandferner | -3 | -3 | -2 | 1 | -2 | 1 | 1 | -1 | -1 | -3 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 | 1 | 2 | 3 | 1 |
| 4 | Vergtferner | -2 | 2 | -1 | -3 | -3 | -2 | -4 | 1 | -2 | -3 | -3 | -4 | -1 | -2 | -1 | 2 | -1 | 3 | 1 | -2 | 3 | -3 |
| 5 | Zongo | | | | | | | | | | | | | | | | | | | -4 | 1 | 3 | -2 |
| 6 | Devon Ice Cap NW | 1 | 2 | -3 | 3 | 1 | -2 | -2 | -3 | 3 | 3 | -1 | 2 | 3 | -1 | -1 | -2 | -1 | 1 | 1 | -2 | 3 | 1 |
| 7 | Helm | | | | | | | | | -3 | 1 | -2 | 1 | -2 | 3 | 1 | -3 | | | | | | |
| 8 | Peyto | 1 | | 2 | 2 | 1 | 1 | 2 | -4 | -3 | -3 | -3 | -1 | -1 | 2 | 1 | -4 | 1 | | | -1 | 4 | 2 |
| 9 | Place | -2 | | | | | | | 1 | 4 | -2 | -2 | 1 | 2 | 1 | -3 | 3 | | | | | -4 | -2 |
| 10 | White | -2 | 1 | -2 | 1 | -1 | -3 | | | | 1 | 2 | 3 | 4 | 4 | -1 | -2 | 1 | 2 | -3 | 1 | 3 | 2 |
| 11 | Allalin | -1 | 2 | 3 | -1 | 1 | 1 | -1 | 1 | 3 | -3 | -2 | -2 | -1 | -1 | -2 | 1 | -1 | -1 | 3 | 2 | 1 | -3 |
| 12 | Basodino | | | | | | | | | | | | | | | | | | | | 3 | 2 | 3 |
| 13 | Gietro | -3 | -3 | -3 | -1 | -2 | -1 | -3 | -1 | 2 | -2 | -2 | -1 | 1 | 1 | 1 | -1 | -3 | 3 | -1 | 1 | -1 | 3 |
| 14 | Gries | -1 | -2 | 3 | -3 | 2 | 2 | -1 | 3 | 3 | 1 | 1 | -3 | -2 | -2 | -1 | 1 | 3 | 3 | 2 | -3 | 3 | -1 |
| 15 | Grosser Aletsch | 2 | -3 | -1 | 1 | 1 | 1 | 1 | 3 | -3 | -4 | -2 | -2 | | | | | | | | | | |
| 16 | Rhone | | | | | | | 3 | 1 | 2 | | | | | | | | | | | | | |
| 17 | Schwarzberg | -1 | -3 | 1 | -2 | -2 | -1 | -2 | -1 | 1 | -2 | -2 | -2 | -1 | -2 | -1 | -1 | -2 | -1 | -3 | -3 | -3 | -3 |
| 18 | Silvretta | -1 | 1 | 3 | 1 | -1 | 1 | 1 | -1 | -2 | 3 | -2 | -2 | -2 | -3 | -2 | -1 | 1 | 1 | 2 | 3 | 3 | -1 |
| 19 | Urumqi Glacier E | | | | | | | | | | | | | | | | -3 | 1 | 1 | 1 | 2 | 2 | -2 |
| 20 | Urumqi Glacier W | | | | | | | | | | | | | | | | -3 | -3 | -2 | -2 | 2 | -1 | -3 |
| 21 | Abramov | 1 | -3 | -1 | -2 | -2 | -2 | -2 | -3 | 3 | -1 | -1 | 1 | -2 | 1 | -1 | -3 | 2 | -2 | -1 | 2 | 1 | 3 |
| 22 | Golubin | | | | | | | | -3 | -2 | 1 | -2 | -1 | -2 | 1 | -1 | -3 | 1 | | | | | |
| 23 | Shumskiy | 2 | -2 | -1 | 2 | -3 | -3 | 1 | 3 | 3 | -1 | -1 | | | | | | | | | | | |
| 24 | Tuyuksuyskiy | -3 | 1 | -3 | -2 | -3 | -2 | -1 | 1 | -1 | -2 | -4 | -1 | -2 | -3 | -1 | -2 | 3 | -2 | 1 | 3 | -2 | 2 |
| 25 | Aalfotbreen | -2 | -2 | -1 | -3 | -2 | -3 | 2 | -3 | -3 | -1 | -1 | -1 | -3 | 1 | -1 | 4 | 2 | -1 | 4 | | -3 | -1 |
| 26 | Austdalsbreen | | | | | | | | | | | | | | | -2 | -3 | -3 | -2 | 3 | -1 | 1 | -1 |
| 27 | Engabreen | 1 | -3 | -3 | 1 | -3 | 1 | 3 | -1 | 1 | -3 | 3 | 1 | -3 | -1 | 2 | 3 | 2 | 1 | 3 | -2 | -2 | -3 |
| 28 | Graasubreen | | | | | | | | | | | | | | | | | | | | | | |
| 29 | Hansebreen | | | | | | | | | | | | | 1 | -1 | 1 | -1 | -2 | -1 | 1 | 3 | 4 | -1 |
| 30 | Hellstugubreen | 2 | -1 | 1 | -3 | 2 | 1 | -4 | 1 | -1 | -1 | 2 | 1 | -3 | -2 | -3 | 2 | 4 | -3 | -3 | 2 | -1 | -1 |
| 31 | Langfordjoekelen | | | | | | | | | | | | | | | | -1 | 1 | 1 | 3 | -1 | | |
| 32 | Nigardsbreen | 3 | 2 | -1 | -2 | -3 | -3 | -1 | -3 | -1 | 2 | 1 | -4 | -2 | -3 | 2 | 1 | 1 | -1 | -1 | -1 | -2 | 2 |
| 33 | Rembesdalskaaka | 1 | 1 | -1 | -1 | | | | | | | | -3 | -1 | -3 | 1 | -2 | -2 | 2 | 1 | -3 | 2 | 3 |
| 34 | Storbreen | | | | | | | | | | | | | | | | | 1 | 4 | 1 | 2 | 1 | 1 |
| 35 | Djankuat | 2 | -2 | -3 | -3 | -2 | -3 | -3 | 2 | -1 | 2 | -1 | -1 | -1 | 3 | 3 | -1 | -3 | 2 | -1 | 4 | 1 | -1 |
| 36 | Garabashi | | | | | | | | | | | -1 | -1 | 2 | -3 | -3 | 1 | -1 | -1 | -3 | 3 | -2 | -3 |
| 37 | Maliy Aktru | -1 | 3 | 3 | 4 | 1 | -2 | 3 | | | | | | | | | | | -3 | -1 | -1 | -1 | -1 |
| 38 | Vodopadniy | | | | | | | | | | | | | | | 3 | 3 | | -3 | 1 | 1 | -2 | -3 |
| 39 | Marmaglaciaeren | | | | | | | | | | | | | | | | | | | | | | 1 |
| 40 | Rabots Glaciaer | | | | | | | | | | | | | -1 | -2 | -1 | 1 | 2 | 3 | 4 | -2 | -1 | 2 |
| 41 | Riukojiet | | | | | | | | | | | | | | | | | | | | | | |
| 42 | Storglaciaeren | -1 | -1 | | | | | | -3 | -2 | 1 | -1 | -2 | -2 | -2 | 1 | 4 | 1 | 1 | 2 | -2 | -3 | 2 |
| 43 | Austre Broeggerbreen | | | | | | | | | | | | | | | | | -1 | 1 | | 3 | 2 | 3 |
| 44 | Midtre Lovenbreen | | | | | | | | | | | | | | | | | | | | | | |
| 45 | Waldemarbreen | | | | | | | | | | | | | | | | | | | | | | |
| 46 | Gulka | | | | | | | | | | | | | | | | | | | | | | |
| 47 | Lemon Creek | | | | | | | | | | | | | | | | | | | | | | |
| 48 | South Cascade | 2 | 1 | 3 | -2 | -2 | -3 | -1 | | | | | | | | | | | | | | | |
| 49 | Wolverine | | | | | | | | | | | | | | | | | | | | | | |

**Annex 7.1 :** Relative ablation gradient values and corresponding interval colors for the 49 selected glaciers and available years in the period of analysis 1954-2017.

## Annex 7.2

The table from Annex 7.2 it splitted on three pages due to its size.



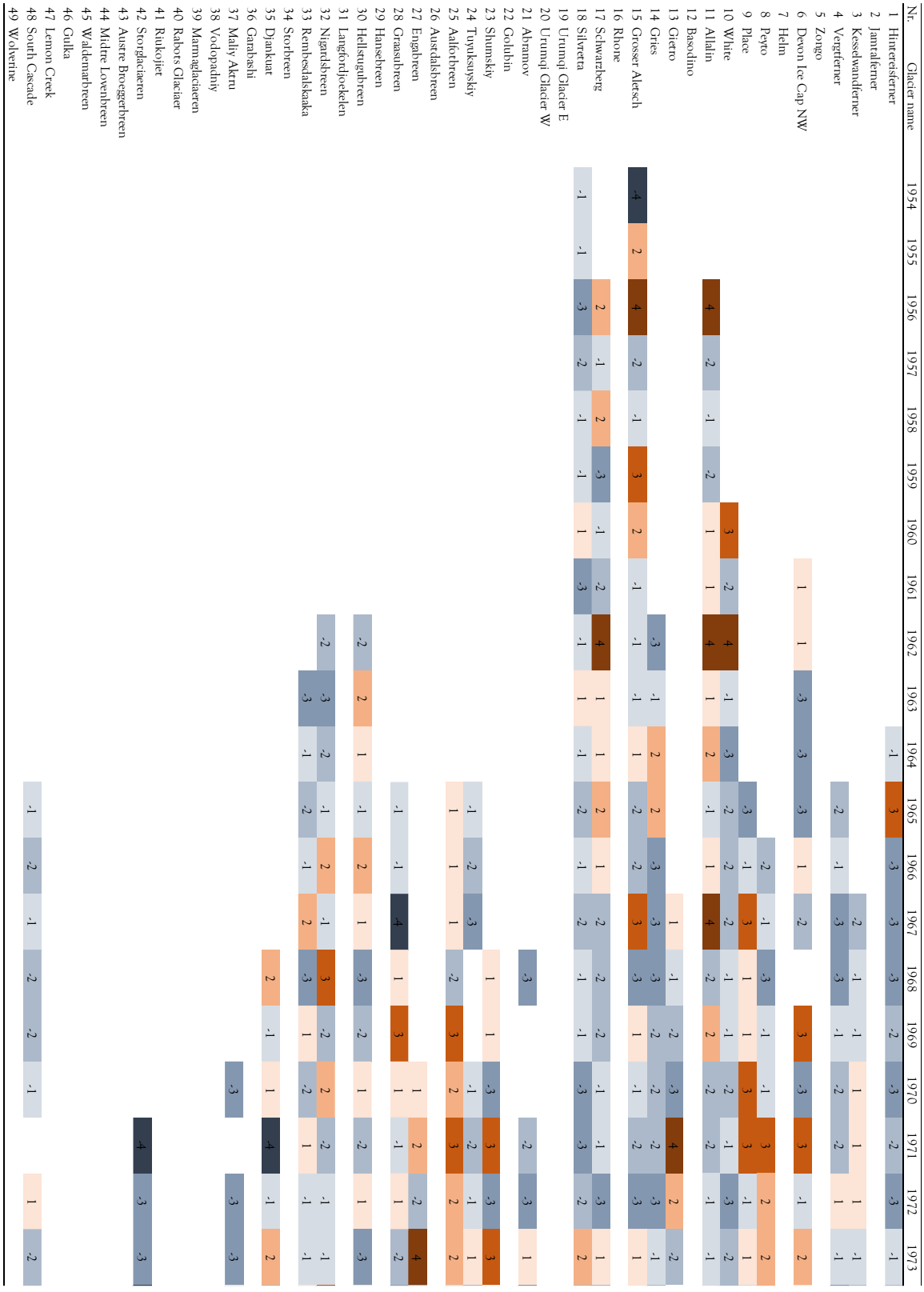
| Nr. | Glacier name | 1954 | 1955 | 1956 | 1957 | 1958 | 1959 | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | | | | | | | | | | | 1 | 2 | -2 | -2 | -2 | 4 | -3 | -1 | -3 | -1 |
| 2 | Jamtalferner | | | | | | | | | | | | | | | | | | | | |
| 3 | Kesselwandferner | | | | | | | | | | | | 2 | -2 | -2 | -2 | 4 | -3 | -1 | -3 | -1 |
| 4 | Vergferner | | | | | | | | | | | | 2 | 2 | 1 | -1 | 2 | 3 | 2 | -2 | 1 |
| 5 | Zongo | | | | | | | | | | | | | | | | | | | | |
| 6 | Devon Ice Cap NW | | | | | | | | -1 | | | | | | | | | | | | |
| 7 | Helm | | | | | | | | | 2 | | -4 | -3 | 1 | -3 | | 3 | -1 | -3 | -3 | 1 |
| 8 | Peyto | | | | | | | | | | -1 | | | | | | | | | | |
| 9 | Place | | | | | | | 2 | | | | | 1 | -3 | 2 | 3 | 3 | 3 | 2 | 1 | 3 |
| 10 | White | | | | | | | | -2 | 3 | -1 | | -1 | -2 | 1 | 1 | 1 | -2 | -1 | -2 | -1 |
| 11 | Allalin | | 2 | -1 | -1 | | -3 | -1 | -1 | -2 | -1 | -2 | -1 | -3 | -2 | 1 | 1 | -1 | -1 | -3 | 3 |
| 12 | Basodino | | | | | | | | | | -4 | -4 | | | | | | | | | |
| 13 | Gietro | | | | | | | | | | | | | 3 | 2 | 1 | -1 | -1 | 3 | 2 | 2 |
| 14 | Gries | | | | | | | | -3 | 2 | -1 | 2 | -1 | -3 | -3 | -3 | 2 | -1 | -1 | -3 | 1 |
| 15 | Grosser Aletsch | 4 | 1 | 2 | -2 | 2 | -1 | 2 | 1 | 2 | 3 | 3 | -1 | 1 | -1 | -1 | -2 | 3 | 1 | 1 | -2 |
| 16 | Rhone | | | | | | | | | | | | | | | | | | | | |
| 17 | Schwarzberg | | 2 | 2 | 1 | -1 | -1 | 1 | -1 | 2 | 1 | 1 | -1 | -1 | -2 | -2 | -1 | -1 | -1 | -3 | 1 |
| 18 | Silvretta | -1 | -2 | -3 | -2 | -1 | -2 | 1 | -3 | -3 | -2 | -2 | -3 | 2 | -2 | -2 | 1 | -3 | -1 | -3 | -1 |
| 19 | Urumqi Glacier E | | | | | | | | | | | | | | | | | | | | |
| 20 | Urumqi Glacier W | | | | | | | | | | | | | | | | | | | | |
| 21 | Abramov | | | | | | | | | | | | | | -4 | | | | -2 | -3 | -2 |
| 22 | Golubin | | | | | | | | | | | | | | | | | | | | |
| 23 | Shumskiy | | | | | | | | | | | | | | | -2 | 3 | 2 | -1 | -3 | 1 |
| 24 | Tuyuksuyskiy | | | | | | | | | | | | -1 | -2 | -1 | 3 | 3 | 1 | -3 | -2 | 1 |
| 25 | Aalfotbreen | | | | | | | | | | | -2 | 2 | -2 | -2 | 2 | 1 | -2 | 2 | 3 | -2 |
| 26 | Austdalsbreen | | | | | | | | | | | | | | | | | | | | |
| 27 | Engabreen | | | | | | | | | | | | | | | -4 | | -3 | -2 | -2 | 3 |
| 28 | Grasubreen | | | | | | | | | | | | | | | | | | | | |
| 29 | Hansebreen | | | | | | | | | | | | | | | | | | | | |
| 30 | Hellstugubreen | | | | | | | | -3 | | | -3 | -2 | 2 | -3 | -3 | -2 | -1 | -1 | -1 | -3 |
| 31 | Langfjordjoekelen | | | | | | | | | | | | | | | | | | | | |
| 32 | Nigardsbreen | | | | | | | | 1 | -3 | 3 | 1 | -1 | -2 | 2 | 2 | -1 | -2 | 2 | 3 | 3 |
| 33 | Rembesdalskaaka | | | | | | | | | -3 | -3 | -3 | -2 | 2 | 2 | 2 | -1 | -2 | 1 | 1 | 2 |
| 34 | Storbreen | | | | | | | | | | | | | | 1 | 1 | 3 | 2 | 4 | 3 | 4 |
| 35 | Djankuat | | | | | | | | | | | | | | | 1 | 3 | 2 | 4 | 3 | 4 |
| 36 | Ganjahashi | | | | | | | | | | | | | | | | | | | | |
| 37 | Maliy Aktru | | | | | | | | | | | | | | | | | -2 | | -3 | -4 |
| 38 | Vodopadniy | | | | | | | | | | | | | | | | | | | | |
| 39 | Mamagdaciaeren | | | | | | | | | | | | | | | | | | | | |
| 40 | Rabots Glaciaer | | | | | | | | | | | | | | | | | | | | |
| 41 | Riukojiet | | | | | | | | | | | | | | | | | | | | |
| 42 | Storglaciaeren | | | | | | | | | | | | | | | | | | -3 | -1 | -2 |
| 43 | Austre Broeggerbreen | | | | | | | | | | | | | | | | | | | -4 | -4 |
| 44 | Midtre Lovenbreen | | | | | | | | | | | | | | | | | | | | |
| 45 | Waldemarbreen | | | | | | | | | | | | | | | | | | | | |
| 46 | Gulka | | | | | | | | | | | | | | | | | | | | |
| 47 | Lemon Creek | | | | | | | | | | | | | | | | | | | | |
| 48 | South Cascade | | | | | | | | | | | | -1 | -3 | -1 | -1 | 3 | -2 | | -3 | -3 |
| 49 | Wolverine | | | | | | | | | | | | | | | | | | | | |

| Nr. | Glacier name | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | -3 | -1 | 1 | 3 | -3 | -2 | -1 | 1 | -2 | -2 | -3 | 1 | 1 | -1 | 2 | -3 | 2 | 1 | 3 | 3 | 3 | -1 |
| 2 | Jamtalferner | | | | | | | | | | | | | | | | 3 | 1 | -1 | -2 | 3 | 1 | -3 |
| 3 | Kesselwandferner | -3 | -2 | 1 | 1 | -2 | -1 | 1 | -1 | -1 | -3 | 1 | -2 | 1 | 1 | -1 | -2 | -1 | -2 | -1 | 1 | 3 | -2 |
| 4 | Vergtferner | -1 | 3 | -3 | -3 | -3 | -2 | -4 | 2 | -1 | -3 | -3 | -3 | 1 | -1 | -1 | 1 | -1 | 4 | 2 | -2 | 3 | -3 |
| 5 | Zongo | | | | | | | | | | | | | | | | | | | -2 | -3 | -2 | -2 |
| 6 | Devon Ice Cap NW | -1 | 2 | | -1 | -2 | 1 | 1 | -3 | 1 | -1 | -2 | 2 | 3 | 1 | 3 | 1 | 1 | 1 | 1 | -1 | 3 | 3 |
| 7 | Helm | | | | | | | | | -4 | -1 | -3 | -1 | -1 | 3 | 1 | 1 | | | | | | |
| 8 | Peyto | 1 | | 1 | 1 | 2 | 2 | 1 | -1 | -1 | -2 | -1 | 1 | 1 | 2 | 3 | -4 | 2 | | | -1 | 3 | 1 |
| 9 | Place | -1 | | | | | | | 1 | 1 | -1 | -3 | -3 | -2 | 2 | -1 | 4 | | | | | -2 | -3 |
| 10 | White | -2 | -2 | -1 | 4 | 2 | -1 | -4 | | | 2 | 1 | -2 | 4 | 3 | | | -1 | -2 | -3 | -1 | -1 | 2 |
| 11 | Allalin | -1 | 1 | 3 | -1 | 1 | 1 | -1 | -1 | 3 | -3 | -3 | -2 | -1 | 1 | -2 | 1 | -1 | -1 | 3 | 2 | 2 | -3 |
| 12 | Basodino | | | | | | | | | | | | | | | | | | | | 4 | 2 | 2 |
| 13 | Gietro | | 1 | 3 | 3 | 1 | 3 | 1 | 3 | 4 | 1 | 3 | 2 | -2 | 1 | -1 | -2 | -3 | -1 | 1 | 1 | -1 | 3 |
| 14 | Gries | -2 | -3 | 2 | -2 | -2 | -1 | 1 | 3 | 3 | -2 | -1 | -3 | -2 | -1 | -1 | 1 | 2 | 3 | 2 | -2 | 4 | -1 |
| 15 | Grosser Aletsch | 2 | -3 | 2 | 1 | 1 | -2 | 1 | 3 | -2 | -4 | -3 | -2 | | | | | | | | | | |
| 16 | Rhone | | | | | | | 1 | -1 | 2 | | | | | | | | | | | | | |
| 17 | Schwarzberg | -2 | -3 | -1 | -3 | -3 | -1 | -3 | -2 | 2 | -1 | -3 | -2 | 1 | -1 | -1 | -1 | 1 | -3 | -3 | -3 | -3 | -3 |
| 18 | Silvretta | -1 | 1 | 1 | 2 | 1 | -2 | 1 | -1 | 1 | 2 | 2 | -2 | -2 | -3 | -3 | 2 | -1 | 1 | 2 | 2 | 3 | -1 |
| 19 | Urumqi Glacier E | | | | | | | | | | | | | | | | -3 | -2 | 2 | -1 | -2 | 1 | -1 |
| 20 | Urumqi Glacier W | | | | | | | | | | | | | | | | -3 | -1 | 2 | -1 | 2 | 3 | -1 |
| 21 | Abramov | 1 | -2 | -1 | -2 | -1 | -1 | -3 | -2 | 3 | -1 | -1 | 2 | -1 | 1 | 1 | -3 | 2 | -3 | -1 | 1 | 1 | 3 |
| 22 | Golubin | | | | | | | | -3 | -3 | 1 | 2 | 1 | -3 | 2 | 2 | -2 | 3 | | | | | |
| 23 | Shumskiy | 2 | -3 | -2 | 3 | -3 | -3 | 1 | 3 | 3 | 1 | -1 | | | | | | | | | | | |
| 24 | Tuyuksuyskiy | -2 | -2 | -2 | -2 | -1 | -2 | | -3 | -1 | -4 | -3 | -3 | -2 | | -3 | -3 | 2 | -1 | -1 | | -2 | 3 |
| 25 | Aalfotbreen | -2 | -3 | -2 | -2 | -2 | -3 | 2 | -2 | -3 | -1 | 1 | -1 | -2 | 2 | -1 | 4 | 1 | -2 | 4 | | -3 | 2 |
| 26 | Austdalsbreen | | | | | | | | | | | | | | | 1 | -1 | -3 | -3 | 2 | -3 | -2 | -3 |
| 27 | Engabreen | 1 | -3 | -3 | -1 | -3 | 1 | 2 | -1 | -1 | -3 | 3 | -2 | -3 | -1 | 2 | 3 | 3 | -1 | 3 | -2 | -3 | -3 |
| 28 | Graasubreen | | | | | | | | | | | | | | | | | | | | | | |
| 29 | Hansebreen | | | | | | | | | | | | | 1 | 3 | 1 | 1 | 1 | -1 | 4 | -1 | 3 | 3 |
| 30 | Hellstugubreen | 1 | -3 | 1 | -3 | 2 | -2 | -2 | -3 | -3 | -1 | -1 | -1 | -1 | -3 | 2 | 3 | 3 | -3 | -1 | 1 | 1 | 2 |
| 31 | Langfordjoekelen | | | | | | | | | | | | | | | | 2 | 1 | -1 | 3 | -1 | | |
| 32 | Nigardsbreen | 3 | 1 | 1 | -2 | -3 | -3 | -1 | -3 | 1 | 2 | 1 | -4 | -1 | -3 | 3 | 2 | 2 | -1 | -1 | 2 | -3 | 1 |
| 33 | Rembesdalskaaka | 1 | 1 | -1 | -2 | | | | | | | | -3 | -1 | -3 | 1 | -3 | -2 | 2 | 2 | -3 | 2 | 2 |
| 34 | Storbreen | | | | | | | | | | | | | | | | | -2 | 3 | -3 | -2 | -3 | -1 |
| 35 | Djankuat | -1 | 1 | 2 | 1 | -2 | -1 | -1 | -2 | 2 | 2 | -1 | -1 | -1 | 2 | 1 | 1 | -2 | 1 | -2 | 1 | 3 | 2 |
| 36 | Garabashi | | | | | | | | | | | -2 | 1 | -1 | -2 | -3 | 2 | -2 | -1 | -3 | -1 | -1 | -3 |
| 37 | Maliy Aktru | -2 | 1 | -1 | 2 | -2 | -3 | 3 | | | | | -4 | | | | | | -3 | 1 | 2 | 2 | 2 |
| 38 | Vodopadniy | | | | | | | | | | | | | | | | | | -3 | -3 | | 3 | 1 |
| 39 | Marmaglaciaeren | | | | | | | | | | | | | | | | | | | | | | -2 |
| 40 | Rabots Glaciaer | | | | | | | | | | | | | -1 | -2 | -1 | -1 | 3 | | -1 | -1 | -3 | 1 |
| 41 | Riukojiet | | | | | | | | | | | | | | | | | | | | | | |
| 42 | Storglaciaeren | -3 | -1 | | | | | | -3 | -2 | -1 | 2 | -2 | 1 | -3 | -2 | 3 | 3 | 2 | 3 | 1 | -3 | 2 |
| 43 | Austre Broeggerbreen | | | | | | | | | | | | | | | | | -2 | -3 | | 1 | -3 | 4 |
| 44 | Midtre Lovenbreen | | | | | | | | | | | | | | | | | | | | | | |
| 45 | Waldemarbreen | | | | | | | | | | | | | | | | | | | | | | |
| 46 | Gulka | | | | | | | | | | | | | | | | | | | | | | |
| 47 | Lemon Creek | | | | | | | | | | | | | | | | | | | | | | |
| 48 | South Cascade | 2 | -1 | 3 | -2 | 1 | 1 | 1 | | | | | | | | | | | | | | | |
| 49 | Wolverine | | | | | | | | | | | | | | | | | | | | | | |

**Annex 7.2 :** Relative glacier-wide gradient values and corresponding interval colors for the 49 selected glaciers and available years in the period of analysis 1954-2017.

## Annex 7.3

The table from Annex 7.3 it splitted on three pages due to its size.



| Nr. | Glacier name | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hintereisferner | -2 | -1 | -1 | 4 | -2 | -2 | 1 | 1 | 1 | -2 | 3 | -3 | 2 | 2 | 2 | -3 | 2 | -1 | 4 | 2 | -1 | 2 |
| 2 | Jamtalferner | | | | | | | | | | | | | | | | 1 | 1 | -1 | 2 | 4 | -2 | -2 |
| 3 | Kesselwandferner | -2 | -1 | -3 | -1 | -3 | -2 | -3 | -3 | 1 | -2 | 1 | -2 | -2 | -3 | -1 | -2 | -2 | -1 | -1 | -2 | 1 | -2 |
| 4 | Vergtferner | -3 | -2 | -3 | -3 | -2 | -3 | -3 | 1 | 2 | -1 | -2 | -2 | 2 | -3 | -1 | -2 | -1 | 3 | 3 | 1 | 3 | -2 |
| 5 | Zongo | | | | | | | | | | | | | | | | | | | 2 | -2 | -2 | 2 |
| 6 | Devon Ice Cap NW | 1 | 2 | | -2 | -1 | -1 | -1 | -1 | -2 | -3 | -2 | 2 | -3 | -2 | 3 | 1 | 1 | 1 | -1 | 2 | 3 | 4 |
| 7 | Helm | | | | | | | | | -3 | -1 | -2 | -1 | -1 | 2 | 3 | 3 | | | | | | |
| 8 | Peyto | 2 | | 1 | -3 | 3 | 3 | -1 | 3 | 2 | -1 | 3 | 3 | 1 | -3 | 1 | -3 | 1 | | | 2 | 3 | 1 |
| 9 | Place | -1 | | | | | | | -2 | -4 | 2 | -3 | -2 | -3 | 1 | -1 | 3 | | | | | 2 | 3 |
| 10 | White | -2 | -3 | -2 | 3 | 2 | -1 | | | | 1 | -1 | -3 | 3 | -1 | | | -1 | -2 | -1 | 1 | -1 | 1 |
| 11 | Allalin | -1 | -2 | -1 | -1 | -1 | -1 | 2 | -2 | 1 | -2 | -3 | -1 | -1 | 1 | -1 | -2 | -1 | 1 | 1 | -1 | -1 | -2 |
| 12 | Basodino | | | | | | | | | | | | | | | | | | | | 1 | -1 | -3 |
| 13 | Gietro | | -2 | 3 | -1 | -1 | 2 | -2 | -1 | 3 | -2 | 3 | -1 | -1 | -1 | 1 | -2 | -3 | 1 | 1 | 1 | 1 | 3 |
| 14 | Gries | -2 | -3 | -2 | -1 | -2 | -1 | -1 | 2 | 2 | -2 | -1 | -2 | -1 | 1 | 1 | -1 | 2 | 3 | 1 | -1 | 3 | -2 |
| 15 | Grosser Aletsch | 1 | 2 | 2 | 2 | 2 | -2 | -2 | 2 | 1 | -2 | -1 | -1 | | | | | | | | | | |
| 16 | Rhone | | | | | | | 3 | 2 | 3 | | | | | | | | | | | | | |
| 17 | Schwarzberg | -2 | -3 | -2 | -3 | -3 | 1 | -3 | -1 | 2 | 1 | -3 | -2 | 1 | 1 | -1 | -2 | 3 | -2 | -2 | -3 | -3 | -3 |
| 18 | Silvretta | -2 | -1 | -2 | -1 | 3 | -2 | -2 | -1 | 1 | -3 | 3 | -2 | -3 | -3 | -3 | 1 | -2 | 1 | 3 | 2 | 2 | -1 |
| 19 | Urumqi Glacier E | | | | | | | | | | | | | | | | -3 | -2 | -1 | -2 | -3 | -1 | -3 |
| 20 | Urumqi Glacier W | | | | | | | | | | | | | | | | -2 | 2 | 4 | 1 | 1 | 4 | -2 |
| 21 | Abramov | -3 | 3 | -1 | -1 | 2 | 1 | -2 | -2 | -1 | 1 | -2 | 1 | 2 | -1 | -2 | -3 | -1 | -2 | -2 | -1 | 1 | 2 |
| 22 | Golubin | | | | | | | | 2 | -2 | -1 | -1 | -2 | -2 | 1 | 3 | 2 | 4 | | | | | |
| 23 | Shumskiy | 1 | 2 | -1 | 2 | 3 | 1 | 2 | -3 | -2 | -2 | -3 | | | | | | | | | | | |
| 24 | Tuyuksuyskiy | -2 | -1 | -1 | -2 | -2 | 1 | | -3 | -3 | -3 | -2 | -2 | -3 | | -3 | -3 | -2 | 1 | -1 | | 3 | 2 |
| 25 | Aalfotbreen | -1 | -2 | -1 | 1 | -2 | -1 | 2 | -1 | 1 | 1 | -3 | -1 | -2 | 3 | 1 | 2 | -3 | -2 | 3 | | -3 | 3 |
| 26 | Austdalsbreen | | | | | | | | | | | | | | | 3 | 4 | -1 | -1 | 3 | 1 | -2 | -3 |
| 27 | Engabreen | -2 | 1 | 4 | -2 | 1 | -1 | 1 | 1 | -1 | -1 | -2 | -3 | 1 | 1 | -2 | -1 | -2 | -2 | 1 | -2 | -2 | -1 |
| 28 | Graasubreen | -3 | | -4 | -2 | 3 | -3 | 3 | -2 | -1 | 1 | -2 | -2 | 1 | | -1 | | | 1 | -1 | -2 | 2 | 1 |
| 29 | Hansebreen | | | | | | | | | | | | | 1 | 4 | 1 | -2 | -1 | -3 | 4 | -2 | 1 | 4 |
| 30 | Hellstugubreen | 1 | -1 | 3 | -3 | -2 | -3 | 3 | -3 | -3 | -1 | -2 | -2 | 1 | -2 | 3 | 3 | 3 | -3 | -1 | -2 | -2 | 4 |
| 31 | Langfordjoekelen | | | | | | | | | | | | | | | | 4 | 2 | -2 | -2 | 1 | | |
| 32 | Nigardsbreen | 3 | -3 | 2 | -1 | 2 | 3 | 1 | 2 | 3 | 1 | 1 | 3 | 2 | -2 | 2 | 4 | 4 | -2 | 2 | 4 | 1 | -2 |
| 33 | Rembesdalskaaka | 1 | -1 | -1 | -2 | | | | | | | | -2 | -3 | 3 | -1 | -2 | 2 | -2 | 2 | -2 | -2 | -2 |
| 34 | Storbreen | | | | | | | | | | | | | | | | | -3 | -3 | -3 | -3 | -3 | -1 |
| 35 | Djankuat | -2 | 1 | 4 | 1 | 2 | 3 | 3 | -3 | 3 | 1 | -3 | -1 | -1 | -1 | -2 | -2 | 3 | 1 | -1 | -2 | 3 | 2 |
| 36 | Garabashi | | | | | | | | | | | -2 | 2 | -2 | 2 | -4 | -3 | -3 | 2 | -3 | 2 | 2 | 2 |
| 37 | Maliy Aktru | 1 | 2 | -1 | -2 | -2 | 1 | -1 | | | | | | | | | | | 1 | -2 | -1 | -1 | 2 |
| 38 | Vodopadniy | | | | | | | | | | | | | | | | | | -2 | -3 | | -2 | 3 |
| 39 | Marmaglaciaeren | | | | | | | | | | | | | | | | | | | | | | -2 |
| 40 | Rabots Glaciaer | | | | | | | | | | | | | -1 | -2 | -1 | -1 | 2 | | -3 | -2 | -2 | 1 |
| 41 | Riukojiet | | | | | | | | | | | | | | | | | | | | | | |
| 42 | Storglaciaeren | -4 | -3 | | | | | | -2 | -2 | -2 | -1 | -1 | 3 | -2 | -2 | 2 | 3 | 3 | 2 | 2 | -1 | 3 |
| 43 | Austre Broeggerbreen | | | | | | | | | | | | | | | | | -1 | -3 | | -3 | -4 | -1 |
| 44 | Midtre Lovenbreen | | | | | | | | | | | | | | | | | | | | | | |
| 45 | Waldemarbreen | | | | | | | | | | | | | | | | | | | | | | |
| 46 | Gulka | | | | | | | | | | | | | | | | | | | | | | |
| 47 | Lemon Creek | | | | | | | | | | | | | | | | | | | | | | |
| 48 | South Cascade | -2 | -2 | -2 | -2 | 1 | -1 | 1 | | | | | | | | | | | | | | | |
| 49 | Wolverine | | | | | | | | | | | | | | | | | | | | | | |

**Annex 7.3 :** Relative accumulation gradient values and corresponding interval colors for the 49 selected glaciers and available years in the period of analysis 1954-2017.

# Annex 8

| Glacier name | $db/dz_{abl}$ | | | $db/dz_{gw}$ | | | $db/dz_{acc}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | Std. | | Mean | Std. | | Mean | Std. | |
| | m w.e. $(100m)^{-1}$ | m w.e. $(100m)^{-1}$ | % of mean | m w.e. $(100m)^{-1}$ | m w.e. $(100m)^{-1}$ | % of mean | m w.e. $(100m)^{-1}$ | m w.e. $(100m)^{-1}$ | % of mean |
| Hintereisferner | 1.076 | 0.138 | 12.9% | 0.783 | 0.097 | 12.4% | 0.375 | 0.108 | 28.9% |
| Jamtalferner | 0.773 | 0.112 | 14.5% | 0.528 | 0.087 | 16.5% | 0.285 | 0.124 | 43.3% |
| Kesselwandferner | 1.168 | 0.289 | 24.8% | 1.028 | 0.182 | 17.7% | 0.437 | 0.214 | 48.9% |
| Vergtferner | 0.872 | 0.183 | 21.0% | 0.697 | 0.132 | 19.0% | 0.241 | 0.118 | 48.8% |
| Zongo | 1.704 | 0.582 | 34.2% | 0.571 | 0.235 | 41.1% | 0.221 | 0.115 | 52.1% |
| Devon Ice Cap NW | 0.105 | 0.032 | 30.0% | 0.099 | 0.022 | 22.7% | 0.071 | 0.035 | 49.2% |
| Helm | 0.748 | 0.424 | 56.6% | 0.743 | 0.278 | 37.4% | 0.514 | 0.347 | 67.6% |
| Peyto | 0.613 | 0.203 | 33.1% | 0.571 | 0.126 | 22.0% | 0.385 | 0.162 | 42.0% |
| Place | 0.961 | 0.328 | 34.1% | 0.549 | 0.087 | 15.9% | 0.426 | 0.139 | 32.7% |
| White | 0.215 | 0.053 | 24.5% | 0.180 | 0.050 | 27.9% | 0.110 | 0.061 | 55.4% |
| Allalin | 0.367 | 0.105 | 28.6% | 0.317 | 0.074 | 23.2% | 0.244 | 0.138 | 56.9% |
| Basodino | 0.695 | 0.283 | 40.6% | 0.619 | 0.157 | 25.3% | 0.316 | 0.194 | 61.5% |
| Gietro | 0.815 | 0.180 | 22.1% | 0.726 | 0.216 | 29.7% | 0.335 | 0.145 | 43.3% |
| Gries | 0.740 | 0.169 | 22.9% | 0.457 | 0.099 | 21.7% | 0.296 | 0.110 | 37.2% |
| Grosser Aletsch | 0.760 | 0.158 | 20.8% | 0.704 | 0.087 | 12.4% | 0.507 | 0.108 | 21.3% |
| Rhone | 0.837 | 0.099 | 11.8% | 0.694 | 0.055 | 7.9% | 0.505 | 0.175 | 34.7% |
| Schwarzberg | 0.716 | 0.214 | 29.9% | 0.527 | 0.148 | 28.0% | 0.351 | 0.108 | 30.7% |
| Silvretta | 0.985 | 0.290 | 29.4% | 0.595 | 0.161 | 27.0% | 0.349 | 0.143 | 41.0% |
| Urumqi Glacier E | 1.278 | 0.222 | 17.4% | 0.684 | 0.134 | 19.6% | 0.358 | 0.132 | 36.8% |
| Urumqi Glacier W | 1.126 | 0.227 | 20.2% | 0.755 | 0.195 | 25.8% | 0.417 | 0.235 | 56.3% |
| Abramov | 0.722 | 0.134 | 18.5% | 0.608 | 0.134 | 22.1% | 0.208 | 0.099 | 47.9% |
| Golubin | 0.587 | 0.177 | 30.2% | 0.582 | 0.115 | 19.7% | 0.562 | 0.436 | 77.5% |
| Shumskiy | 0.313 | 0.060 | 19.0% | 0.321 | 0.051 | 16.0% | 1.096 | 0.596 | 54.3% |
| Tuyuksuyskiy | 0.458 | 0.135 | 29.4% | 0.538 | 0.122 | 22.6% | 0.526 | 0.374 | 71.1% |
| Aalfotbreen | 0.761 | 0.326 | 42.9% | 0.740 | 0.230 | 31.1% | 0.604 | 0.245 | 40.5% |
| Austdalsbreen | 1.425 | 0.312 | 21.9% | 1.057 | 0.201 | 19.0% | 0.433 | 0.192 | 44.3% |
| Engabreen | 1.065 | 0.156 | 14.6% | 0.991 | 0.131 | 13.2% | 0.496 | 0.286 | 57.6% |
| Graasubreen | x | x | x | x | x | x | 0.434 | 0.169 | 38.9% |
| Hansebreen | 0.757 | 0.243 | 32.0% | 0.909 | 0.247 | 27.2% | 0.656 | 0.417 | 63.6% |
| Hellstugubreen | 0.696 | 0.130 | 18.7% | 0.601 | 0.101 | 16.9% | 0.537 | 0.190 | 35.5% |
| Langfordjoekelen | 0.754 | 0.146 | 19.3% | 0.649 | 0.112 | 17.3% | 0.369 | 0.170 | 46.0% |
| Nigardsbreen | 0.865 | 0.125 | 14.5% | 0.794 | 0.091 | 11.4% | 0.463 | 0.178 | 38.4% |
| Rembesdalskaaka | 0.967 | 0.147 | 15.2% | 0.940 | 0.129 | 13.7% | 0.438 | 0.206 | 47.0% |
| Storbreen | 0.674 | 0.182 | 27.0% | 0.638 | 0.123 | 19.3% | 0.623 | 0.203 | 32.5% |
| Djankuat | 0.868 | 0.150 | 17.3% | 0.748 | 0.084 | 11.3% | 0.506 | 0.117 | 23.2% |
| Garabashi | 0.437 | 0.096 | 22.0% | 0.548 | 0.111 | 20.2% | 0.846 | 0.254 | 30.0% |
| Maliy Aktru | 0.455 | 0.118 | 25.8% | 0.422 | 0.052 | 12.4% | 0.412 | 0.213 | 51.7% |
| Vodopadniy | 0.453 | 0.158 | 34.9% | 0.508 | 0.144 | 28.4% | 0.130 | 0.089 | 68.5% |
| Marmaglaciaeren | 0.441 | 0.156 | 35.3% | 0.924 | 0.370 | 40.1% | 1.392 | 0.660 | 47.4% |
| Rabots Glaciaer | 0.658 | 0.274 | 41.6% | 0.664 | 0.239 | 35.9% | 0.728 | 0.460 | 63.3% |
| Riukojietna | 0.400 | 0.196 | 49.0% | 0.408 | 0.190 | 46.6% | 0.318 | 0.157 | 49.4% |
| Storglaciaeren | 0.828 | 0.217 | 26.2% | 0.986 | 0.199 | 20.1% | 1.088 | 0.336 | 30.9% |
| Austre Broeggerbreen | 0.562 | 0.215 | 38.2% | 0.409 | 0.073 | 17.8% | 0.334 | 0.111 | 33.1% |
| Midtre Lovenbreen | 0.503 | 0.136 | 27.0% | 0.463 | 0.068 | 14.8% | 0.455 | 0.070 | 15.4% |
| Waldemarbreen | 0.636 | 0.250 | 39.4% | 0.550 | 0.098 | 17.8% | 0.528 | 0.136 | 25.8% |
| Gulkana | 0.935 | 0.183 | 19.6% | x | x | x | x | x | x |
| Lemon Creek | 1.178 | 0.098 | 8.3% | 1.145 | 0.199 | 17.4% | 0.785 | 0.293 | 37.3% |
| South Cascade | 2.302 | 0.854 | 37.1% | 1.523 | 0.357 | 23.4% | 0.840 | 0.818 | 97.4% |
| Wolverine | 1.000 | 0.305 | 30.5% | x | x | x | x | x | x |
| **Mean** | **0.797** | **0.208** | **26.8%** | **0.663** | **0.143** | **21.9%** | **0.480** | **0.221** | **45.9%** |
| Median | 0.756 | 0.179 | 26.0% | 0.628 | 0.127 | 19.9% | 0.434 | 0.170 | 44.3% |
| Std. | 0.375 | 0.135 | 10.1% | 0.253 | 0.076 | 8.4% | 0.254 | 0.158 | 15.6% |
| Min. | 0.105 | 0.032 | 8.3% | 0.099 | 0.022 | 7.9% | 0.071 | 0.035 | 15.4% |
| 1st Quartile | 0.580 | 0.134 | 19.3% | 0.530 | 0.088 | 16.6% | 0.334 | 0.118 | 35.1% |
| 3rd Quartile | 0.942 | 0.244 | 33.4% | 0.747 | 0.194 | 26.7% | 0.532 | 0.249 | 54.9% |
| Max. | 2.302 | 0.854 | 56.6% | 1.523 | 0.370 | 46.6% | 1.392 | 0.818 | 97.4% |

**Annex 8 :** mean, absolute and relative standard deviation of the calculated annual absolute gradient datasets for the 49 selected glaciers. The descriptive statistics of their distribution between glaciers is mentioned on the lower part of the table.

## Annex 9

The table from Annex 9 it splitted on three pages due to its size.

| Nr. | Glacier name | Gradient | Modelled gradient (m w.e. (100 m)$^{-1}$) | | | *Mean gradient (m w.e. (100 m)$^{-1}$)* | Change over total period (%) | *# of years of the period* | Mean annual rate of change | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | First year | Last year | Difference | | | | m w.e. (100 m)$^{-1}$ | % |
| | | Ablation | 0.973 | 1.178 | 0.204 | *1.076* | 19% | | 0.00379 | 0.35% |
| 1 | Hintereisferner | Glacier wide | 0.768 | 0.797 | 0.029 | *0.783* | 4% | *54* | 0.00053 | 0.07% |
| | | Accumulation | 0.325 | 0.425 | 0.100 | *0.375* | 27% | | 0.00186 | 0.49% |
| | | Ablation | 0.759 | 0.787 | 0.028 | *0.773* | 4% | | 0.00101 | 0.13% |
| 2 | Jamtalferner | Glacier wide | 0.555 | 0.501 | -0.054 | *0.528* | -10% | *28* | -0.00193 | -0.37% |
| | | Accumulation | 0.329 | 0.242 | -0.087 | *0.285* | -31% | | -0.00312 | -1.09% |
| | | Ablation | 1.112 | 1.226 | 0.113 | *1.168* | 10% | | 0.00222 | 0.19% |
| 3 | Kesselwandferner | Glacier wide | 1.003 | 1.053 | 0.051 | *1.028* | 5% | *51* | 0.00099 | 0.10% |
| | | Accumulation | 0.202 | 0.679 | 0.477 | *0.437* | 109% | | 0.00936 | 2.14% |
| | | Ablation | 0.867 | 0.876 | 0.009 | *0.872* | 1% | | 0.00018 | 0.02% |
| 4 | Vernagtferner | Glacier wide | 0.686 | 0.708 | 0.023 | *0.697* | 3% | *51* | 0.00044 | 0.06% |
| | | Accumulation | 0.126 | 0.357 | 0.232 | *0.241* | 96% | | 0.00454 | 1.88% |
| | | Ablation | 1.768 | 1.645 | -0.123 | *1.704* | -7% | | -0.00512 | -0.30% |
| 5 | Zongo | Glacier wide | 0.430 | 0.702 | 0.271 | *0.571* | 47% | *24* | 0.01131 | 1.98% |
| | | Accumulation | 0.192 | 0.249 | 0.057 | *0.221* | 26% | | 0.00236 | 1.07% |
| | | Ablation | 0.104 | 0.106 | 0.002 | *0.105* | 2% | | 0.00006 | 0.06% |
| 6 | Devon Ice Cap NW | Glacier wide | 0.084 | 0.112 | 0.028 | *0.099* | 28% | *40* | 0.00070 | 0.71% |
| | | Accumulation | 0.050 | 0.092 | 0.041 | *0.071* | 58% | | 0.00104 | 1.46% |
| | | Ablation | 0.510 | 1.260 | 0.750 | *0.748* | 100% | | 0.03126 | 4.18% |
| 7 | Helm | Glacier wide | 0.568 | 1.120 | 0.552 | *0.743* | 74% | *24* | 0.02300 | 3.10% |
| | | Accumulation | 0.584 | 0.363 | -0.222 | *0.514* | -43% | | -0.00924 | -1.80% |
| | | Ablation | 0.504 | 0.723 | 0.220 | *0.613* | 36% | | 0.00549 | 0.90% |
| 8 | Peyto | Glacier wide | 0.592 | 0.550 | -0.042 | *0.571* | -7% | *40* | -0.00104 | -0.18% |
| | | Accumulation | 0.468 | 0.302 | -0.166 | *0.385* | -43% | | -0.00415 | -1.08% |
| | | Ablation | 0.933 | 1.005 | 0.072 | *0.961* | 8% | | 0.00176 | 0.18% |
| 9 | Place | Glacier wide | 0.577 | 0.506 | -0.071 | *0.549* | -13% | *41* | -0.00173 | -0.31% |
| | | Accumulation | 0.440 | 0.403 | -0.038 | *0.426* | -9% | | -0.00092 | -0.22% |
| | | Ablation | 0.214 | 0.216 | 0.002 | *0.215* | 1% | | 0.00003 | 0.01% |
| 10 | White | Glacier wide | 0.164 | 0.196 | 0.032 | *0.180* | 18% | *57* | 0.00057 | 0.32% |
| | | Accumulation | 0.084 | 0.137 | 0.053 | *0.110* | 48% | | 0.00093 | 0.84% |
| | | Ablation | 0.330 | 0.404 | 0.074 | *0.367* | 20% | | 0.00121 | 0.33% |
| 11 | Allalin | Glacier wide | 0.293 | 0.342 | 0.049 | *0.317* | 15% | *61* | 0.00081 | 0.25% |
| | | Accumulation | 0.285 | 0.202 | -0.083 | *0.244* | -34% | | -0.00137 | -0.56% |
| | | Ablation | 1.062 | 0.182 | -0.880 | *0.695* | -127% | | -0.03667 | -5.27% |
| 12 | Basodino | Glacier wide | 0.797 | 0.329 | -0.468 | *0.619* | -76% | *24* | -0.01949 | -3.15% |
| | | Accumulation | 0.288 | 0.351 | 0.064 | *0.316* | 20% | | 0.00266 | 0.84% |
| | | Ablation | 0.594 | 1.035 | 0.441 | *0.815* | 54% | | 0.00881 | 1.08% |
| 13 | Gietro | Glacier wide | 0.978 | 0.481 | -0.497 | *0.726* | -69% | *50* | -0.00995 | -1.37% |
| | | Accumulation | 0.387 | 0.284 | -0.103 | *0.335* | -31% | | -0.00205 | -0.61% |
| | | Ablation | 0.698 | 0.788 | 0.090 | *0.740* | 12% | | 0.00164 | 0.22% |
| 14 | Gries | Glacier wide | 0.404 | 0.518 | 0.114 | *0.457* | 25% | *55* | 0.00207 | 0.45% |
| | | Accumulation | 0.197 | 0.408 | 0.211 | *0.296* | 71% | | 0.00383 | 1.29% |
| | | Ablation | 0.868 | 0.652 | -0.216 | *0.760* | -28% | | -0.00675 | -0.89% |
| 15 | Grosser Aletsch | Glacier wide | 0.765 | 0.643 | -0.122 | *0.704* | -17% | *32* | -0.00382 | -0.54% |
| | | Accumulation | 0.527 | 0.486 | -0.040 | *0.507* | -8% | | -0.00126 | -0.25% |
| | | Ablation | 0.918 | 0.756 | -0.162 | *0.837* | -19% | | -0.00450 | -0.54% |
| 16 | Rhone | Glacier wide | 0.703 | 0.685 | -0.018 | *0.694* | -3% | *36* | -0.00051 | -0.07% |
| | | Accumulation | 0.685 | 0.324 | -0.361 | *0.505* | -72% | | -0.01004 | -1.99% |
| | | Ablation | 0.659 | 0.773 | 0.114 | *0.716* | 16% | | 0.00188 | 0.26% |
| 17 | Schwarzberg | Glacier wide | 0.439 | 0.614 | 0.175 | *0.527* | 33% | *61* | 0.00287 | 0.54% |
| | | Accumulation | 0.313 | 0.390 | 0.077 | *0.351* | 22% | | 0.00126 | 0.36% |
| | | Ablation | 0.924 | 1.052 | 0.129 | *0.985* | 13% | | 0.00205 | 0.21% |
| 18 | Silvretta | Glacier wide | 0.464 | 0.738 | 0.274 | *0.595* | 46% | *63* | 0.00434 | 0.73% |
| | | Accumulation | 0.231 | 0.478 | 0.247 | *0.349* | 71% | | 0.00392 | 1.12% |

| Nr. | Glacier name | Gradient | Modelled gradient (m w.e. (100 m)$^{-1}$) | | | *Mean gradient (m w.e. (100 m)$^{-1}$)* | Change over total period (%) | *# of years of the period* | Mean annual rate of change | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | First year | Last year | Difference | | | | m w.e. (100 m)$^{-1}$ | % |
| | | Ablation | 1.299 | 1.257 | -0.042 | *1.278* | -3% | | -0.00150 | -0.12% |
| 19 | Urumqi Glacier E | Glacier wide | 0.680 | 0.687 | 0.008 | *0.684* | 1% | *28* | 0.00027 | 0.04% |
| | | Accumulation | 0.291 | 0.421 | 0.131 | *0.358* | 37% | | 0.00467 | 1.31% |
| | | Ablation | 1.029 | 1.222 | 0.193 | *1.126* | 17% | | 0.00689 | 0.61% |
| 20 | Urumqi Glacier W | Glacier wide | 0.866 | 0.644 | -0.222 | *0.755* | -29% | *28* | -0.00793 | -1.05% |
| | | Accumulation | 0.563 | 0.272 | -0.291 | *0.417* | -70% | | -0.01039 | -2.49% |
| | | Ablation | 0.609 | 0.875 | 0.266 | *0.722* | 37% | | 0.00542 | 0.75% |
| 21 | Abramov | Glacier wide | 0.494 | 0.764 | 0.270 | *0.608* | 44% | *49* | 0.00551 | 0.91% |
| | | Accumulation | 0.156 | 0.278 | 0.122 | *0.208* | 59% | | 0.00249 | 1.20% |
| | | Ablation | 0.460 | 0.755 | 0.295 | *0.587* | 50% | | 0.00820 | 1.40% |
| 22 | Golubin | Glacier wide | 0.574 | 0.593 | 0.019 | *0.582* | 3% | *36* | 0.00054 | 0.09% |
| | | Accumulation | 0.743 | 0.322 | -0.420 | *0.562* | -75% | | -0.01167 | -2.08% |
| | | Ablation | 0.299 | 0.326 | 0.027 | *0.313* | 9% | | 0.00158 | 0.50% |
| 23 | Shumskiy | Glacier wide | 0.312 | 0.331 | 0.019 | *0.321* | 6% | *17* | 0.00113 | 0.35% |
| | | Accumulation | 1.347 | 0.846 | -0.501 | *1.096* | -46% | | -0.02945 | -2.69% |
| | | Ablation | 0.386 | 0.528 | 0.142 | *0.458* | 31% | | 0.00274 | 0.60% |
| 24 | Tuyuksuyskiy | Glacier wide | 0.434 | 0.636 | 0.201 | *0.538* | 37% | *52* | 0.00387 | 0.72% |
| | | Accumulation | 0.161 | 0.859 | 0.698 | *0.526* | 133% | | 0.01342 | 2.55% |
| | | Ablation | 0.615 | 0.908 | 0.293 | *0.761* | 38% | | 0.00552 | 0.73% |
| 25 | Aalfotbreen | Glacier wide | 0.657 | 0.817 | 0.159 | *0.740* | 22% | *53* | 0.00300 | 0.41% |
| | | Accumulation | 0.717 | 0.499 | -0.218 | *0.604* | -36% | | -0.00411 | -0.68% |
| | | Ablation | 1.429 | 1.421 | -0.008 | *1.425* | -1% | | -0.00028 | -0.02% |
| 26 | Austdalsbreen | Glacier wide | 0.971 | 1.143 | 0.172 | *1.057* | 16% | *29* | 0.00594 | 0.56% |
| | | Accumulation | 0.527 | 0.340 | -0.187 | *0.433* | -43% | | -0.00646 | -1.49% |
| | | Ablation | 1.038 | 1.092 | 0.053 | *1.065* | 5% | | 0.00114 | 0.11% |
| 27 | Engabreen | Glacier wide | 0.960 | 1.023 | 0.063 | *0.991* | 6% | *47* | 0.00134 | 0.14% |
| | | Accumulation | 0.591 | 0.401 | -0.189 | *0.496* | -38% | | -0.00403 | -0.81% |
| | | Ablation | x | x | x | *x* | x | | x | x |
| 28 | Graasubreen | Glacier wide | x | x | x | *x* | x | *54* | x | x |
| | | Accumulation | 0.343 | 0.517 | 0.174 | *0.434* | 40% | | 0.00322 | 0.74% |
| | | Ablation | 0.781 | 0.733 | -0.048 | *0.757* | -6% | | -0.00154 | -0.20% |
| 29 | Hansebreen | Glacier wide | 1.112 | 0.709 | -0.403 | *0.909* | -44% | *31* | -0.01299 | -1.43% |
| | | Accumulation | 0.902 | 0.413 | -0.489 | *0.656* | -74% | | -0.01576 | -2.40% |
| | | Ablation | 0.620 | 0.772 | 0.152 | *0.696* | 22% | | 0.00276 | 0.40% |
| 30 | Hellstugubreen | Glacier wide | 0.532 | 0.671 | 0.139 | *0.601* | 23% | *55* | 0.00253 | 0.42% |
| | | Accumulation | 0.465 | 0.609 | 0.144 | *0.537* | 27% | | 0.00262 | 0.49% |
| | | Ablation | 0.861 | 0.657 | -0.203 | *0.754* | -27% | | -0.00726 | -0.96% |
| 31 | Langfjordjoekelen | Glacier wide | 0.736 | 0.570 | -0.166 | *0.649* | -26% | *28* | -0.00592 | -0.91% |
| | | Accumulation | 0.472 | 0.274 | -0.198 | *0.369* | -54% | | -0.00709 | -1.92% |
| | | Ablation | 0.851 | 0.880 | 0.029 | *0.865* | 3% | | 0.00052 | 0.06% |
| 32 | Nigardsbreen | Glacier wide | 0.824 | 0.764 | -0.060 | *0.794* | -8% | *55* | -0.00109 | -0.14% |
| | | Accumulation | 0.534 | 0.391 | -0.143 | *0.463* | -31% | | -0.00259 | -0.56% |
| | | Ablation | 0.943 | 0.988 | 0.044 | *0.967* | 5% | | 0.00082 | 0.09% |
| 33 | Rembesdalskaaka | Glacier wide | 0.900 | 0.975 | 0.075 | *0.940* | 8% | *54* | 0.00139 | 0.15% |
| | | Accumulation | 0.347 | 0.520 | 0.173 | *0.438* | 40% | | 0.00321 | 0.73% |
| | | Ablation | 0.750 | 0.599 | -0.151 | *0.674* | -22% | | -0.00561 | -0.83% |
| 34 | Storbreen | Glacier wide | 0.595 | 0.682 | 0.086 | *0.638* | 14% | *27* | 0.00320 | 0.50% |
| | | Accumulation | 0.507 | 0.739 | 0.233 | *0.623* | 37% | | 0.00861 | 1.38% |
| | | Ablation | 0.939 | 0.797 | -0.142 | *0.868* | -16% | | -0.00339 | -0.39% |
| 35 | Djankuat | Glacier wide | 0.827 | 0.668 | -0.159 | *0.748* | -21% | *42* | -0.00379 | -0.51% |
| | | Accumulation | 0.533 | 0.479 | -0.054 | *0.506* | -11% | | -0.00128 | -0.25% |
| | | Ablation | 0.395 | 0.481 | 0.086 | *0.437* | 20% | | 0.00278 | 0.64% |
| 36 | Garabashi | Glacier wide | 0.456 | 0.646 | 0.189 | *0.548* | 35% | *31* | 0.00611 | 1.11% |
| | | Accumulation | 0.780 | 0.917 | 0.137 | *0.846* | 16% | | 0.00441 | 0.52% |

| Nr. | Glacier name | Gradient | Modelled gradient (m w.e. (100 m)$^{-1}$) | | | *Mean gradient (m w.e. (100 m)$^{-1}$)* | Change over total period (%) | *# of years of the period* | Mean annual rate of change | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | First year | Last year | Difference | | | | m w.e. (100 m)$^{-1}$ | % |
| | | Ablation | 0.521 | 0.397 | -0.124 | *0.455* | -27% | | -0.00288 | -0.63% |
| 37 | Maliy Aktru | Glacier wide | 0.374 | 0.465 | 0.091 | *0.422* | 22% | *43* | 0.00213 | 0.50% |
| | | Accumulation | 0.243 | 0.563 | 0.320 | *0.412* | 78% | | 0.00744 | 1.81% |
| | | Ablation | 0.524 | 0.379 | -0.145 | *0.453* | -32% | | -0.01118 | -2.47% |
| 38 | Vodopaniy | Glacier wide | 0.238 | 0.677 | 0.438 | *0.508* | 86% | *13* | 0.03373 | 6.65% |
| | | Accumulation | 0.059 | 0.169 | 0.110 | *0.130* | 84% | | 0.00843 | 6.47% |
| | | Ablation | 0.358 | 0.552 | 0.193 | *0.441* | 44% | | 0.00879 | 1.99% |
| 39 | Marmaglaciaeren | Glacier wide | 0.827 | 1.049 | 0.222 | *0.924* | 24% | *22* | 0.01009 | 1.09% |
| | | Accumulation | 1.596 | 1.174 | -0.422 | *1.392* | -30% | | -0.01920 | -1.38% |
| | | Ablation | 0.808 | 0.482 | -0.326 | *0.658* | -50% | | -0.01087 | -1.65% |
| 40 | Rabots Glaciaer | Glacier wide | 0.620 | 0.712 | 0.093 | *0.664* | 14% | *30* | 0.00309 | 0.46% |
| | | Accumulation | 0.469 | 1.013 | 0.545 | *0.728* | 75% | | 0.01815 | 2.49% |
| | | Ablation | 0.550 | 0.223 | -0.327 | *0.400* | -82% | | -0.01634 | -4.09% |
| 41 | Riukojietna | Glacier wide | 0.552 | 0.237 | -0.315 | *0.408* | -77% | *20* | -0.01575 | -3.86% |
| | | Accumulation | 0.341 | 0.290 | -0.052 | *0.318* | -16% | | -0.00258 | -0.81% |
| | | Ablation | 0.727 | 0.914 | 0.186 | *0.828* | 22% | | 0.00405 | 0.49% |
| 42 | Storglaciaeren | Glacier wide | 0.860 | 1.092 | 0.232 | *0.986* | 24% | *46* | 0.00504 | 0.51% |
| | | Accumulation | 0.788 | 1.341 | 0.553 | *1.088* | 51% | | 0.01202 | 1.10% |
| | | Ablation | 0.790 | 0.357 | -0.433 | *0.562* | -77% | | -0.02164 | -3.85% |
| 43 | Austre Broeggerbreen | Glacier wide | 0.390 | 0.426 | 0.036 | *0.409* | 9% | *20* | 0.00181 | 0.44% |
| | | Accumulation | 0.189 | 0.465 | 0.276 | *0.334* | 82% | | 0.01379 | 4.12% |
| | | Ablation | 0.596 | 0.419 | -0.177 | *0.503* | -35% | | -0.01266 | -2.52% |
| 44 | Midtre Lovenbreen | Glacier wide | 0.466 | 0.460 | -0.007 | *0.463* | -1% | *14* | -0.00049 | -0.11% |
| | | Accumulation | 0.436 | 0.472 | 0.037 | *0.455* | 8% | | 0.00262 | 0.58% |
| | | Ablation | 0.537 | 0.757 | 0.221 | *0.636* | 35% | | 0.01225 | 1.93% |
| 45 | Waldemarbreen | Glacier wide | 0.464 | 0.654 | 0.190 | *0.550* | 35% | *18* | 0.01057 | 1.92% |
| | | Accumulation | 0.424 | 0.654 | 0.229 | *0.528* | 43% | | 0.01274 | 2.42% |
| | | Ablation | 1.089 | 0.781 | -0.308 | *0.935* | -33% | | -0.03080 | -3.29% |
| 46 | Gulkana | Glacier wide | x | x | x | *x* | x | *10* | x | x |
| | | Accumulation | x | x | x | *x* | x | | x | x |
| | | Ablation | 1.270 | 1.086 | -0.184 | *1.178* | -16% | | -0.02043 | -1.73% |
| 47 | Lemon Creek | Glacier wide | 1.005 | 1.285 | 0.280 | *1.145* | 24% | *9* | 0.03115 | 2.72% |
| | | Accumulation | 0.562 | 1.007 | 0.445 | *0.785* | 57% | | 0.04949 | 6.31% |
| | | Ablation | 2.087 | 2.725 | 0.637 | *2.302* | 28% | | 0.01250 | 0.54% |
| 48 | South Cascade | Glacier wide | 1.375 | 1.799 | 0.424 | *1.523* | 28% | *51* | 0.00832 | 0.55% |
| | | Accumulation | 0.229 | 1.986 | 1.758 | *0.840* | 209% | | 0.03447 | 4.10% |
| | | Ablation | 0.623 | 1.377 | 0.754 | *1.000* | 75% | | 0.07540 | 7.54% |
| 49 | Wolverine | Glacier wide | x | x | x | *x* | x | *10* | x | x |
| | | Accumulation | x | x | x | *x* | x | | x | x |

**Annex 9 :** modelled absolute gradients resulting from the linear regression equation of the annual gradients over the years in the first and last year of the period and the resulting absolute difference. The calculated change over the total period given in % to the mean gradient for each glacier, the number of years of the period and the mean annual rate of change in m w.e. (100m)$^{-1}$ and in % to the mean gradient for each glacier.

# Annex 10

| Glacier name | Annual rate of change (%) | | |
|---|---|---|---|
| | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Hintereisferner* | 0.35% | 0.07% | 0.49% |
| Jamtalferner* | 0.13% | -0.37% | -1.09% |
| Kesselwandferner* | 0.19% | 0.10% | 2.14% |
| Vergtferner* | 0.02% | 0.06% | 1.88% |
| Zongo* | -0.30% | 1.98% | 1.07% |
| Devon Ice Cap NW | 0.06% | 0.71% | 1.46% |
| Helm | 4.18% | 3.10% | -1.80% |
| Peyto | 0.90% | -0.18% | -1.08% |
| Place | 0.18% | -0.31% | -0.22% |
| White* | 0.01% | 0.32% | 0.84% |
| Allalin* | 0.33% | 0.25% | -0.56% |
| Basodino | -5.27% | -3.15% | 0.84% |
| Gietro* | 1.08% | -1.37% | -0.61% |
| Gries* | 0.22% | 0.45% | 1.29% |
| Grosser Aletsch | -0.89% | -0.54% | -0.25% |
| Rhone* | -0.54% | -0.07% | -1.99% |
| Schwarzberg* | 0.26% | 0.54% | 0.36% |
| Silvretta* | 0.21% | 0.73% | 1.12% |
| Urumqi Glacier E* | -0.12% | 0.04% | 1.31% |
| Urumqi Glacier W* | 0.61% | -1.05% | -2.49% |
| Abramov* | 0.75% | 0.91% | 1.20% |
| Golubin* | 1.40% | 0.09% | -2.08% |
| Shumskiy | 0.50% | 0.35% | -2.69% |
| Tuyuksuyskiy* | 0.60% | 0.72% | 2.55% |
| Aalfotbreen* | 0.73% | 0.41% | -0.68% |
| Austdalsbreen* | -0.02% | 0.56% | -1.49% |
| Engabreen* | 0.11% | 0.14% | -0.81% |
| Graasubreen | x | x | 0.74% |
| Hansebreen* | -0.20% | -1.43% | -2.40% |
| Hellstugubreen* | 0.40% | 0.42% | 0.49% |
| Langfordjoekelen* | -0.96% | -0.91% | -1.92% |
| Nigardsbreen* | 0.06% | -0.14% | -0.56% |
| Rembesdalskaaka* | 0.09% | 0.15% | 0.73% |
| Storbreen* | -0.83% | 0.50% | 1.38% |
| Djankuat | -0.39% | -0.51% | -0.25% |
| Garabashi* | 0.64% | 1.11% | 0.52% |
| Maliy Aktru | -0.63% | 0.50% | 1.81% |
| Vodopadniy | -2.47% | 6.65% | 6.47% |
| Marmaglaciaeren | 1.99% | 1.09% | -1.38% |
| Rabots Glaciaer* | -1.65% | 0.46% | 2.49% |
| Riukojietna | -4.09% | -3.86% | -0.81% |
| Storglaciaeren* | 0.49% | 0.51% | 1.10% |
| Austre Broeggerbreen | -3.85% | 0.44% | 4.12% |
| Midtre Lovenbreen | -2.52% | -0.11% | 0.58% |
| Waldemarbreen | 1.93% | 1.92% | 2.42% |
| Gulkana | -3.29% | x | x |
| Lemon Creek | -1.73% | 2.72% | 6.31% |
| South Cascade* | 0.54% | 0.55% | 4.10% |
| Wolverine | 7.54% | x | x |
| Mean | -0.07% | 0.32% | 0.52% |
| **Median** | **0.12%** | **0.33%** | **0.52%** |
| Std. | 1.94% | 1.50% | 2.02% |
| Min. | -5.27% | -3.86% | -2.69% |
| 1st Quartile | -0.56% | -0.13% | -0.81% |
| 3rd Quartile | 0.56% | 0.56% | 1.34% |
| Max. | 7.54% | 6.65% | 6.47% |
| Total change over median time coverage (36 years) | 4.3% | 12.0% | 18.7% |
| **Median (30 glaciers*)** | **0.20%** | **0.29%** | **0.51%** |
| Total change over median time coverage (30 glaciers*, 50 years) | 9.9% | 14.3% | 25.4% |

**Annex 10 :** annual rate of changes in % to the mean gradient for the three gradients and the descriptive statistics of their distribution between glaciers. The total change over the median time coverage is calculated for the 49 selected glaciers as well as for the 30 more meaningful glaciers marked with an *

# Annex 11

| Glacier name | *n* | Degree of freedom (n-2) | Critical value |
|---|---|---|---|
| Hintereisferner | *54* | 52 | 0.250 |
| Jamtalferner | *25* | 23 | 0.396 |
| Kesselwandferner | *50* | 48 | 0.273 |
| Vergtferner | *51* | 49 | 0.273 |
| Zongo | *22* | 20 | 0.423 |
| Devon Ice Cap NW | *38* | 36 | 0.304 |
| Helm | *10* | 8 | 0.632 |
| Peyto | *37* | 35 | 0.325 |
| Place | *23* | 21 | 0.413 |
| White | *50* | 48 | 0.273 |
| Allalin | *61* | 59 | 0.250 |
| Basodino | *18* | 16 | 0.468 |
| Gietro | *49* | 47 | 0.273 |
| Gries | *51* | 49 | 0.273 |
| Grosser Aletsch | *32* | 30 | 0.349 |
| Rhone | *6* | 4 | 0.811 |
| Schwarzberg | *61* | 59 | 0.250 |
| Silvretta | *60* | 58 | 0.250 |
| Urumqi Glacier E | *24* | 22 | 0.404 |
| Urumqi Glacier W | *26* | 24 | 0.388 |
| Abramov | *34* | 32 | 0.325 |
| Golubin | *16* | 14 | 0.497 |
| Shumskiy | *17* | 15 | 0.482 |
| Tuyuksuyskiy | *47* | 45 | 0.288 |
| Aalfotbreen | *50* | 48 | 0.273 |
| Austdalsbreen | *29* | 27 | 0.367 |
| Engabreen | *47* | 45 | 0.288 |
| Graasubreen | *x* | x | x |
| Hansebreen | *30* | 28 | 0.361 |
| Hellstugubreen | *55* | 53 | 0.250 |
| Langfordjoekelen | *26* | 24 | 0.388 |
| Nigardsbreen | *55* | 53 | 0.250 |
| Rembesdalskaaka | *47* | 45 | 0.288 |
| Storbreen | *27* | 25 | 0.381 |
| Djankuat | *42* | 40 | 0.304 |
| Garabashi | *30* | 28 | 0.361 |
| Maliy Aktru | *29* | 27 | 0.367 |
| Vodopadniy | *9* | 7 | 0.666 |
| Marmaglaciaeren | *18* | 16 | 0.468 |
| Rabots Glaciaer | *20* | 18 | 0.444 |
| Riukojietna | *15* | 13 | 0.514 |
| Storglaciaeren | *41* | 39 | 0.304 |
| Austre Broeggerbreen | *18* | 16 | 0.468 |
| Midtre Lovenbreen | *13* | 11 | 0.553 |
| Waldemarbreen | *14* | 12 | 0.532 |
| Gulkana | *x* | x | x |
| Lemon Creek | *8* | 6 | 0.707 |
| South Cascade | *20* | 18 | 0.444 |
| Wolverine | *x* | x | x |

**Annex 11 :** number of years of the smallest gradient dataset used for the correlation between the three sets of of annual gradients (*n*), degree of freedom (*n-2*) and resulting critical value for the Pearson's correlation coefficient *r*

# Annex 12

| Nr. | Glacier name | Climatic parameters | | | |
|---|---|---|---|---|---|
| | | Continentality | Region | Latitude | Min.elevation |
| 1 | Hintereisferner | Transitional | 1 | Low | Low |
| 2 | Jamtalferner | Maritime | 1 | Low | Low |
| 3 | Kesselwandferner | Transitional | 1 | Low | High |
| 4 | Vergtferner | Transitional | 1 | Low | High |
| 5 | Zongo | Continental | x | Low | x |
| 6 | Devon Ice Cap NW | Continental | 4 | High | x |
| 7 | Helm | Maritime | 6 | Low | x |
| 8 | Peyto | Transitional | 6 | Low | x |
| 9 | Place | Maritime | 6 | Low | x |
| 10 | White | Continental | 4 | High | x |
| 11 | Allalin | Transitional | 1 | Low | High |
| 12 | Basodino | Maritime | 1 | Low | High |
| 13 | Gietro | Transitional | 1 | Low | High |
| 14 | Gries | Maritime | 1 | Low | Low |
| 15 | Grosser Aletsch | Transitional | 1 | Low | x |
| 16 | Rhone | Maritime | 1 | Low | Low |
| 17 | Schwarzberg | Transitional | 1 | Low | High |
| 18 | Silvretta | Maritime | 1 | Low | Low |
| 19 | Urumqi Glacier E | Continental | 3 | Low | High |
| 20 | Urumqi Glacier W | Continental | 3 | Low | High |
| 21 | Abramov | Continental | 3 | Low | High |
| 22 | Golubin | Continental | 3 | Low | Low |
| 23 | Shumskiy | Continental | 3 | Low | Low |
| 24 | Tuyuksuyskiy | Continental | 3 | Low | Low |
| 25 | Aalfotbreen | Maritime | 2 | Medium | Medium |
| 26 | Austdalsbreen | Maritime | 2 | Medium | x |
| 27 | Engabreen | Maritime | 2 | Medium | Low |
| 28 | Graasubreen | Continental | 2 | Medium | High |
| 29 | Hansebreen | Maritime | 2 | Medium | Medium |
| 30 | Hellstugubreen | Continental | 2 | Medium | High |
| 31 | Langfordjoekelen | Transitional | 2 | Medium | Low |
| 32 | Nigardsbreen | Maritime | 2 | Medium | Low |
| 33 | Rembesdalskaaka | Transitional | 2 | Medium | Medium |
| 34 | Storbreen | Transitional | 2 | Medium | High |
| 35 | Djankuat | Maritime | 8 | Low | x |
| 36 | Garabashi | Transitional | 8 | Low | x |
| 37 | Maliy Aktru | Transitional | 3 | Low | x |
| 38 | Vodopadniy | Transitional | 3 | Low | Low |
| 39 | Marmaglaciaeren | Transitional | 2 | Medium | High |
| 40 | Rabots Glaciaer | Transitional | 2 | Medium | Medium |
| 41 | Riukojietna | Transitional | 2 | Medium | Medium |
| 42 | Storglaciaeren | Transitional | 2 | Medium | Medium |
| 43 | Austre Broeggerbreen | Continental | 5 | High | x |
| 44 | Midtre Lovenbreen | Continental | 5 | High | x |
| 45 | Waldemarbreen | Continental | 5 | High | x |
| 46 | Gulkana | Transitional | 7 | Medium | x |
| 47 | Lemon Creek | Maritime | 7 | Medium | x |
| 48 | South Cascade | Maritime | 6 | Low | x |
| 49 | Wolverine | Maritime | 7 | Medium | x |

| Class | Frequency | Class | Frequency | Class | Frequency | (Region) | Class | Frequency |
|---|---|---|---|---|---|---|---|---|
| Continental | 14 | 1 | 12 | High | 5 | 1 | High | 6 |
| Transitional | 19 | 2 | 14 | Medium | 17 | | Low | 5 |
| Maritime | 16 | 3 | 8 | Low | 27 | 2 | High | 4 |
| | | 4 | 2 | | | | Medium | 6 |
| | | 5 | 3 | | | | Low | 3 |
| | | 6 | 4 | | | 3 | High | 3 |
| | | 7 | 3 | | | | Low | 4 |
| | | 8 | 2 | | | | | |

**Annexe 12:** Class assignation of the four analyzed climatic parameters for each glacier and calculated glacier frequency in each class

## Annex 13

The table from Annex 13 it splitted on two pages due to its size.

| Glacier name | °N | Med. Elevation (m a.s.l.) | **Continentality** | Temperature at the *ELA (color)* | Position as compared to $ELA_{lat}$ |
|---|---|---|---|---|---|
| Hintereisferner | 46.80 | 3064 | **Transitional** | Yellow | On |
| Jamtalferner | 46.86 | 2780 | **Maritime** | Orange | Below |
| Kesselwandferner | 46.84 | 3190 | **Transitional** | Yellow | Above |
| Vergtferner | 46.88 | 3143 | **Transitional** | Yellow | Above |
| Zongo | -16.28 | 5420 | **Continental** | Light blue | Well above |
| Devon Ice Cap NW | 75.42 | 1200 | **Continental** | Grey | Above |
| Helm | 49.96 | 1900 | **Maritime** | Red | Below |
| Peyto | 51.66 | 2640 | **Transitional** | Orange | Above |
| Place | 50.43 | 2089 | **Maritime** | Orange | Below |
| White | 79.45 | 1160 | **Continental** | Grey | Well above |
| Allalin | 46.05 | 3323 | **Transitional** | Yellow | Above |
| Basodino | 46.42 | 2886 | **Maritime** | Orange | Below |
| Gietro | 46.00 | 3229 | **Transitional** | Yellow/Orange | Above |
| Gries | 46.44 | 2945 | **Maritime** | Orange | Below |
| Grosser Aletsch | 46.50 | 3153 | **Transitional** | Yellow | Above |
| Rhone | 46.62 | 2958 | **Maritime** | Orange | Below |
| Schwarzberg | 46.02 | 3044 | **Transitional** | Yellow | On |
| Silvretta | 46.85 | 2782 | **Maritime** | Orange | Below |
| Urumqi Glacier E | 43.12 | 4021 | **Continental** | Orange | Well above |
| Urumqi Glacier W | 43.12 | 4121 | **Continental** | Orange | Well above |
| Abramov | 39.62 | 4231 | **Continental** | Orange | Well above |
| Golubin | 42.46 | 3825 | **Continental** | Red | Above |
| Shumskiy | 45.08 | 3663 | **Continental** | Orange | Well above |
| Tuyuksuyskiy | 43.05 | 3822 | **Continental** | Orange | Well above |
| Aalfotbreen | 61.75 | 1230 | **Maritime** | Orange | Below |
| Austdalsbreen | 61.82 | 1495 | **Maritime** | orange | On |
| Engabreen | 66.65 | 1220 | **Maritime** | Yellow/Grey | Above |
| Graasubreen | 61.66 | 2085 | **Continental** | Yellow | Well above |
| Hansebreen | 61.75 | 1150 | **Maritime** | Orange | Below |
| Hellstugubreen | 61.56 | 1900 | **Continental** | Yellow/Orange | Well above |
| Langfordjoekelen | 70.13 | 850 | **Transitional** | Yellow | Well above |
| Nigardsbreen | 61.72 | 1627 | **Maritime** | Orange | Above |
| Rembesdalskaaka | 60.54 | 1735 | **Transitional** | Orange | Above |
| Storbreen | 61.57 | 1775 | **Transitional** | Orange | Above |
| Djankuat | 43.19 | 3280 | **Maritime** | Orange | Below |
| Garabashi | 43.30 | 3880 | **Transitional** | Red | Above |
| Maliy Aktru | 50.05 | 3200 | **Transitional** | Yellow/Orange | Above |
| Vodopadniy | 50.05 | 3230 | **Transitional** | Yellow | Above |
| Marmaglaciaeren | 68.08 | 1530* | **Transitional** | Yellow | Well above |
| Rabots Glaciaer | 67.91 | 1505* | **Transitional** | Yellow | Well above |
| Riukojietna | 68.08 | 1300* | **Transitional** | Yellow | Well above |
| Storglaciaeren | 67.90 | 1430* | **Transitional** | Yellow | Well above |
| Austre Broeggerbreen | 78.89 | 260 | **Continental** | Yellow | Well above |
| Midtre Lovenbreen | 78.88 | 330 | **Continental** | Yellow | Well above |
| Waldemarbreen | 78.68 | 320 | **Continental** | Yellow | Well above |
| Gulkana | 63.28 | 1840 | **Transitional** | Orange | Well above |
| Lemon Creek | 58.39 | 1100 | **Maritime** | Red | Below |
| South Cascade | 48.35 | 1920 | **Maritime** | Pink | Well Below |
| Wolverine | 60.42 | 1310 | **Maritime** | Orange | Below |

| Glacier name | Annual Precipitation Sum (mm) | Other | Source |
|---|---|---|---|
| Hintereisferner | | | |
| Jamtalferner | | | |
| Kesselwandferner | | | |
| Vergtferner | 1550 mm | | *Ohmura et al., 2007* |
| Zongo | | | |
| Devon Ice Cap NW | 240 mm | | *Ohmura et al., 2007* |
| Helm | 2350 mm | | *Ohmura et al., 2007* |
| Peyto | 1600 mm | | *Ohmura et al., 2007* |
| Place | 2240 mm | | |
| White | a few hundreds mm | | *WGMS, 2013* |
| Allalin | | | |
| Basodino | | | |
| Gietro | | | |
| Gries | | | |
| Grosser Aletsch | | | |
| Rhone | 1980 mm | 4°C in summer at ELA | *WGMS, 2017* |
| Schwarzberg | | | |
| Silvretta | | | |
| Urumqi Glacier E | 500 to 700 mm | | *Ohmura et al., 2007* |
| Urumqi Glacier W | 500 to 700 mm | | *Ohmura et al., 2007* |
| Abramov | 1000mm | | *WGMS, 2017* |
| Golubin | | Classified as Continental | *WGMS, 2013* |
| Shumskiy | | | |
| Tuyuksuyskiy | | Minus 7.5°C at ELA | *WGMS, 2017* |
| Aalfotbreen | 3770 mm | Classified as Maritime | *Rasmussen and Andreassen, 2005* |
| Austdalsbreen | | Classified as Maritime | *Rasmussen and Andreassen, 2005* |
| Engabreen | 3050 mm | Classified as Maritime | *Rasmussen and Andreassen, 2005* |
| Graasubreen | 1000 mm | Classified as Continental | *Rasmussen and Andreassen, 2005* |
| Hansebreen | | | |
| Hellstugubreen | | Classified as Continental | *Rasmussen and Andreassen, 2005* |
| Langfordjoekelen | | Classified as Maritime | *Rasmussen and Andreassen, 2005* |
| Nigardsbreen | 2000 mm | Classified as Maritime | *Ohmura et al., 2007* |
| Rembesdalskaaka | 1850 mm | | |
| Storbreen | 1700 mm | | |
| Djankuat | 2800 mm | | |
| Garabashi | | | |
| Maliy Aktru | | | |
| Vodopadniy | | | |
| Marmaglaciaeren | | Continental Climate | *Holmlund and Schneider, 1996* |
| Rabots Glaciaer | | | |
| Riukojietna | | | |
| Storglaciaeren | 1600 mm (1000 mm) | | *Ohmura et al., 2007 (WGMS, 2013)* |
| Austre Broeggerbreen | 780 mm | | *Ohmura et al., 2007* |
| Midtre Lovenbreen | 810 mm | | *Ohmura et al., 2007* |
| Waldemarbreen | | | |
| Gulkana | 1600 mm | Classified as Continental | *WGMS, 2013* |
| Lemon Creek | 2400 mm | | *Ohmura et al., 2007* |
| South Cascade | 2900 mm | | *Ohmura et al., 2007* |
| Wolverine | 1300 mm | | *Ohmura et al., 2007* |

**Annex 13 :** Information used for the glacier classification in the three different continentality classes. The median glacier elevation (*WGMS, 2017*) of the Swedish glacier is given by the mean* elevation as this information is not available. The temperature at the *ELA* and the position of the glacier comparing to the $ELA_{lat}$ is given according to the study of *Huss and Farinotti (2012)*. Complementary information are also given when available and their source is mentionned.

## Annex 14

The table from Annex 14 it splitted on two pages due to its size.

| Geometric parameters | | |
|---|---|---|
| Glacier name | Lenght | Area |
| | Class | Class |
| Hintereisferner | Long | Medium |
| Jamtalferner | Short | Medium |
| Kesselwandferner | Medium | Medium |
| Vergtferner | Short | Medium |
| Zongo | Short | Small |
| Devon Ice Cap NW | Long | Large |
| Helm | Short | Small |
| Peyto | Medium | Medium |
| Place | Medium | Medium |
| White | Long | Large |
| Allalin | Long | Medium |
| Basodino | Short | Small |
| Gietro | Medium | Medium |
| Gries | Medium | Medium |
| Grosser Aletsch | Long | Large |
| Rhone | Long | Large |
| Schwarzberg | Medium | Small |
| Silvretta | Medium | Small |
| Urumqi Glacier E | Short | Small |
| Urumqi Glacier W | Short | Small |
| Abramov | Long | Large |
| Golubin | Medium | Medium |
| Shumskiy | Medium | Small |
| Tuyuksuyskiy | Short | Small |
| Aalfotbreen | Short | Medium |
| Austdalsbreen | Medium | Medium |
| Engabreen | Long | Large |
| Graasubreen | Short | Small |
| Hansebreen | Short | Small |
| Hellstugubreen | Medium | Small |
| Langfordjoekelen | Medium | Medium |
| Nigardsbreen | Long | Large |
| Rembesdalskaaka | Long | Large |
| Storbreen | Short | Medium |
| Djankuat | Medium | Small |
| Garabashi | Medium | Medium |
| Maliy Aktru | Medium | Small |
| Vodopadniy | Short | Small |
| Marmaglaciaeren | Medium | Medium |
| Rabots Glaciaer | Medium | Medium |
| Riukojietna | Short | Small |
| Storglaciaeren | Medium | Small |
| Austre Broeggerbreen | Long | Medium |
| Midtre Lovenbreen | Medium | Medium |
| Waldemarbreen | Medium | Small |
| Gulkana | Long | Large |
| Lemon Creek | Medium | Medium |
| South Cascade | Short | Small |
| Wolverine | Long | Large |
| Class | Frequency | Class | Frequency |
| Short | 15 | Small | 19 |
| Medium | 21 | Medium | 20 |
| Long | 13 | Large | 10 |

| Glacier name | Geometric parameters | | | | | |
|---|---|---|---|---|---|---|
| | Lenght/area ratio | | Slope | | Elevation coverage of the upper half area | |
| | Class | *Calculated value* | Class | *Calculated value* | Class | *Calculated value (%)* |
| Hintereisferner | Medium | *0.99* | Medium | *0.19* | Medium | *51* |
| Jamtalferner | Medium | *0.90* | Steep | *0.26* | Medium | *47* |
| Kesselwandferner | Medium | *1.00* | Medium | *0.18* | Medium | *47* |
| Vergtferner | Low | *0.36* | Steep | *0.32* | Large | *58* |
| Zongo | High | *1.42* | Steep | *0.43* | Large | *59* |
| Devon Ice Cap NW | Low | *0.03* | Low | *0.04* | Low | *34* |
| Helm | High | *3.00* | Medium | *0.19* | Large | *56* |
| Peyto | Low | *0.46* | Medium | *0.21* | Medium | *50* |
| Place | High | *1.31* | Medium | *0.19* | Large | *64* |
| White | Low | *0.40* | Low | *0.11* | Low | *36* |
| Allalin | Low | *0.70* | Medium | *0.23* | Large | *54* |
| Basodino | Medium | *0.83* | Steep | *0.41* | Medium | *48* |
| Gietro | Medium | *0.83* | Steep | *0.25* | Large | *52* |
| Gries | High | *1.25* | Medium | *0.16* | Medium | *42* |
| Grosser Aletsch | Low | *0.30* | Low | *0.10* | Low | *39* |
| Rhone | Low | *0.65* | Low | *0.13* | Medium | *47* |
| Schwarzberg | Medium | *0.80* | Medium | *0.23* | Large | *53* |
| Silvretta | High | *1.22* | Medium | *0.18* | Medium | *49* |
| Urumqi Glacier E | High | *2.10* | Steep | *0.36* | Large | *69* |
| Urumqi Glacier W | High | *3.00* | Steep | *0.33* | Large | *60* |
| Abramov | Low | *0.33* | Medium | *0.16* | Large | *55* |
| Golubin | Medium | *0.87* | Medium | *0.22* | Medium | *51* |
| Shumskiy | High | *1.25* | Steep | *0.37* | Large | *61* |
| Tuyuksuyskiy | Medium | *1.13* | Steep | *0.28* | Large | *54* |
| Aalfotbreen | Low | *0.73* | Medium | *0.16* | Low | *29* |
| Austdalsbreen | Low | *0.54* | Low | *0.10* | Medium | *46* |
| Engabreen | Low | *0.31* | Low | *0.12* | Low | *23* |
| Graasubreen | Medium | *1.10* | Medium | *0.20* | Medium | *44* |
| Hansebreen | Medium | *0.89* | Low | *0.15* | Medium | *42* |
| Hellstugubreen | Medium | *1.17* | Medium | *0.22* | Medium | *44* |
| Langfordjoekelen | High | *1.31* | Medium | *0.18* | Low | *27* |
| Nigardsbreen | Low | *0.21* | Medium | *0.17* | Low | *20* |
| Rembesdalskaaka | Low | *0.47* | Low | *0.10* | Low | *15* |
| Storbreen | Low | *0.57* | Medium | *0.24* | Medium | *47* |
| Djankuat | High | *1.26* | Steep | *0.30* | Medium | *45* |
| Garabashi | High | *1.32* | Steep | *0.29* | Large | *66* |
| Maliy Aktru | High | *1.56* | Steep | *0.35* | Low | *35* |
| Vodopadniy | High | *1.75* | Steep | *0.37* | Large | *63* |
| Marmaglaciaeren | Medium | *0.83* | Low | *0.13* | x | *x* |
| Rabots Glaciaer | Medium | *1.00* | Medium | *0.23* | x | *x* |
| Riukojietna | Medium | *0.82* | Low | *0.12* | x | *x* |
| Storglaciaeren | Medium | *1.17* | Medium | *0.17* | x | *x* |
| Austre Broeggerbreen | Medium | *0.98* | Low | *0.09* | Large | *62* |
| Midtre Lovenbreen | Medium | *0.89* | Low | *0.13* | Large | *53* |
| Waldemarbreen | High | *1.38* | Low | *0.13* | Large | *60* |
| Gulkana | Low | *0.46* | Medium | *0.17* | Medium | *50* |
| Lemon Creek | Low | *0.57* | Low | *0.11* | Medium | *46* |
| South Cascade | High | *1.88* | Medium | *0.17* | Medium | *42* |
| Wolverine | Low | *0.50* | Low | *0.15* | Low | *29* |
| | Class Frequency | | Class Frequency | | Class Frequency | |
| | Low 17 | | Low 15 | | Low 10 | |
| | Medium 17 | | Medium 21 | | Medium 18 | |
| | High 15 | | Steep 13 | | Large 17 | |

**Annex 14:** Class assignation of the five analyzed geometric parameters for each glacier and calculated glacier frequency in each class

## Annex 15

| Nr. | Glacier name | Gradient-related parameters | |
|---|---|---|---|
| | | Mean $db/dz_{gw}$ Class | Std. $db/dz_{acc}$ Class |
| 1 | Hintereisferner | Large | Small |
| 2 | Jamtalferner | Small | Medium |
| 3 | Kesselwandferner | Large | Medium |
| 4 | Vergtferner | Medium | Medium |
| 5 | Zongo | Medium | Large |
| 6 | Devon Ice Cap NW | Small | Medium |
| 7 | Helm | Large | Large |
| 8 | Peyto | Medium | Medium |
| 9 | Place | Medium | Small |
| 10 | White | Small | Large |
| 11 | Allalin | Small | Large |
| 12 | Basodino | Medium | Large |
| 13 | Gietro | Large | Medium |
| 14 | Gries | Small | Small |
| 15 | Grosser Aletsch | Medium | Small |
| 16 | Rhone | Medium | Small |
| 17 | Schwarzberg | Small | Small |
| 18 | Silvretta | Medium | Medium |
| 19 | Urumqi Glacier E | Medium | Small |
| 20 | Urumqi Glacier W | Large | Large |
| 21 | Abramov | Medium | Medium |
| 22 | Golubin | Medium | Large |
| 23 | Shumskiy | Small | Large |
| 24 | Tuyuksuyskiy | Small | Large |
| 25 | Aalfotbreen | Large | Medium |
| 26 | Austdalsbreen | Large | Medium |
| 27 | Engabreen | Large | Large |
| 28 | Graasubreen | Small | Medium |
| 29 | Hansebreen | Large | Large |
| 30 | Hellstugubreen | Medium | Small |
| 31 | Langfordjoekelen | Medium | Medium |
| 32 | Nigardsbreen | Large | Medium |
| 33 | Rembesdalskaaka | Large | Medium |
| 34 | Storbreen | Medium | Small |
| 35 | Djankuat | Large | Small |
| 36 | Garabashi | Medium | Small |
| 37 | Maliy Aktru | Small | Medium |
| 38 | Vodopadniy | Small | Large |
| 39 | Marmaglaciaeren | Large | Medium |
| 40 | Rabots Glaciaer | Medium | Large |
| 41 | Riukojietna | Small | Medium |
| 42 | Storglaciaeren | Large | Small |
| 43 | Austre Broeggerbreen | Small | Small |
| 44 | Midtre Lovenbreen | Small | Small |
| 45 | Waldemarbreen | Medium | Small |
| 46 | Gulkana | x | x |
| 47 | Lemon Creek | Large | Small |
| 48 | South Cascade | Large | Large |
| 49 | Wolverine | x | x |
| | | Class Frequency | Class Frequency |
| | | Small 14 | Small 16 |
| | | Medium 17 | Medium 17 |
| | | Large 16 | Large 14 |

**Annex 15 :** Class assignation of the two analyzed gradient-related parameters for each glacier and calculated glacier frequency in each class

# Annex 16

| | 1954 | 1955 | 1956 | 1957 | 1958 | 1959 | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean $db/dz_{a,bl}$ | 1.50 | -0.50 | 0.50 | 0.50 | 0.50 | -1.50 | 0.80 | -0.67 | -1.56 | 0.00 | -1.08 | -0.81 | 0.00 | -1.00 | 0.10 | 0.57 | -0.52 | 0.12 |
| Number of glaciers | 2 | 2 | 4 | 4 | 4 | 4 | 5 | 6 | 9 | 11 | 12 | 16 | 17 | 19 | 20 | 21 | 23 | 25 |
| Mean $db/dz_{gw}$ | 1.50 | -0.50 | 0.75 | -0.75 | 0.25 | -1.75 | 1.00 | -1.17 | -0.11 | -0.50 | -1.00 | -0.75 | -0.65 | -0.42 | -0.57 | 1.29 | -0.52 | 0.30 |
| Number of glaciers | 2 | 2 | 4 | 4 | 4 | 4 | 5 | 6 | 9 | 10 | 12 | 16 | 17 | 19 | 21 | 21 | 23 | 23 |
| Mean $db/dz_{a,ac}$ | -2.50 | 0.50 | 1.75 | -1.75 | -0.25 | -0.75 | 1.20 | -1.00 | 0.44 | -0.70 | -0.36 | -0.82 | -0.72 | -0.70 | -1.33 | -0.24 | -0.88 | -0.38 |
| Number of glaciers | 2 | 2 | 4 | 4 | 4 | 4 | 5 | 6 | 9 | 10 | 11 | 17 | 18 | 20 | 21 | 21 | 24 | 24 |

| | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean $db/dz_{a,bl}$ | -0.76 | 0.20 | -0.28 | -0.57 | -0.35 | -0.57 | -1.14 | -1.09 | -0.50 | -0.52 | -0.13 | -0.79 | -1.08 | -0.96 | -0.81 | -0.62 | -0.32 | -0.28 |
| Number of glaciers | 25 | 25 | 25 | 23 | 23 | 23 | 22 | 22 | 22 | 23 | 24 | 24 | 25 | 25 | 26 | 26 | 28 | 32 |
| Mean $db/dz_{gw}$ | -1.20 | 0.00 | -0.54 | -0.87 | 0.18 | -0.22 | -0.95 | -0.95 | -0.14 | -0.70 | 0.08 | -0.96 | -0.72 | -1.27 | -0.50 | 0.00 | 0.08 | 0.13 |
| Number of glaciers | 25 | 26 | 24 | 23 | 22 | 23 | 22 | 22 | 22 | 23 | 24 | 24 | 25 | 26 | 26 | 25 | 26 | 30 |
| Mean $db/dz_{a,ac}$ | -1.04 | -0.08 | -1.00 | -0.78 | -0.39 | -0.83 | 0.04 | -0.35 | 0.05 | -0.58 | 0.08 | -0.88 | -1.04 | -1.04 | -0.33 | -0.16 | -0.07 | -0.30 |
| Number of glaciers | 26 | 26 | 25 | 23 | 23 | 24 | 23 | 23 | 22 | 24 | 25 | 25 | 26 | 26 | 27 | 25 | 27 | 30 |

| | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean $db/dz_{a,bl}$ | 0.16 | 0.13 | 0.39 | 0.52 | 0.53 | -0.23 | 0.31 | 0.47 | 0.74 | 0.63 | 1.00 | -0.26 | 0.59 | -0.34 | -0.60 | 1.24 | 0.27 | 1.23 |
| Number of glaciers | 31 | 31 | 31 | 33 | 34 | 35 | 36 | 36 | 31 | 32 | 36 | 34 | 32 | 32 | 35 | 37 | 33 | 31 |
| Mean $db/dz_{gw}$ | 0.29 | -0.47 | 0.23 | -0.06 | 0.32 | 0.09 | -0.33 | 0.28 | 0.93 | 0.15 | 0.83 | -0.06 | 0.69 | 0.00 | -0.51 | 0.89 | 0.76 | 1.06 |
| Number of glaciers | 31 | 30 | 31 | 31 | 34 | 35 | 36 | 36 | 29 | 33 | 36 | 34 | 32 | 32 | 35 | 37 | 33 | 32 |
| Mean $db/dz_{a,ac}$ | 0.19 | -0.39 | 0.19 | -0.22 | -0.03 | 0.31 | -0.72 | -0.24 | 0.93 | 0.53 | -0.30 | 0.20 | 0.21 | 0.97 | -0.72 | 0.34 | 0.67 | 0.85 |
| Number of glaciers | 31 | 31 | 32 | 32 | 35 | 36 | 36 | 37 | 30 | 34 | 37 | 35 | 33 | 33 | 36 | 38 | 33 | 33 |

| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|---|---|
| Mean $db/dz_{a,bl}$ | 0.63 | 0.43 | -0.69 | -0.13 | -0.03 | -0.18 | 0.12 | 0.06 | 0.11 | -1.75 |
| Number of glaciers | 35 | 35 | 29 | 32 | 33 | 33 | 34 | 34 | 27 | 4 |
| Mean $db/dz_{gw}$ | 0.85 | 0.33 | -1.21 | -0.07 | -0.13 | -0.30 | 0.41 | 0.03 | -0.50 | -3.00 |
| Number of glaciers | 33 | 33 | 28 | 29 | 31 | 30 | 32 | 32 | 26 | 2 |
| Mean $db/dz_{a,ac}$ | 0.15 | -0.09 | 0.14 | 0.33 | 0.56 | 0.19 | -0.15 | 0.26 | -0.67 | 1.00 |
| Number of glaciers | 34 | 34 | 28 | 30 | 32 | 31 | 34 | 35 | 27 | 2 |

**Annex 16 :** Evolution of the annual relative mean mass balance gradients over the total period of analysis of the 49 glaciers. They are obtained by the weighted average from all glaciers with available data in the corresponding year. The number of glaciers from which the gradients are averaged is also mentioned

## Annex 17

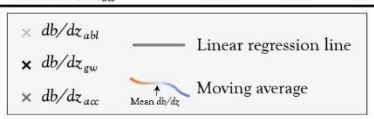
| Year | Mean annual temperature (°C) | Annual precipitation sum (mm) |
|---|---|---|
| 1959 | -1.6 | 936.1 |
| 1960 | -2.9 | 1248.5 |
| 1961 | -1.4 | 1193.6 |
| 1962 | -3.2 | 1063.9 |
| 1963 | -2.6 | 903.5 |
| 1964 | -1.8 | 1151.9 |
| 1965 | -3.6 | 1370.5 |
| 1966 | -2.7 | 1295.7 |
| 1967 | -2.2 | 1139.7 |
| 1968 | -2.8 | 1302.4 |
| 1969 | -3 | 881.3 |
| 1970 | -3.1 | 1527 |
| 1971 | -2.2 | 803.8 |
| 1972 | -2.5 | 859 |
| 1973 | -2.7 | 1232.3 |
| 1974 | -3.1 | 1303.2 |
| 1975 | -1.8 | 998.2 |
| 1976 | -2.8 | 1013.6 |
| 1977 | -2.3 | 1126.6 |
| 1978 | -2.8 | 1136 |
| 1979 | -2.9 | 1317.4 |
| 1980 | -3.3 | 1112.7 |
| 1981 | -2.9 | 1863.3 |
| 1982 | -2.1 | 1477.5 |
| 1983 | -1.4 | 1388 |
| 1984 | -3.6 | 1330.4 |
| 1985 | -3 | 1222.4 |
| 1986 | -2.4 | 1347.5 |
| 1987 | -2.5 | 1537.1 |
| 1988 | -2.2 | 1436.6 |
| 1989 | -1.1 | 1064.8 |
| 1990 | -1.3 | 1490.2 |
| 1991 | -2.2 | 1310.1 |
| 1992 | -1.1 | 1399.8 |
| 1993 | -2.1 | 1360.4 |
| 1994 | -1.1 | 1472.8 |
| 1995 | -2.4 | 1605.4 |
| 1996 | -2.7 | 1302.5 |
| 1997 | -1.2 | 1379.9 |
| 1998 | -1.8 | 1274 |
| 1999 | -2 | 1878.7 |
| 2000 | -1.3 | 1653.9 |
| 2001 | -1.9 | 1692.5 |
| 2002 | -1.2 | 1679 |
| 2003 | -1 | 1178.8 |
| 2004 | -2.1 | 1268.3 |
| 2005 | -2.5 | 1301.8 |
| 2006 | -1.1 | 1211 |
| 2007 | -1.1 | 1451.3 |
| 2008 | -1.6 | 1346.1 |
| 2009 | -1.9 | 1129.7 |
| 2010 | -2.9 | 1254.4 |
| 2011 | -0.5 | 1331.3 |
| 2012 | -1.4 | 1600.1 |
| 2013 | -2 | 1206.6 |
| 2014 | -1 | 1400.7 |
| 2015 | -0.3 | 1226 |
| 2016 | -1.2 | 1581.3 |

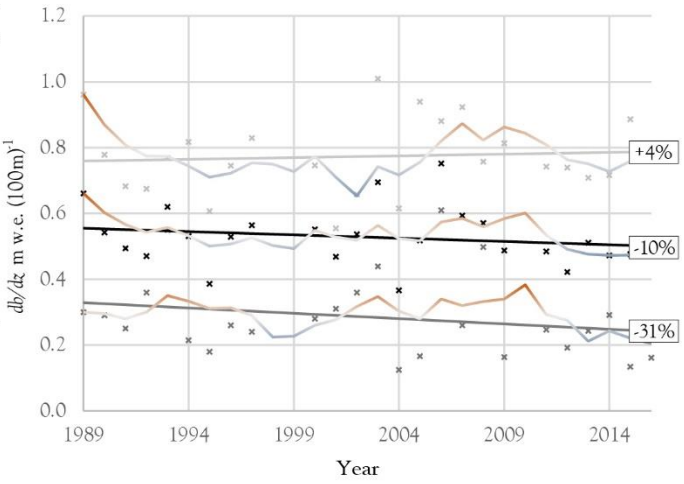
**Annex 17 :** mean annual temperature and annual precipitation sum between 1959 and 2016 at the Weissfluhjoch station in Switzerland located at 2691m a.s.l. (*MeteoSwiss*)

## Annex 18

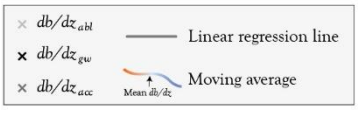
Annex 18 contains the individual evolution results from the 38 glaciers not directly presented in the results chapter. They appear according to their assigned number for the present study (see chapter 3.1.2). Their period of analysis is always mentionned, as well as the glacier's name.

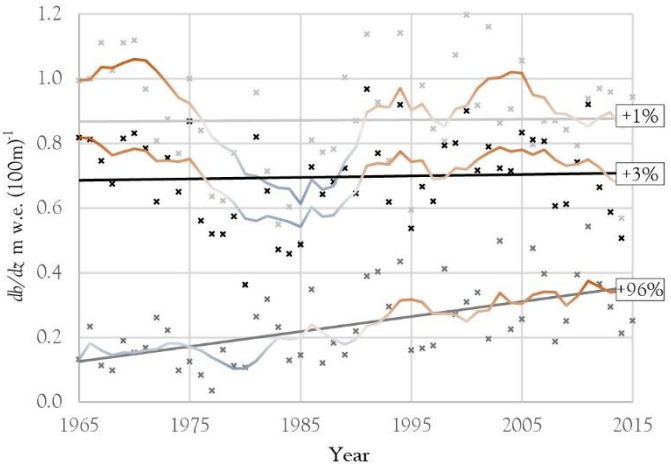
| Jamtalferner | 1989-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.773 | 0.528 | 0.285 |
| Mean annual $R^2$ | 0.98 | 0.93 | 0.90 |
| Std. | 0.112 | 0.087 | 0.124 |
| Min. | 0.555 | 0.366 | 0.125 |
| Max. | 1.009 | 0.752 | 0.610 |
| General trend | ↗ | ↘ | ↘ |
| Change over total period (%) | +4% | -10% | -31% |
| Annual rate of change (%) | +0.13% | -0.37% | -1.09% |
| $r$ with $db/dz_{abl}$ | x | 0.69 | 0.14 |
| $r$ with $db/dz_{gw}$ | 0.69 | x | 0.74 |
| $r$ with $db/dz_{acc}$ | 0.14 | 0.74 | x |



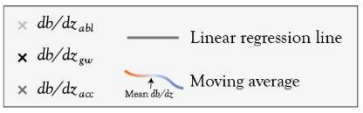



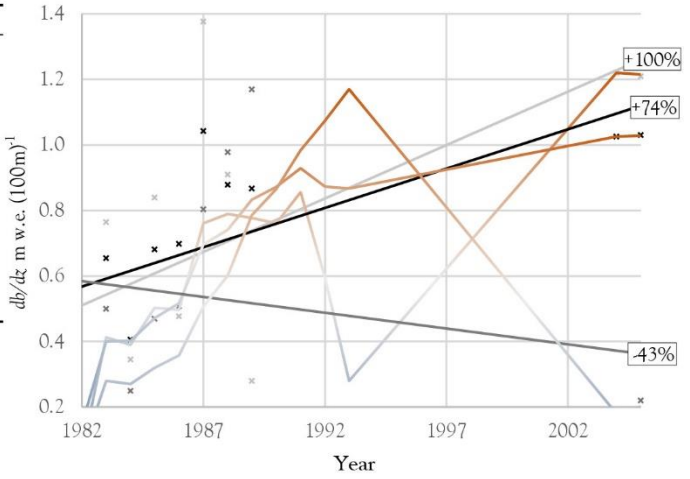

| Vernagtferner | 1965-2015 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.872 | 0.697 | 0.241 |
| Mean annual $R^2$ | 0.96 | 0.94 | 0.94 |
| Std. | 0.183 | 0.132 | 0.118 |
| Min. | 0.363 | 0.363 | 0.036 |
| Max. | 1.198 | 0.968 | 0.543 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +1% | +3% | +96% |
| Annual rate of change (%) | +0.02% | +0.06% | +1.88% |
| $r$ with $db/dz_{abl}$ | x | 0.83 | 0.21 |
| $r$ with $db/dz_{gw}$ | 0.83 | x | 0.50 |
| $r$ with $db/dz_{acc}$ | 0.21 | 0.50 | x |



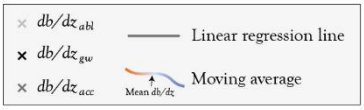



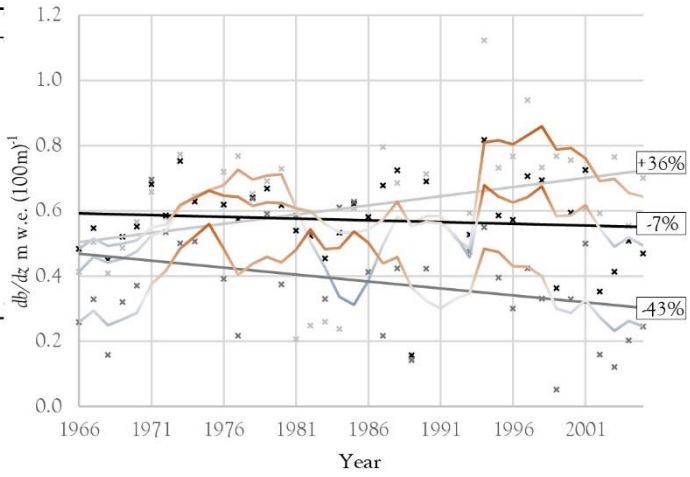
| Helm | 1982-2005 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.748 | 0.743 | 0.514 |
| Mean annual $R^2$ | 0.92 | 0.97 | x (1) |
| Std. | 0.424 | 0.278 | 0.347 |
| Min. | 0.060 | 0.145 | 0.060 |
| Max. | 1.377 | 1.042 | 1.170 |
| General trend | ↗ | ↗ | ↘ |
| Change over total period (%) | +100% | +74% | -43% |
| Annual rate of change (%) | +4.18% | +3.10% | -1.80% |
| $r$ with $db/dz_{abl}$ | x | 0.83 | 0.05 |
| $r$ with $db/dz_{gw}$ | 0.83 | x | 0.43 |
| $r$ with $db/dz_{acc}$ | 0.05 | 0.43 | x |



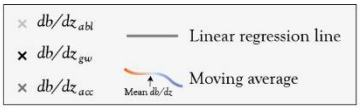



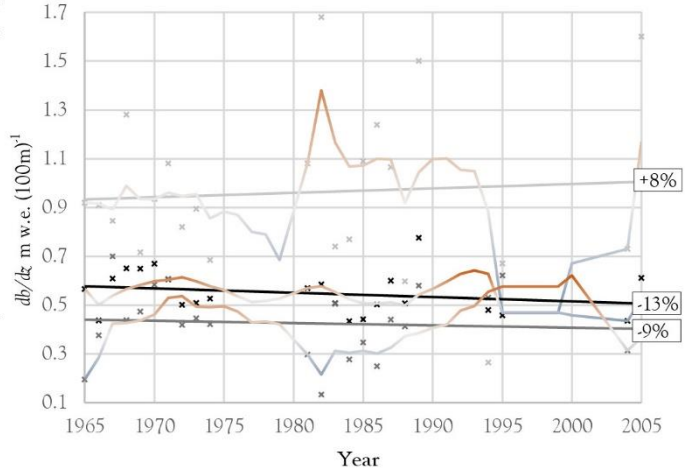

| Peyto | 1966-2005 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.613 | 0.571 | 0.385 |
| Mean annual $R^2$ | 0.89 | 0.94 | 0.91 |
| Std. | 0.203 | 0.126 | 0.162 |
| Min. | 0.147 | 0.156 | 0.051 |
| Max. | 1.123 | 0.817 | 0.696 |
| General trend | ↗ | ↘ | ↘ |
| Change over total period (%) | +36% | -7% | -43% |
| Annual rate of change (%) | +0.90% | -0.18% | -1.08% |
| $r$ with $db/dz_{abl}$ | x | 0.59 | -0.01 |
| $r$ with $db/dz_{gw}$ | 0.59 | x | 0.63 |
| $r$ with $db/dz_{acc}$ | -0.01 | 0.63 | x |



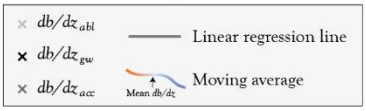



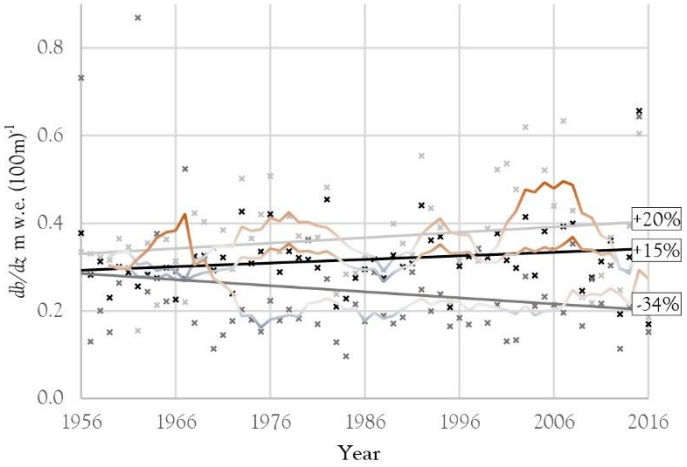

| Place | 1965-2005 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.961 | 0.549 | 0.426 |
| Mean annual $R^2$ | 0.97 | 0.93 | 0.92 |
| Std. | 0.328 | 0.087 | 0.139 |
| Min. | 0.265 | 0.434 | 0.134 |
| Max. | 1.680 | 0.776 | 0.700 |
| General trend | ↗ | ↘ | ↘ |
| Change over total period (%) | +8% | -13% | -9% |
| Annual rate of change (%) | +0.18% | -0.31% | -0.22% |
| $r$ with $db/dz_{abl}$ | x | 0.52 | -0.29 |
| $r$ with $db/dz_{gw}$ | 0.52 | x | 0.34 |
| $r$ with $db/dz_{acc}$ | -0.29 | 0.34 | x |



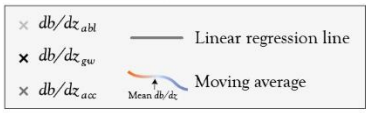



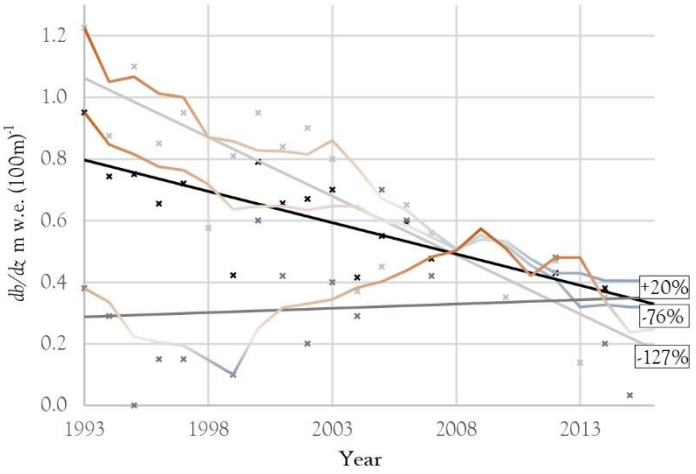
| Allalin | 1956-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.367 | 0.317 | 0.244 |
| Mean annual $R^2$ | 0.93 | 0.95 | 0.89 |
| Std. | 0.105 | 0.074 | 0.138 |
| Min. | 0.155 | 0.170 | 0.097 |
| Max. | 0.634 | 0.657 | 0.869 |
| General trend | ↗ | ↗ | ↘ |
| Change over total period (%) | +20% | +15% | -34% |
| Annual rate of change (%) | +0.33% | +0.25% | -0.56% |
| $r$ with $db/dz_{abl}$ | x | 0.79 | -0.08 |
| $r$ with $db/dz_{gw}$ | 0.79 | x | 0.33 |
| $r$ with $db/dz_{acc}$ | -0.08 | 0.33 | x |



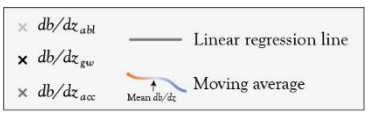



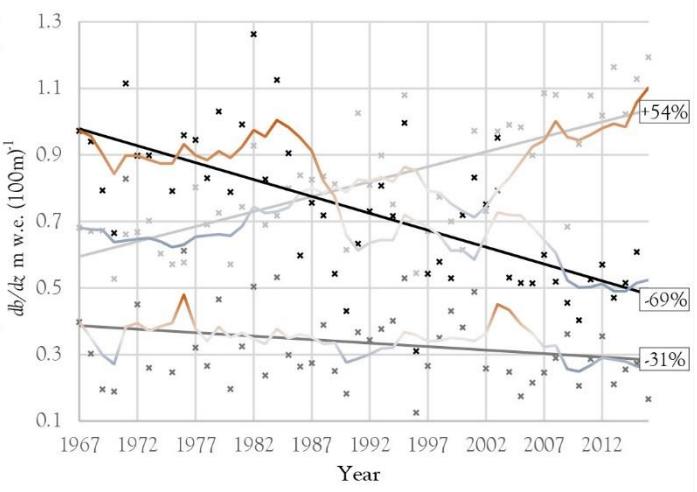

| Basodino | 1993-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.695 | 0.619 | 0.316 |
| Mean annual $R^2$ | 0.98 | 0.96 | x (1) |
| Std. | 0.283 | 0.157 | 0.194 |
| Min. | 0.139 | 0.380 | 0.000 |
| Max. | 1.225 | 0.951 | 0.700 |
| General trend | ↘ | ↘ | ↗ |
| Change over total period (%) | -127% | -76% | +20% |
| Annual rate of change (%) | -5.27% | -3.15% | +0.84% |
| $r$ with $db/dz_{abl}$ | x | 0.88 | -0.32 |
| $r$ with $db/dz_{gw}$ | 0.88 | x | 0.00 |
| $r$ with $db/dz_{acc}$ | -0.32 | 0.00 | x |



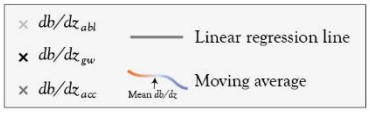



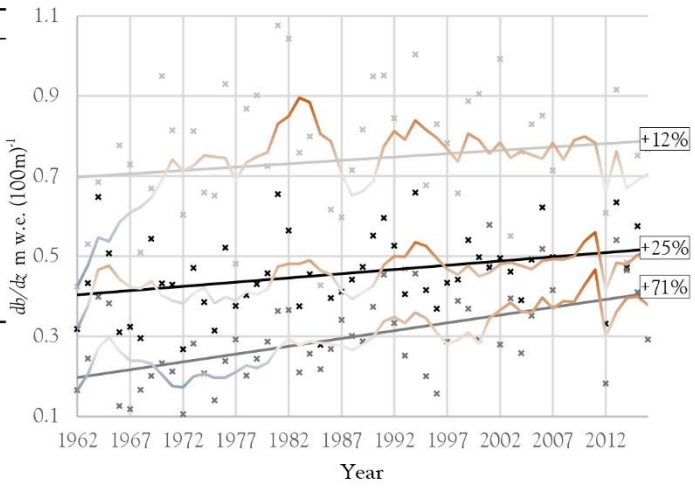

| Gietro | 1967-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.815 | 0.726 | 0.335 |
| Mean annual $R^2$ | 0.96 | 0.88 | 0.89 |
| Std. | 0.180 | 0.216 | 0.145 |
| Min. | 0.528 | 0.310 | 0.125 |
| Max. | 1.194 | 1.263 | 0.828 |
| General trend | ↗ | ↘ | ↘ |
| Change over total period (%) | +54% | -69% | -31% |
| Annual rate of change (%) | +1.08% | -1.37% | -0.61% |
| $r$ with $db/dz_{abl}$ | x | -0.27 | -0.04 |
| $r$ with $db/dz_{gw}$ | -0.27 | x | 0.65 |
| $r$ with $db/dz_{acc}$ | -0.04 | 0.65 | x |



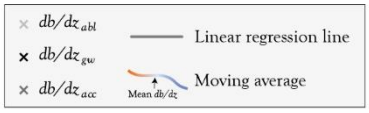



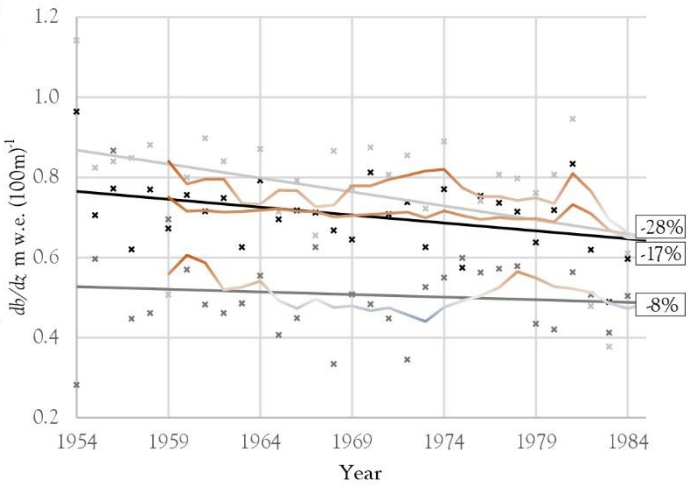
| Gries | 1962-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.740 | 0.457 | 0.296 |
| Mean annual $R^2$ | 0.97 | 0.93 | 0.96 |
| Std. | 0.169 | 0.099 | 0.110 |
| Min. | 0.425 | 0.268 | 0.106 |
| Max. | 1.077 | 0.659 | 0.579 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +12% | +25% | +71% |
| Annual rate of change (%) | +0.22% | +0.45% | +1.29% |
| $r$ with $db/dz_{abl}$ | x | 0.57 | 0.17 |
| $r$ with $db/dz_{gw}$ | 0.57 | x | 0.77 |
| $r$ with $db/dz_{acc}$ | 0.17 | 0.77 | x |



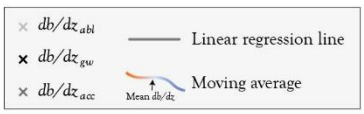



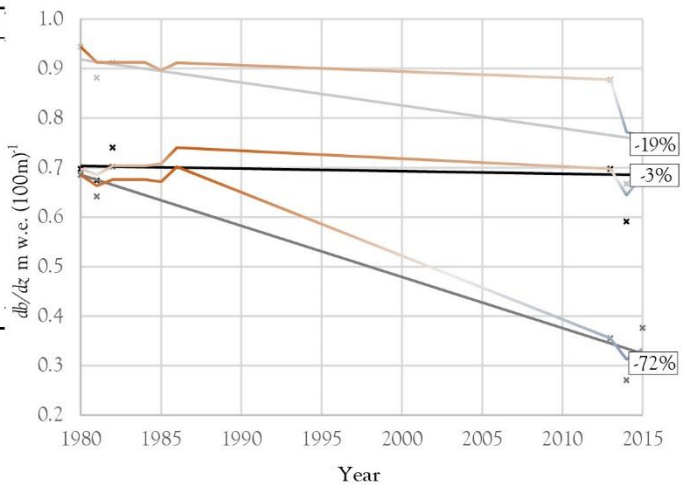

| Grosser Aletsch | 1954-1985 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.760 | 0.704 | 0.507 |
| Mean annual $R^2$ | 0.90 | 0.95 | 0.97 |
| Std. | 0.158 | 0.087 | 0.108 |
| Min. | 0.377 | 0.489 | 0.281 |
| Max. | 1.142 | 0.963 | 0.866 |
| General trend | ↘ | ↘ | ↘ |
| Change over total period (%) | -28% | -17% | -8% |
| Annual rate of change (%) | -0.89% | -0.54% | -0.25% |
| $r$ with $db/dz_{abl}$ | x | 0.83 | -0.22 |
| $r$ with $db/dz_{gw}$ | 0.83 | x | -0.02 |
| $r$ with $db/dz_{acc}$ | -0.22 | -0.02 | x |



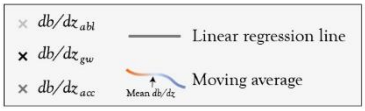



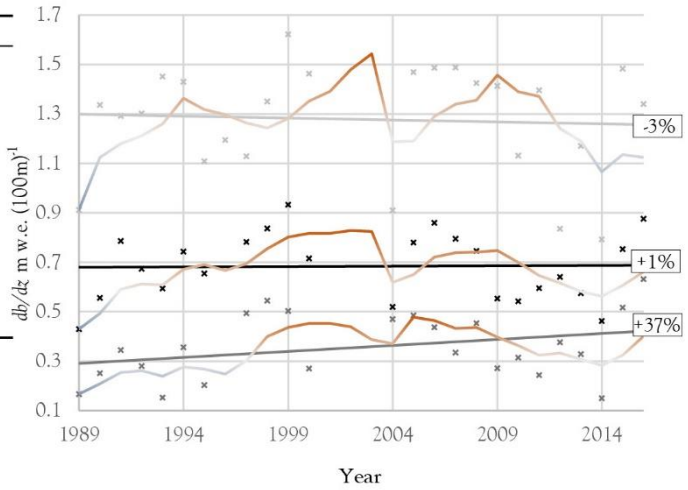

| Rhone | 1980-2015 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.837 | 0.694 | 0.505 |
| Mean annual $R^2$ | 0.94 | 0.97 | 0.98 |
| Std. | 0.099 | 0.055 | 0.175 |
| Min. | 0.667 | 0.591 | 0.270 |
| Max. | 0.944 | 0.764 | 0.701 |
| General trend | ↘ | ↘ | ↘ |
| Change over total period (%) | -19% | -3% | -72% |
| Annual rate of change (%) | -0.54% | -0.07% | -1.99% |
| $r$ with $db/dz_{abl}$ | x | 0.43 | 0.83 |
| $r$ with $db/dz_{gw}$ | 0.43 | x | 0.37 |
| $r$ with $db/dz_{acc}$ | 0.83 | 0.37 | x |



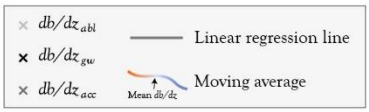



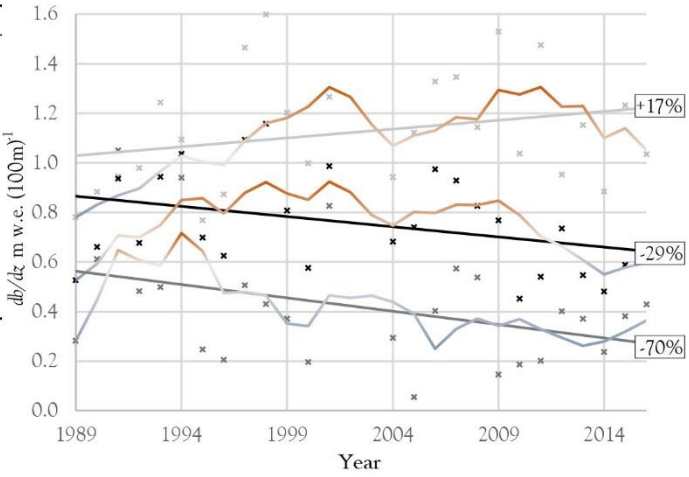
| Urumqi Glacier E | 1989-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 1.278 | 0.684 | 0.358 |
| Mean annual $R^2$ | 0.98 | 0.89 | 0.93 |
| Std. | 0.222 | 0.134 | 0.132 |
| Min. | 0.792 | 0.429 | 0.150 |
| Max. | 1.623 | 0.933 | 0.632 |
| General trend | ↘ | ↗ | ↗ |
| Change over total period (%) | -3% | +1% | 37% |
| Annual rate of change (%) | -0.12% | +0.04% | 1.31% |
| $r$ with $db/dz_{abl}$ | x | 0.66 | 0.30 |
| $r$ with $db/dz_{gw}$ | 0.66 | x | 0.73 |
| $r$ with $db/dz_{acc}$ | 0.30 | 0.73 | x |



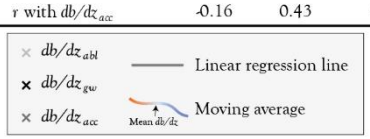



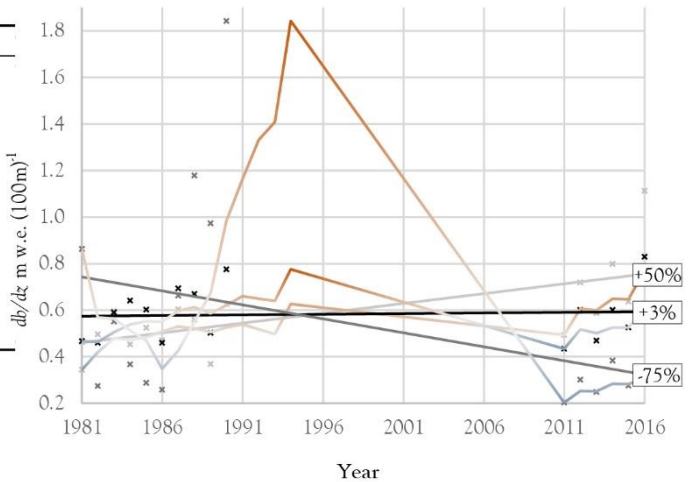

| Urumqi Glacier W | 1989-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 1.126 | 0.755 | 0.417 |
| Mean annual $R^2$ | 0.94 | 0.91 | 0.88 |
| Std. | 0.227 | 0.195 | 0.235 |
| Min. | 0.768 | 0.451 | 0.054 |
| Max. | 1.598 | 1.158 | 1.050 |
| General trend | ↗ | ↘ | ↘ |
| Change over total period (%) | +17% | -29% | -70% |
| Annual rate of change (%) | +0.61% | -1.05% | -2.49% |
| $r$ with $db/dz_{abl}$ | x | 0.54 | 0.02 |
| $r$ with $db/dz_{gw}$ | 0.54 | x | 0.60 |
| $r$ with $db/dz_{acc}$ | 0.02 | 0.60 | x |



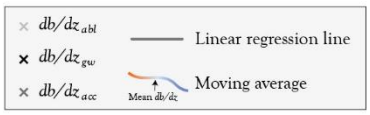



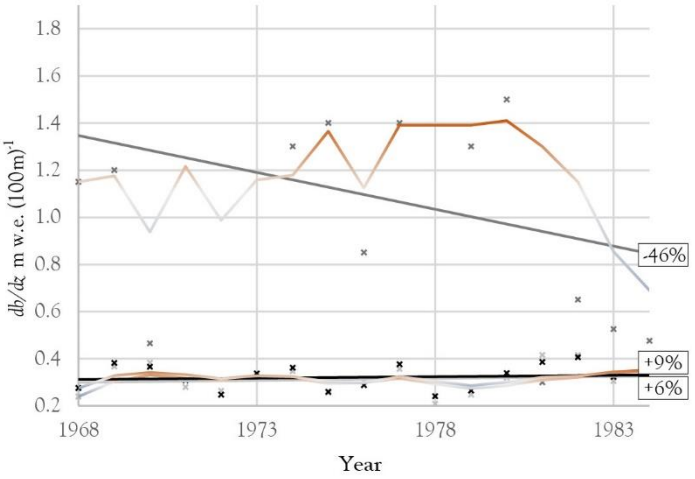

| Golubin | 1981-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.587 | 0.582 | 0.562 |
| Mean annual $R^2$ | 0.91 | 0.94 | 0.94 |
| Std. | 0.177 | 0.115 | 0.436 |
| Min. | 0.344 | 0.434 | 0.203 |
| Max. | 1.113 | 0.829 | 1.843 |
| General trend | ↗ | ↗ | ↘ |
| Change over total period (%) | +50% | +3% | -75% |
| Annual rate of change (%) | +1.40% | +0.09% | -2.08% |
| $r$ with $db/dz_{abl}$ | x | 0.66 | -0.16 |
| $r$ with $db/dz_{gw}$ | 0.66 | x | 0.43 |
| $r$ with $db/dz_{acc}$ | -0.16 | 0.43 | x |



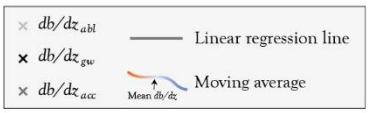



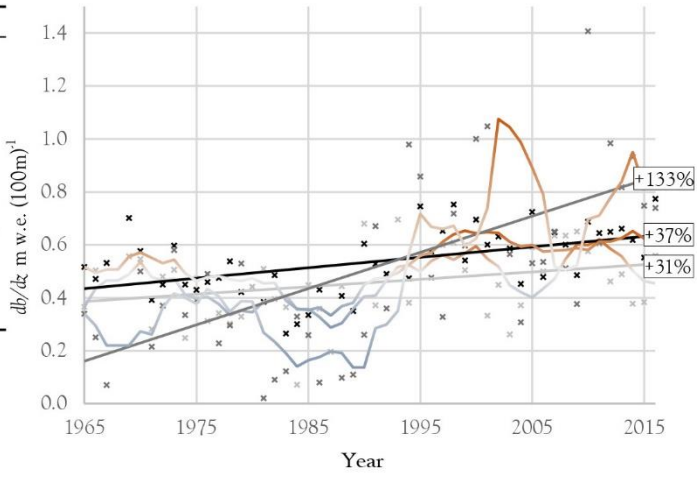
| Shumskiy | 1968-1984 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.313 | 0.321 | 1.096 |
| Mean annual $R^2$ | 0.86 | 0.88 | 0.88 |
| Std. | 0.060 | 0.051 | 0.596 |
| Min. | 0.207 | 0.240 | 0.075 |
| Max. | 0.415 | 0.406 | 2.050 |
| General trend | ↗ | ↗ | ↘ |
| Change over total period (%) | +9% | +6% | -46% |
| Annual rate of change (%) | +0.50% | +0.35% | -2.69% |
| $r$ with $db/dz_{abl}$ | x | 0.96 | -0.37 |
| $r$ with $db/dz_{gw}$ | 0.96 | x | -0.18 |
| $r$ with $db/dz_{acc}$ | -0.37 | -0.18 | x |



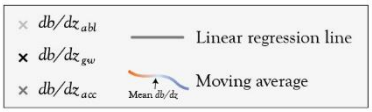



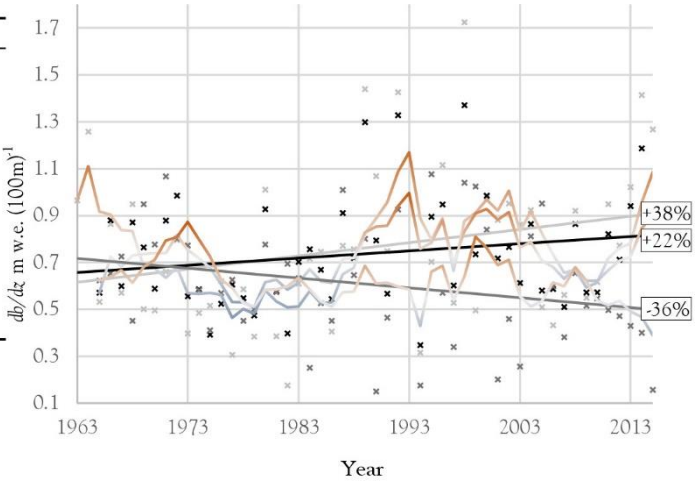

| Tuyuksuyskiy | 1965-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.458 | 0.538 | 0.526 |
| Mean annual $R^2$ | 0.91 | 0.95 | 0.92 |
| Std. | 0.135 | 0.122 | 0.374 |
| Min. | 0.072 | 0.265 | 0.020 |
| Max. | 0.695 | 0.774 | 2.013 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +31% | +37% | +133% |
| Annual rate of change (%) | +0.60% | +0.72% | +2.55% |
| $r$ with $db/dz_{abl}$ | x | 0.61 | 0.18 |
| $r$ with $db/dz_{gw}$ | 0.61 | x | 0.60 |
| $r$ with $db/dz_{acc}$ | 0.18 | 0.60 | x |



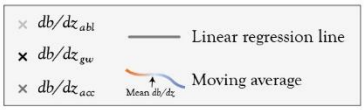



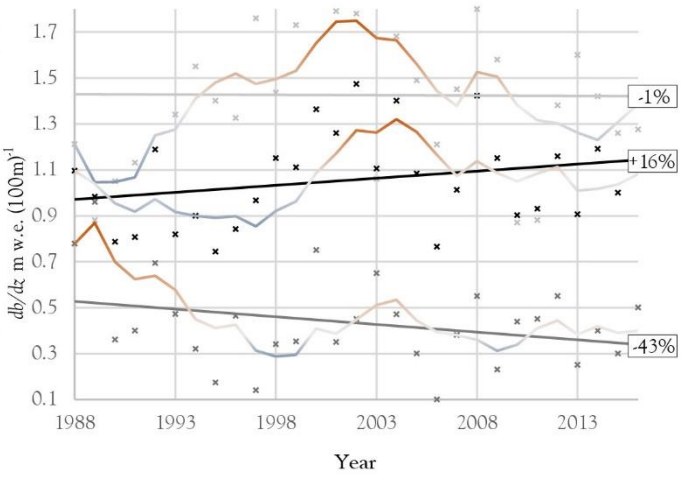

| Aalfotbreen | 1963-2015 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.761 | 0.740 | 0.604 |
| Mean annual $R^2$ | 0.95 | 0.97 | 0.95 |
| Std. | 0.326 | 0.230 | 0.245 |
| Min. | 0.175 | 0.348 | 0.150 |
| Max. | 1.723 | 1.370 | 1.075 |
| General trend | ↗ | ↗ | ↘ |
| Change over total period (%) | +38% | +22% | -36% |
| Annual rate of change (%) | +0.73% | +0.41% | -0.68% |
| $r$ with $db/dz_{abl}$ | x | 0.88 | 0.04 |
| $r$ with $db/dz_{gw}$ | 0.88 | x | 0.39 |
| $r$ with $db/dz_{acc}$ | 0.04 | 0.39 | x |



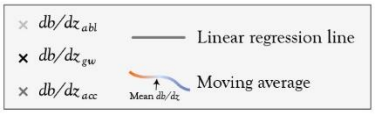



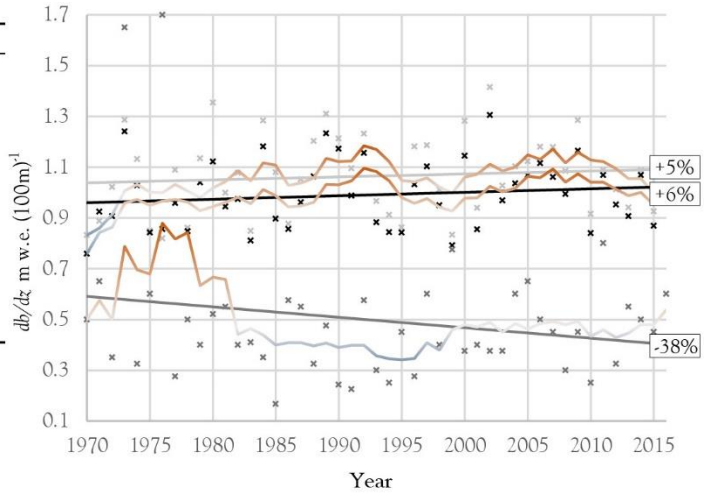
| Austdalsbreen | 1988-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 1.425 | 1.057 | 0.433 |
| Mean annual $R^2$ | 0.98 | 0.94 | 0.88 |
| Std. | 0.312 | 0.201 | 0.192 |
| Min. | 0.870 | 0.744 | 0.100 |
| Max. | 2.010 | 1.473 | 0.960 |
| General trend | ↘ | ↗ | ↘ |
| Change over total period (%) | -1% | +16% | -43% |
| Annual rate of change (%) | -0.02% | +0.56% | -1.49% |
| $r$ with $db/dz_{abl}$ | x | 0.61 | -0.11 |
| $r$ with $db/dz_{gw}$ | 0.61 | x | 0.37 |
| $r$ with $db/dz_{acc}$ | -0.11 | 0.37 | x |



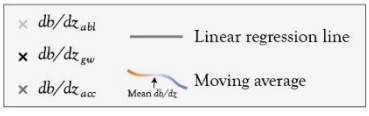



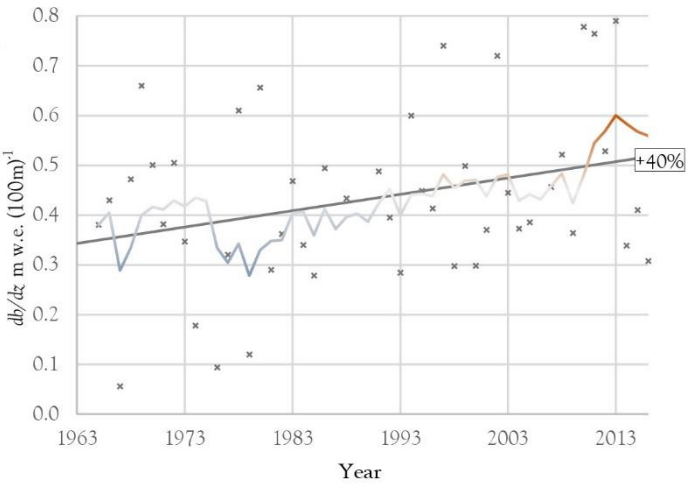

| Engabreen | 1970-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 1.065 | 0.991 | 0.496 |
| Mean annual $R^2$ | 0.99 | 0.99 | 0.89 |
| Std. | 0.156 | 0.131 | 0.286 |
| Min. | 0.819 | 0.759 | 0.167 |
| Max. | 1.415 | 1.305 | 1.700 |
| General trend | ↗ | ↗ | ↘ |
| Change over total period (%) | +5% | +6% | -38% |
| Annual rate of change (%) | +0.11% | +0.14% | -0.81% |
| $r$ with $db/dz_{abl}$ | x | 0.95 | -0.11 |
| $r$ with $db/dz_{gw}$ | 0.95 | x | 0.07 |
| $r$ with $db/dz_{acc}$ | -0.11 | 0.07 | x |



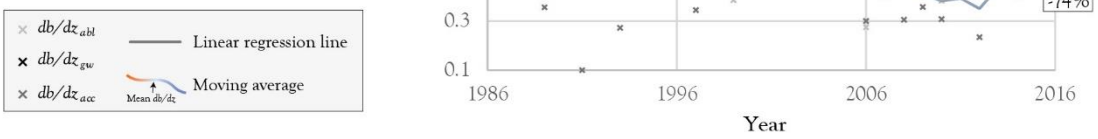




| Graasubreen | 1963-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | x | x | 0.434 |
| Mean annual $R^2$ | x | x | 0.93 |
| Std. | x | x | 0.169 |
| Min. | x | x | 0.056 |
| Max. | x | x | 0.790 |
| General trend | x | x | ↗ |
| Change over total period (%) | x | x | +40% |
| Annual rate of change (%) | x | x | +0.74% |
| $r$ with $db/dz_{abl}$ | x | x | x |
| $r$ with $db/dz_{gw}$ | x | x | x |
| $r$ with $db/dz_{acc}$ | x | x | x |



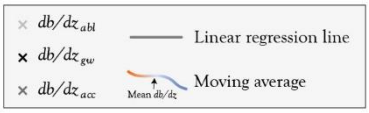
| Hansebreen | 1986-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.757 | 0.909 | 0.656 |
| Mean annual $R^2$ | 0.93 | 0.95 | 0.91 |
| Std. | 0.243 | 0.247 | 0.417 |
| Min. | 0.275 | 0.460 | 0.100 |
| Max. | 1.280 | 1.567 | 1.680 |
| General trend | ↘ | ↘ | ↘ |
| Change over total period (%) | -6% | -44% | -74% |
| Annual rate of change (%) | -0.20% | -1.43% | -2.40% |
| $r$ with $db/dz_{abl}$ | x | 0.56 | -0.08 |
| $r$ with $db/dz_{gw}$ | 0.56 | x | 0.64 |
| $r$ with $db/dz_{acc}$ | -0.08 | 0.64 | x |

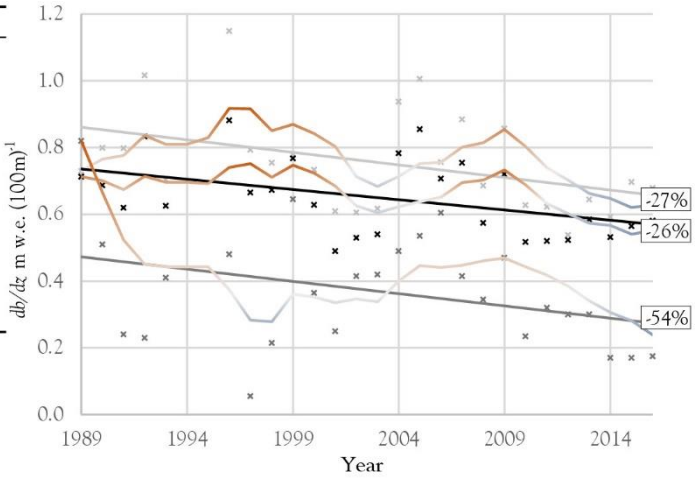




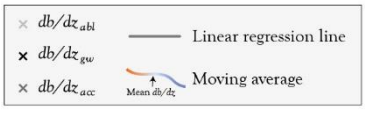


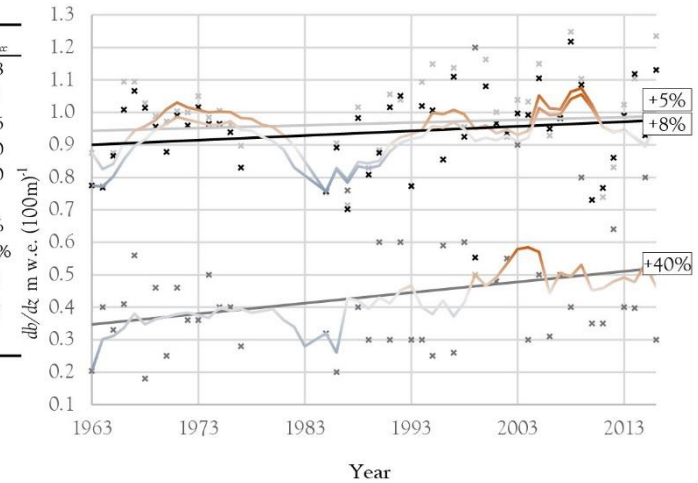
| Langfjordjoekelen | 1989-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.754 | 0.649 | 0.369 |
| Mean annual $R^2$ | 0.99 | 0.98 | 0.95 |
| Std. | 0.146 | 0.112 | 0.170 |
| Min. | 0.538 | 0.490 | 0.055 |
| Max. | 1.149 | 0.882 | 0.820 |
| General trend | ↘ | ↘ | ↘ |
| Change over total period (%) | -27% | -26% | -54% |
| Annual rate of change (%) | -0.96% | -0.91% | -1.92% |
| $r$ with $db/dz_{abl}$ | x | 0.94 | 0.28 |
| $r$ with $db/dz_{gw}$ | 0.94 | x | 0.48 |
| $r$ with $db/dz_{acc}$ | 0.28 | 0.48 | x |



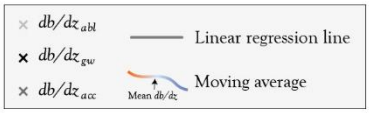



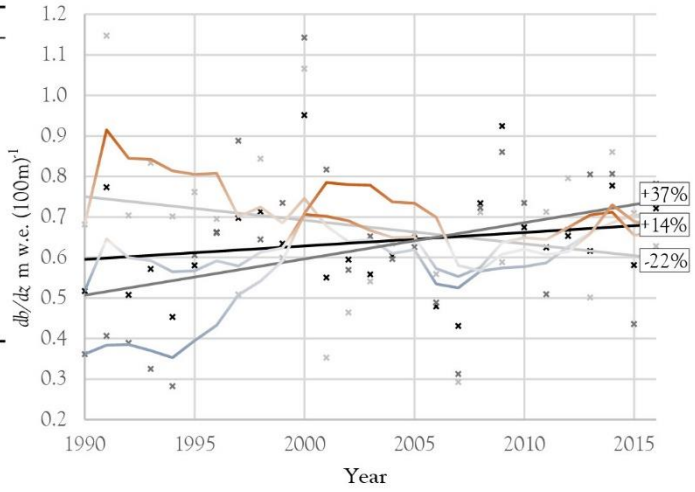

| Rembesdalskaaka | 1963-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.967 | 0.940 | 0.438 |
| Mean annual $R^2$ | 0.99 | 0.99 | 0.90 |
| Std. | 0.147 | 0.129 | 0.206 |
| Min. | 0.500 | 0.553 | 0.060 |
| Max. | 1.248 | 1.218 | 1.200 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +5% | +8% | +40% |
| Annual rate of change (%) | +0.09% | +0.15% | +0.73% |
| $r$ with $db/dz_{abl}$ | x | 0.97 | -0.33 |
| $r$ with $db/dz_{gw}$ | 0.97 | x | -0.24 |
| $r$ with $db/dz_{acc}$ | -0.33 | -0.24 | x |



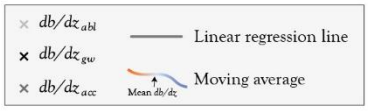



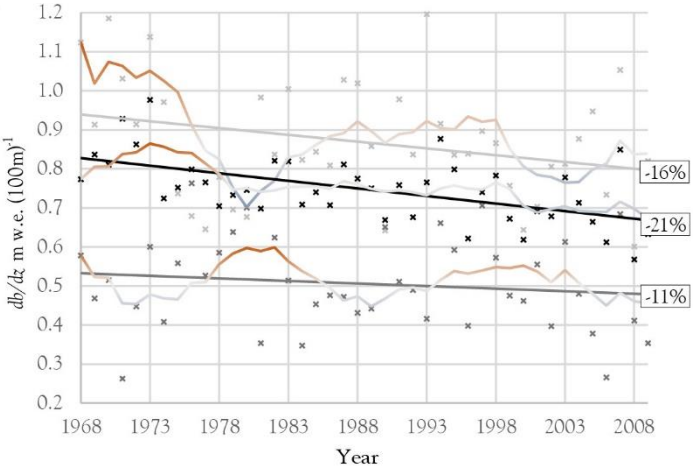
| Storbreen | 1990-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.674 | 0.638 | 0.623 |
| Mean annual $R^2$ | 0.95 | 0.97 | 0.96 |
| Std. | 0.182 | 0.123 | 0.203 |
| Min. | 0.293 | 0.431 | 0.282 |
| Max. | 1.148 | 0.951 | 1.143 |
| General trend | ↘ | ↗ | ↗ |
| Change over total period (%) | -22% | +14% | +37% |
| Annual rate of change (%) | -0.83% | +0.50% | +1.38% |
| $r$ with $db/dz_{abl}$ | x | 0.52 | 0.04 |
| $r$ with $db/dz_{gw}$ | 0.52 | x | 0.74 |
| $r$ with $db/dz_{acc}$ | 0.04 | 0.74 | x |



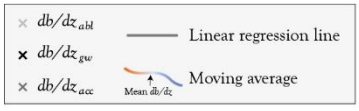



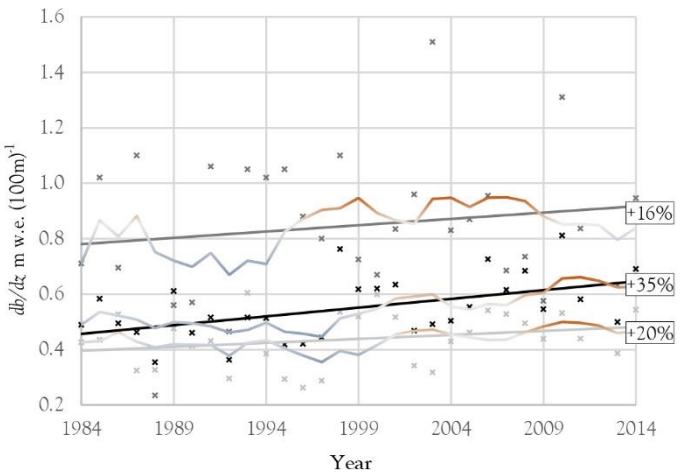

| Djankuat | 1968-2009 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.868 | 0.748 | 0.506 |
| Mean annual $R^2$ | 0.91 | 0.96 | 0.93 |
| Std. | 0.150 | 0.084 | 0.117 |
| Min. | 0.601 | 0.568 | 0.263 |
| Max. | 1.196 | 0.976 | 0.763 |
| General trend | ↘ | ↘ | ↘ |
| Change over total period (%) | -16% | -21% | -11% |
| Annual rate of change (%) | -0.39% | -0.51% | -0.25% |
| $r$ with $db/dz_{abl}$ | x | 0.57 | -0.15 |
| $r$ with $db/dz_{gw}$ | 0.57 | x | 0.34 |
| $r$ with $db/dz_{acc}$ | -0.15 | 0.34 | x |



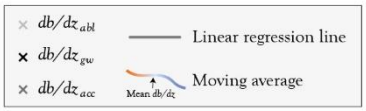



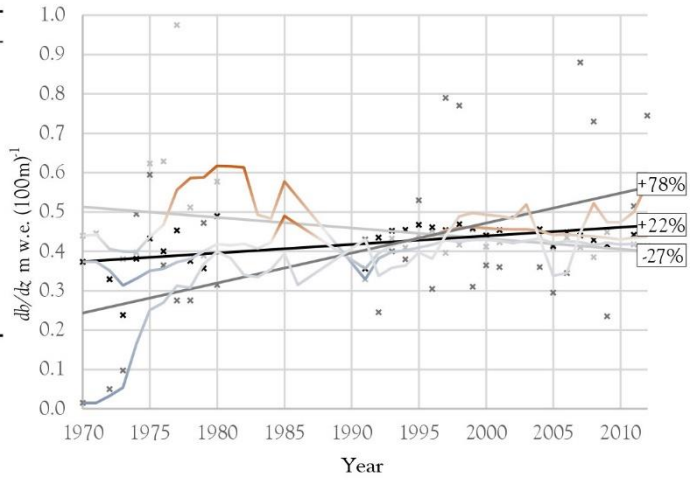

| Garabashi | 1984-2014 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.437 | 0.548 | 0.846 |
| Mean annual $R^2$ | 0.97 | 0.96 | 0.86 |
| Std. | 0.096 | 0.111 | 0.254 |
| Min. | 0.262 | 0.354 | 0.235 |
| Max. | 0.604 | 0.811 | 1.510 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +20% | +35% | +16% |
| Annual rate of change (%) | +0.64% | +1.11% | +0.52% |
| $r$ with $db/dz_{abl}$ | x | 0.77 | 0.03 |
| $r$ with $db/dz_{gw}$ | 0.77 | x | 0.33 |
| $r$ with $db/dz_{acc}$ | 0.03 | 0.33 | x |



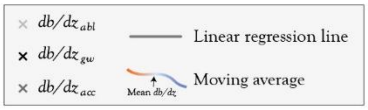



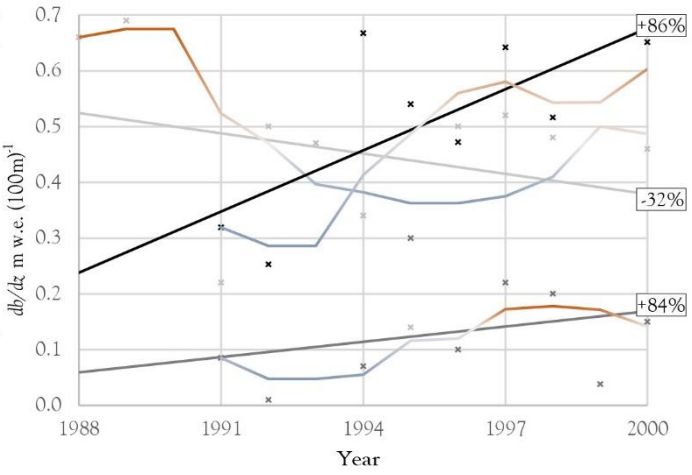
| Maliy Aktru | 1970-2012 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.455 | 0.422 | 0.412 |
| Mean annual $R^2$ | 0.95 | 0.95 | 0.87 |
| Std. | 0.118 | 0.052 | 0.213 |
| Min. | 0.329 | 0.238 | 0.015 |
| Max. | 0.975 | 0.490 | 0.880 |
| General trend | ↘ | ↗ | ↗ |
| Change over total period (%) | -27% | +22% | +78% |
| Annual rate of change (%) | -0.63% | +0.50% | +1.81% |
| $r$ with $db/dz_{abl}$ | x | 0.27 | -0.11 |
| $r$ with $db/dz_{gw}$ | 0.27 | x | 0.45 |
| $r$ with $db/dz_{acc}$ | -0.11 | 0.45 | x |



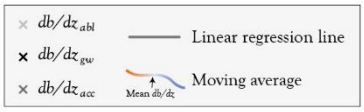



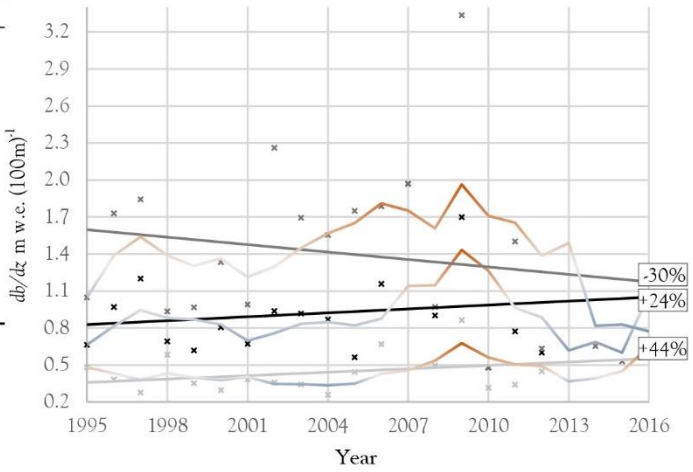

| Vodopadniy | 1988-2000 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.453 | 0.508 | 0.130 |
| Mean annual $R^2$ | x (1) | 0.89 | 0.75 |
| Std. | 0.158 | 0.144 | 0.089 |
| Min. | 0.140 | 0.253 | 0.010 |
| Max. | 0.690 | 0.667 | 0.300 |
| General trend | ↘ | ↗ | ↗ |
| Change over total period (%) | -32% | +86% | +84% |
| Annual rate of change (%) | -2.47% | +6.65% | +6.47% |
| $r$ with $db/dz_{abl}$ | x | 0.08 | -0.31 |
| $r$ with $db/dz_{gw}$ | 0.08 | x | 0.51 |
| $r$ with $db/dz_{acc}$ | -0.31 | 0.51 | x |



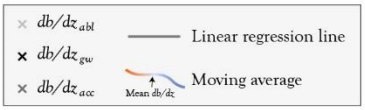



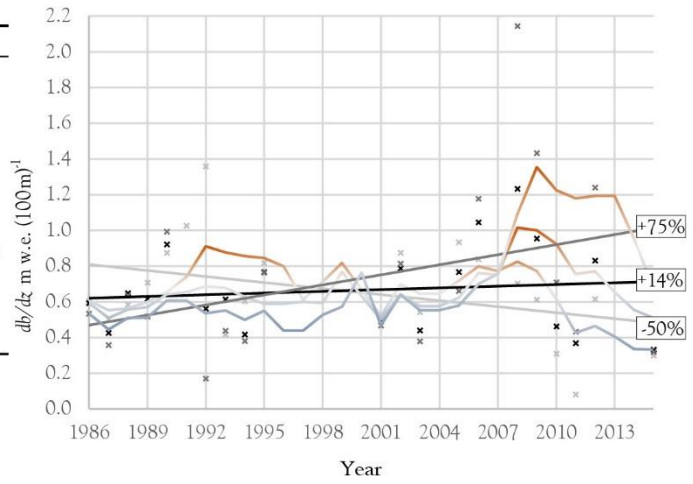

| Marmaglaciaeren | 1995-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.441 | 0.924 | 1.392 |
| Mean annual $R^2$ | 0.89 | 0.89 | 0.90 |
| Std. | 0.156 | 0.370 | 0.660 |
| Min. | 0.259 | 0.480 | 0.482 |
| Max. | 0.864 | 1.970 | 3.335 |
| General trend | ↗ | ↗ | ↘ |
| Change over total period (%) | +44% | +24% | -30% |
| Annual rate of change (%) | +1.99% | +1.09% | -1.38% |
| $r$ with $db/dz_{abl}$ | x | 0.57 | 0.40 |
| $r$ with $db/dz_{gw}$ | 0.57 | x | 0.73 |
| $r$ with $db/dz_{acc}$ | 0.40 | 0.73 | x |



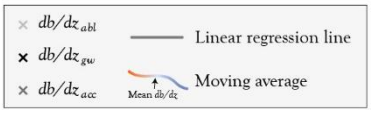



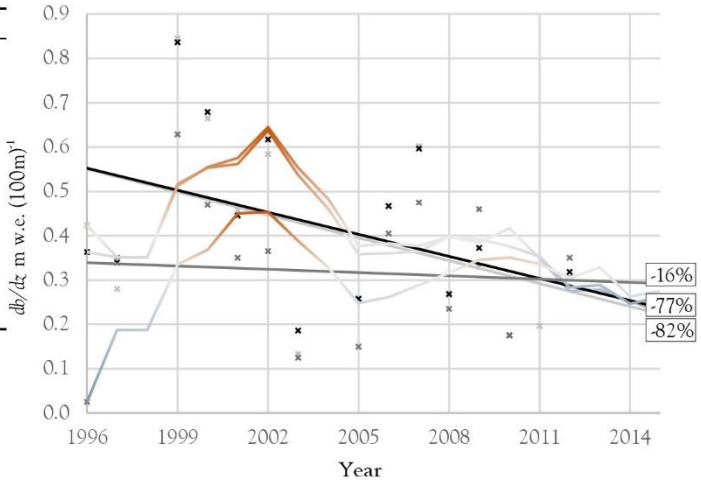
| Rabots Glaciaer | 1986-2015 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.658 | 0.664 | 0.728 |
| Mean annual $R^2$ | 0.90 | 0.95 | 0.95 |
| Std. | 0.274 | 0.239 | 0.460 |
| Min. | 0.081 | 0.331 | 0.169 |
| Max. | 1.358 | 1.232 | 2.144 |
| General trend | ↘ | ↗ | ↗ |
| Change over total period (%) | -50% | +14% | +75% |
| Annual rate of change (%) | -1.65% | +0.46% | +2.49% |
| $r$ with $db/dz_{abl}$ | x | 0.47 | 0.13 |
| $r$ with $db/dz_{gw}$ | 0.47 | x | 0.89 |
| $r$ with $db/dz_{acc}$ | 0.13 | 0.89 | x |



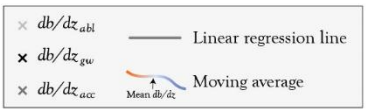



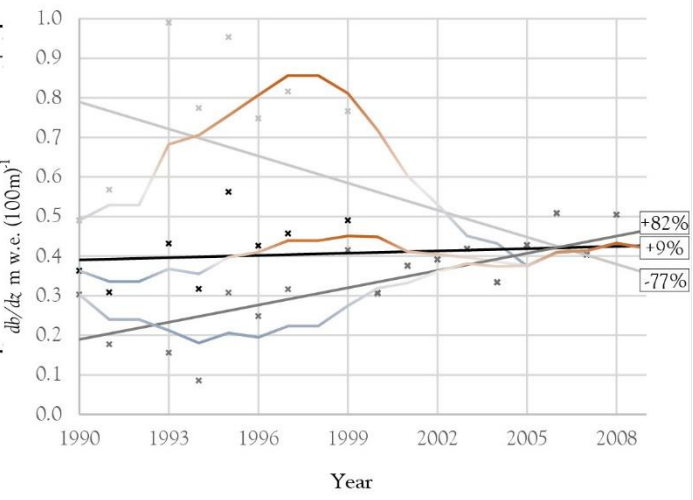

| Riukojietna | 1996-2015 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.400 | 0.408 | 0.318 |
| Mean annual $R^2$ | 0.93 | 0.96 | 0.93 |
| Std. | 0.196 | 0.190 | 0.157 |
| Min. | 0.134 | 0.175 | 0.025 |
| Max. | 0.845 | 0.836 | 0.629 |
| General trend | ↘ | ↘ | ↘ |
| Change over total period (%) | -82% | -77% | -16% |
| Annual rate of change (%) | -4.09% | -3.86% | -0.81% |
| $r$ with $db/dz_{abl}$ | x | 0.99 | 0.73 |
| $r$ with $db/dz_{gw}$ | 0.99 | x | 0.80 |
| $r$ with $db/dz_{acc}$ | 0.73 | 0.80 | x |



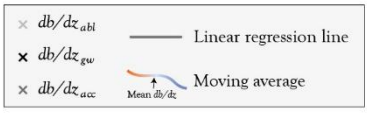



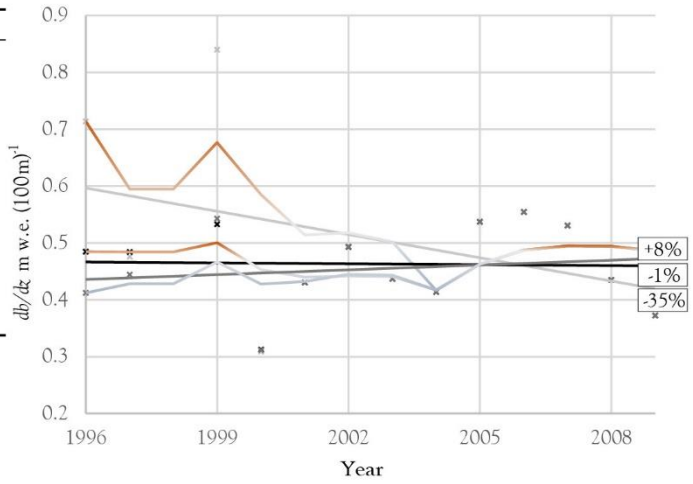

| Austre Broeggerbreen | 1990-2009 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.562 | 0.409 | 0.334 |
| Mean annual $R^2$ | 0.98 | 0.95 | 0.95 |
| Std. | 0.215 | 0.073 | 0.111 |
| Min. | 0.304 | 0.307 | 0.086 |
| Max. | 0.990 | 0.563 | 0.508 |
| General trend | ↘ | ↗ | ↗ |
| Change over total period (%) | -77% | +9% | +82% |
| Annual rate of change (%) | -3.85% | +0.44% | +4.12% |
| $r$ with $db/dz_{abl}$ | x | 0.50 | -0.49 |
| $r$ with $db/dz_{gw}$ | 0.50 | x | 0.50 |
| $r$ with $db/dz_{acc}$ | -0.49 | 0.50 | x |



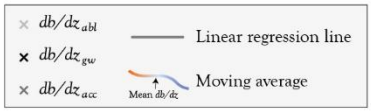



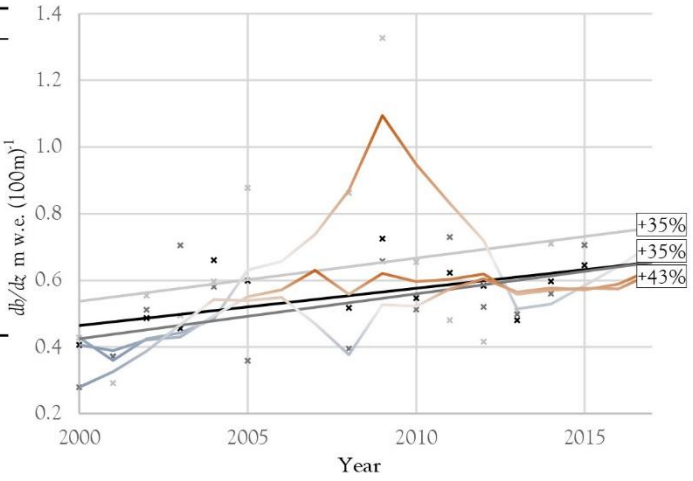
| Midtre Lovenbreen | 1996-2009 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.503 | 0.463 | 0.455 |
| Mean annual $R^2$ | 0.99 | 0.99 | 0.98 |
| Std. | 0.136 | 0.068 | 0.070 |
| Min. | 0.308 | 0.312 | 0.312 |
| Max. | 0.840 | 0.554 | 0.554 |
| General trend | ↘ | ↘ | ↗ |
| Change over total period (%) | -35% | -1% | +8% |
| Annual rate of change (%) | -2.52% | -0.11% | +0.58% |
| $r$ with $db/dz_{abl}$ | x | 0.73 | 0.62 |
| $r$ with $db/dz_{gw}$ | 0.73 | x | 0.95 |
| $r$ with $db/dz_{acc}$ | 0.62 | 0.95 | x |



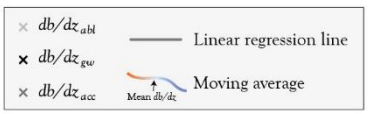



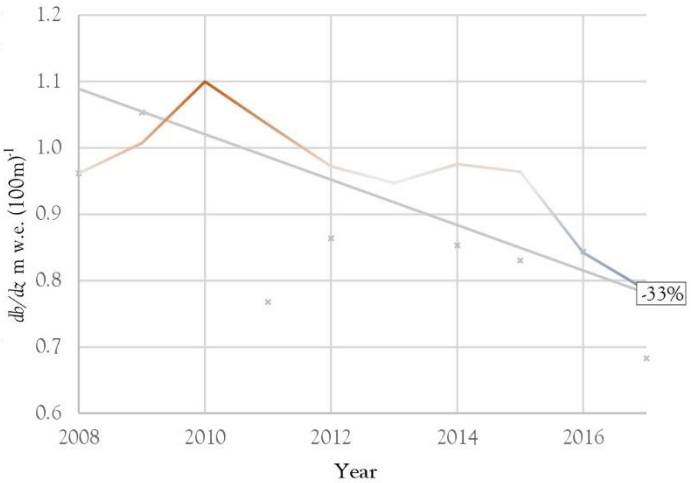

| Waldemarbreen | 2000-2017 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.636 | 0.550 | 0.528 |
| Mean annual $R^2$ | 0.97 | 0.98 | 0.94 |
| Std. | 0.250 | 0.098 | 0.136 |
| Min. | 0.291 | 0.371 | 0.279 |
| Max. | 1.327 | 0.725 | 0.730 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +35% | +35% | +43% |
| Annual rate of change (%) | +1.93% | +1.92% | +2.42% |
| $r$ with $db/dz_{abl}$ | x | 0.67 | 0.18 |
| $r$ with $db/dz_{gw}$ | 0.67 | x | 0.58 |
| $r$ with $db/dz_{acc}$ | 0.18 | 0.58 | x |



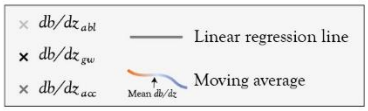



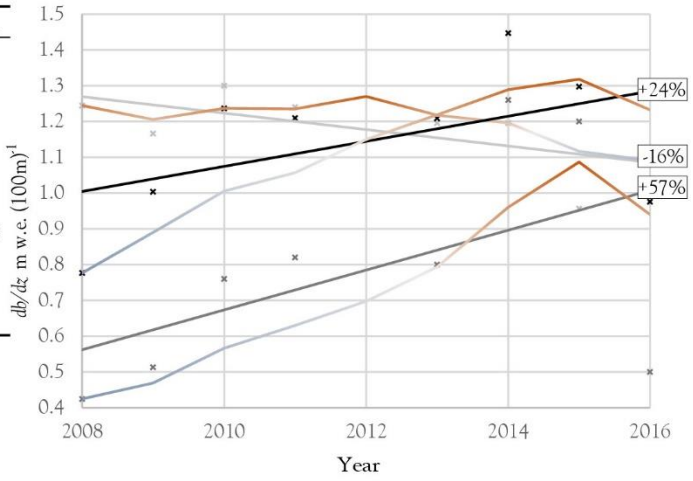

| Gulkana | 2008-2017 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 0.935 | x | x |
| Mean annual $R^2$ | 0.94 | x | x |
| Std. | 0.183 | x | x |
| Min. | 0.683 | x | x |
| Max. | 1.285 | x | x |
| General trend | ↘ | x | x |
| Change over total period (%) | -33% | x | x |
| Annual rate of change (%) | -3.29% | x | x |
| $r$ with $db/dz_{abl}$ | x | x | x |
| $r$ with $db/dz_{gw}$ | x | x | x |
| $r$ with $db/dz_{acc}$ | x | x | x |



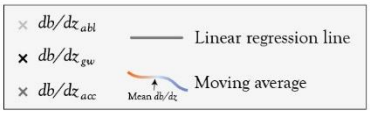



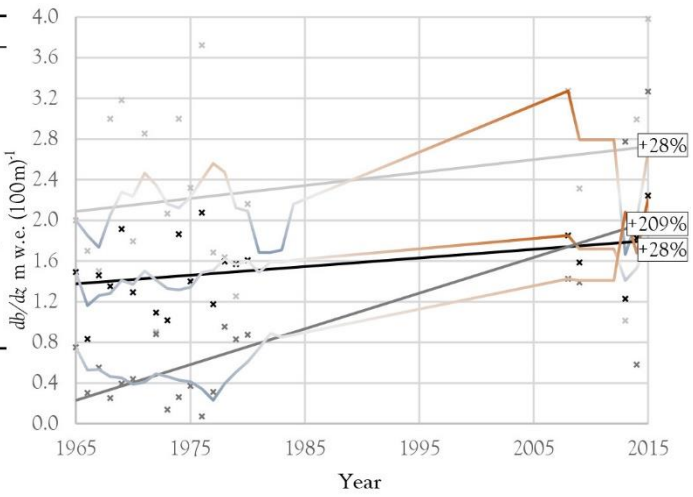
| Lemon Creek | 2008-2016 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 1.178 | 1.145 | 0.785 |
| Mean annual $R^2$ | 0.97 | 0.96 | 0.89 |
| Std. | 0.098 | 0.199 | 0.293 |
| Min. | 0.957 | 0.776 | 0.425 |
| Max. | 1.300 | 1.447 | 1.260 |
| General trend | ↘ | ↗ | ↗ |
| Change over total period (%) | -16% | +24% | +57% |
| Annual rate of change (%) | -1.73% | +2.72% | +6.31% |
| $r$ with $db/dz_{abl}$ | x | -0.16 | -0.39 |
| $r$ with $db/dz_{gw}$ | -0.16 | x | 0.92 |
| $r$ with $db/dz_{acc}$ | -0.39 | 0.92 | x |



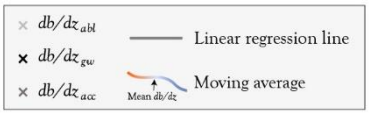



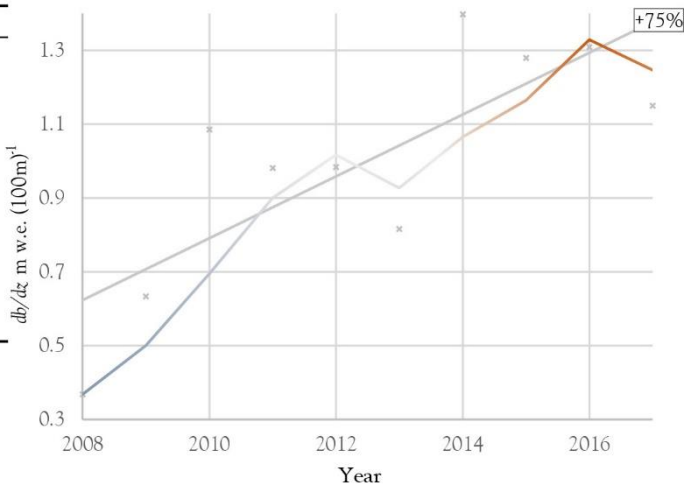

| South Cascade | 1965-2015 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 2.302 | 1.523 | 0.840 |
| Mean annual $R^2$ | 0.90 | 0.89 | 0.96 |
| Std. | 0.854 | 0.357 | 0.818 |
| Min. | 0.902 | 0.831 | 0.070 |
| Max. | 3.983 | 2.244 | 3.269 |
| General trend | ↗ | ↗ | ↗ |
| Change over total period (%) | +28% | +28% | +209% |
| Annual rate of change (%) | +0.54% | +0.55% | +4.10% |
| $r$ with $db/dz_{abl}$ | x | 0.78 | 0.06 |
| $r$ with $db/dz_{gw}$ | 0.78 | x | 0.29 |
| $r$ with $db/dz_{acc}$ | 0.06 | 0.29 | x |




| Wolverine | 2008-2017 | | |
|---|---|---|---|
| Parameter | $db/dz_{abl}$ | $db/dz_{gw}$ | $db/dz_{acc}$ |
| Mean annual $db/dz$ | 1.000 | x | x |
| Mean annual $R^2$ | x (1) | x | x |
| Std. | 0.305 | x | x |
| Min. | 0.368 | x | x |
| Max. | 1.398 | x | x |
| General trend | ↗ | x | x |
| Change over total period (%) | +75% | x | x |
| Annual rate of change (%) | +7.54% | x | x |
| $r$ with $db/dz_{abl}$ | x | x | x |
| $r$ with $db/dz_{gw}$ | x | x | x |
| $r$ with $db/dz_{acc}$ | x | x | x |



## Annex 19

| | 1954 | 1955 | 1956 | 1957 | 1958 | 1959 | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Glacier-wide Balance (mm w.e.) | 130 | -41 | -306 | -287 | -762 | -459 | 28 | -220 | 3 | -504 | -292 | 287 | -195 |
| Difference *ELA* with $ELA_0$ (*m*) | 17 | -73 | 28 | -22 | 128 | 131 | 32 | 35 | 174 | 82 | 2 | -90 | 45 |
| AAR (%) | 55 | 74 | 59 | 62 | 41 | 42 | 61 | 62 | 43 | 45 | 57 | 76 | 55 |

| | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Glacier-wide Balance (mm w.e.) | 183 | 14 | -433 | -448 | -170 | -91 | -175 | 79 | 20 | 21 | -99 | -111 | -352 |
| Difference *ELA* with $ELA_0$ (*m*) | -36 | -3 | 50 | 72 | 52 | -4 | 50 | 12 | -19 | -13 | 2 | 7 | 85 |
| AAR (%) | 72 | 65 | 47 | 48 | 51 | 59 | 49 | 67 | 62 | 59 | 56 | 56 | 47 |

| | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Glacier-wide Balance (mm w.e.) | -270 | -87 | -474 | -120 | -90 | -519 | -542 | 15 | -681 | 185 | -167 | -497 | 4 |
| Difference *ELA* with $ELA_0$ (*m*) | 22 | 14 | 160 | 46 | 35 | 106 | 110 | 29 | 92 | -14 | 76 | 137 | 34 |
| AAR (%) | 52 | 58 | 38 | 51 | 55 | 43 | 41 | 55 | 36 | 59 | 50 | 39 | 54 |

| | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Glacier-wide Balance (mm w.e.) | 132 | -331 | -71 | -369 | -485 | -866 | -333 | -38 | -571 | -775 | -1386 | -592 | -553 |
| Difference *ELA* with $ELA_0$ (*m*) | -14 | 82 | 43 | 58 | 91 | 192 | 86 | 33 | 82 | 99 | 235 | 126 | 120 |
| AAR (%) | 62 | 49 | 54 | 45 | 40 | 28 | 43 | 53 | 38 | 32 | 18 | 34 | 39 |

| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Glacier-wide Balance (mm w.e.) | -1452 | -478 | -328 | -568 | -944 | -1035 | -403 | -716 | -762 | -577 | -551 | -1388 |
| Difference *ELA* with $ELA_0$ (*m*) | 217 | 110 | 80 | 99 | 176 | 208 | 109 | 107 | 132 | 93 | 114 | 182 |
| AAR (%) | 18 | 37 | 41 | 37 | 23 | 17 | 40 | 36 | 31 | 41 | 36 | 8 |

**Annex 19 :** Annual averages of Glacier-wide Balance (*B*), *ELA* (expressed in difference of the *ELA* as compared to the $ELA_0$) and *AAR* of the glaciers from which the relative evolution curves were calculated. Data are from the *WGMS (2017)*.