The Gepatschferner from 1850 - 2006

Changes in Length, Area and Volume in Relation to Climate

DIPLOMA THESIS

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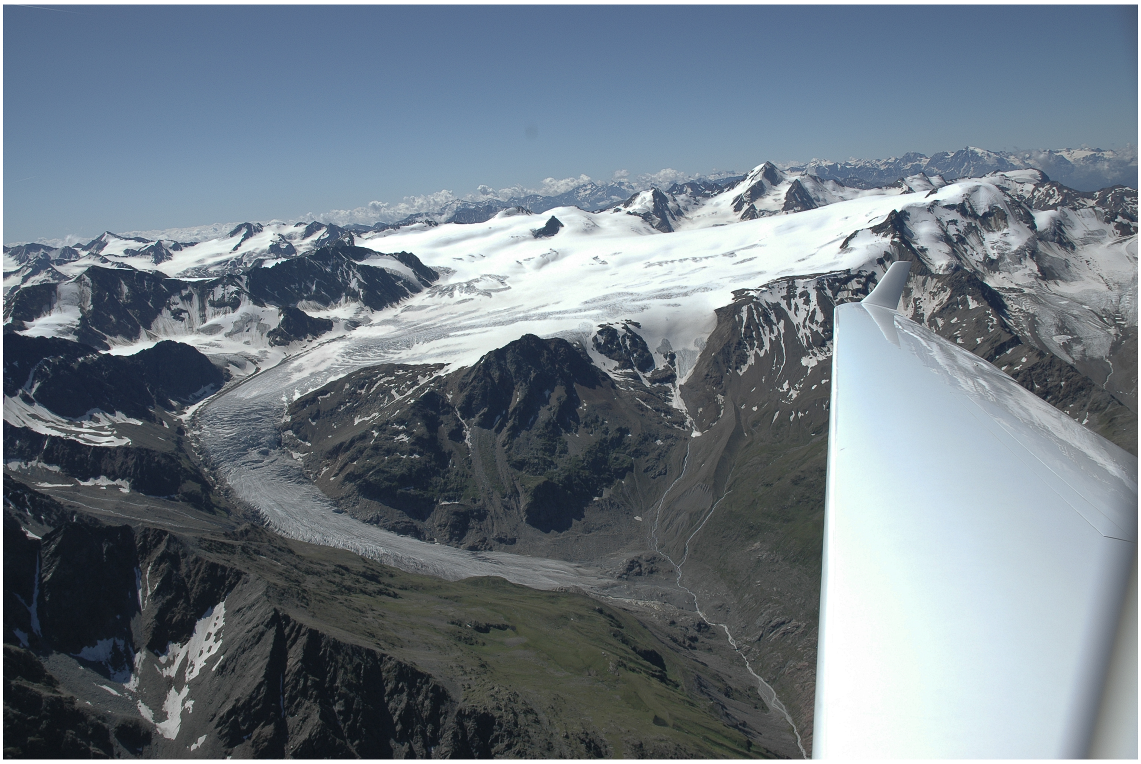
The physical landscape is baffling in its ability to transcend whatever we would make of it.

(Barry Lopez, Arctic Dreams)

I would like to thank my advisor Andrea Fischer for her good natured and patient help, Kay Helfricht for his valuable advice and proof reading, Lorenzo Rieg for his general helpfulness and Thibault Le Guen for the excellent tech support. Most importantly, I thank my parents for their financial and moral support.



Gepatschferner as seen during a survey flight on July 29th, 2009. (Foto: IMGI)

Abstract

This study investigates changes at Gepatschferner in length, area and volume since the last glacier maximum in 1850 and their relation to climate. Changes are discussed for the following time periods: 1850-1922, 1922-1971, 1971-1997, 1997-2006. Digital elevation models were created for 1850 from geomorphological data and for 1922 and 1971 from historical maps. Existing DEMs for 1997 and 2006 were further analysed.

Since 1850 Gepatschferner has retreated by 2 km in length and has lost 32% of its area and 36% of its volume. The rate of loss of volume is increasing faster than the rate of loss of area and losses in the upper regions of the glacier are becoming increasingly more important to overall losses. The largest losses per 50 m elevation increment occur at the tongue. These losses are greatest in the most recent time step studied, 1997-2006, and exceed previous values by 40% and more.

Comparing long term, gridded temperature data from the HISTALP project with the changes at Gepatschferner and particularly changes in length at the tongue shows good correlation between these parameters. The gridded temperature data also shows the same trends as station data from Innsbruck and Vent, although these trends are less pronounced in the grid.

Gridded precipitation data corresponds with station data from Innsbruck to some extent. However, an increase in winter precipitation as suggested by the Innsbruck data is not clearly reflected. Correlations between precipitation and length change at the tongue are not apparent.

Zusammenfassung

Diese Arbeit untersucht Längen-, Flächen- und Volumensänderungen am Gepatschferner seit dem letzten Gletscherhöchststand 1850. Die Änderungen des Gletschers werden in Beziehung zu klimatischen Parametern gesetzt. Die Zeitabschnitte 1850-1922, 1922-1971, 1971-1997 und 1997-2006 werden genauer besprochen. Digitale Höhenmodelle (DHMs) für 1850 (aus geomorphologischen Daten), 1922 und 1971 (anhand historischer Karten) wurden erstellt. Bereits zur Verfügung stehende DHMs von 1997 und 2006 aus dem Gletscherinventar wurden genauer analysiert.

Seit 1850 hat sich der Gepatschferner um 2 km zurück gezogen, 32% an Fläche- und 36% an Volumen verloren. Das Volumen nimmt zunehmend schneller ab als die Fläche und Verluste im oberen Bereich des Gletschers spielen eine immer größere Rolle für den Gesamtverlust. Die größten Verluste pro 50 m Höhenstufe sind an der Zunge zu verzeichnen. Diese sind von 1997 bis 2006 mit mehr als 40% über dem Maximalwert der früheren Abschnitte am höchsten.

Ein Vergleich der Änderungen am Gepatschferner mit Temperaturdaten aus dem HISTALP Projekt zeigt Zusammenhänge vor allem mit der hochaufgelösten Zeitreihe der Längenänderungen an der Zunge. Die HISTALP Zeitreihen zeigen die gleichen Trends in Stations- wie Grid Daten, wobei diese Trends an den untersuchten Stationen (Innsbruck und Vent) stärker ausfallen als im modellierten Grid.

Niederschlagsdaten aus Innsbruck und entsprechende Grid Daten stimmen bedingt überein. Eine Zunahme des Winterniederschlags in den Stationsdaten ist in den Grid Daten nicht gut zu sehen. Ein Zusammenhang zwischen Niederschlag und Längenänderungen der Zunge ist nicht fest zu stellen.

Contents

Chapter 1

Introduction

Glacier ice covers around 10% of the land surface on earth (Lemke et al. 2007). About one percent of this ice is the site of "normal human activity" (Paterson 2000). The remaining, vastly larger expanse of land based glacial ice is mostly left to insects and passing birds with only very occasional visits from human explorers.

The one percent of ice that regularly sees humans is naturally of interest, as "normal human activity" usually pertains some socio-economic relevance. This is certainly true in the case of glaciers in the Alps, a mountain region which is developed in terms of settlement and infrastructure and accessible for tourism like perhaps no other.

The climatic drivers most relevant to alpine glaciers are winter precipitation, snowfall events during summers, which can interrupt ablation for several days and summer temperature. During the climatically exceptional summer of 2003, which broke temperature records in many regions across Europe, the mean specific mass balance at Hintereisferner was almost 4 times as negative as the 1953-2006 average (-1.8 m w.e. in 2003, -0.5 m w.e. long term average).

The end of the little ice age in 1850 marks the last glacier maximum. Since then the extent of glaciers in Austria has diminished by over 50% (Lambrecht and Kuhn 2007; Gross 1987). Apart from a vague sense of public regret sometimes encountered in media opinion in the face of diminishing but still imposing and majestic natural phenomena, the recession of Austrian glaciers is increasingly becoming an issue of economic context. Beniston (2004) suggests that weather conditions as experienced during the summer of 2003, which was characterised not only by high temperatures but also by a lack of convective rainfall, may occur more frequently in the future.

Under climate scenarios where current warming trends continue, the Alps could lose major parts of their glacial cover within decades (Haeberli and Beniston 1998; Zemp et al. 2006). As the glaciers melt, associated ecosystems are affected on many levels. Changes in runoff and the water cycle lead to changes in sediment flux and new growth conditions for vegetation. This in turn affects animal life. Hazards to summer tourism increase due to the thawing of permafrost and resulting issues of slope stability. As lower lying ski areas struggle, glacier ski resorts are becoming more important and face the technical challenges of maintaining infrastructure on the receding ice. In order to adapt to such changes, good process understanding and a detailed knowledge of what is happening to the alpine glaciers is key.

1.1 Goals and structure

This study investigates changes at Gepatschferner, Austria's second largest glacier, since 1850, with a focus on the following research questions:

- How has Gepatschferner changed since 1850 in terms of area, volume and length?
- Can these changes be explained with long term climate data and could glaciers therefore be reconstructed with such data?

An introductory chapter describes location and characteristics of the Gepatschferner. Chapter 2 explains the methodical approaches employed during this study, such as the generation of digital elevation models from historical maps and the calculation of mass changes in elevation increments throughout the glacier. The data used is listed and described in detail in Chapter 3. In Chapter 4 the results are presented, considering changes during each time period studied (1850-1922, 1922-1971, 1971-1997, 1997-2006) and over the entire time span from 1850 to 2006, as well as possible errors. This is followed by a discussion of the results in light of temperature and precipitation data from the HISTALP project and vice versa. An attempt is made to establish whether or not the HISTALP time series can be used to explain the changes at the glacier. The final chapter provides a short summary and general conclusion, as well as a brief outlook into possible future research at Gepatschferner.

1.2 The Gepatschferner

Gepatschferner (Ferner is a regional word for glacier) is situated at the southern end of Kaunertal (Kauner-valley) in Tyrol, Austria (Figure 1.1). In its highest regions, the glacier is intersected by the Austro-Italian border. Unfortunately, glacier inventory data was only available for the Austrian part of Gepatschferner and the about 23% of total glaciated area which are part of Italy are not further discussed in this study (roughly 17 km^2 lie in Austria and 4 km^2 in Italy). The Italian border can be seen in the map of Gepatschferner and the surrounding terrain in Figure 1.2.

Today, the vertical extent of Gepatschferner ranges from about 2100 m to a little over 3500 m of altitude at Weisseespitze, which marks the high point in the north-western part of the main ice body. In a south-easterly direction from here, the glacier boundary follows the Langtauferer Eiswände to Vernagel peak. In the north east of Vernagl, the glacier is contained by the three Hintereisspitzen (Hintere" , Vordere- and Mittlere Hintereisspitze). The glacier tongue has cut its way north in between Rauher Kopf to its orographic left and Schwarzwand Spitze to its right. The tongue curves around Rauher Kopf to the north-west and currently faces almost due west in its lowest regions. There is a smaller, secondary tongue in the west, between Nöderberg and Rauher Kopf, which used to connect to the main tongue so that the rock island of Großer and Kleiner Rauher Kopf was completely encircled. (See Figure 1.2)

To the north-east of Gepatschferner lies Wannetferner, a small tributary glacier which was connected to the main ice body until about a century ago. There is a fairly steep tributary glacier south of Schwarzwand Spitze, which meets the tongue at 2850 m. Currently, Gepatschferner connects with other ice bodies at three points: A small serac fall crossing the Langtauferer Eiswände flows into Langtauferer Ferner in the south-west. Between Weißseespitze and the rock formation known as Zahn ("Tooth") in its north-east, a steep ice face breaks off from the main glacier plateau connecting it with the Weißseeferner in the north-west. In the eastern part of the main glacier basin the ice covered, saddle-type terrain of Kesselwandjoch constitutes a large ice divide between Gepatsch- and Kesselwandferner. Together, the two glaciers are Austria's largest connecting glaciated area with about 18 km^2.

Gepatschferner can be accessed from Kaunertal where the road to the ski area on Weißseeferner conveniently passes at only about 2 kilometers distance and roughly 200 vertical meters from the tongue. In winter the main ice body can be reached easily via a short ascent from the ski resort. The glacier's good accessibility make it and the surrounding peaks popular destinations for skiers and mountaineers. Brandenburgerhaus, a large Alpine Club hut, is situated at 3272 m on the northern side of Kesselwandjoch and is often used as a base for multi day trips both in summer and in winter.

Gepatschferner lies in the neighbourhood of several exceptionally well studied glaciers: The University of Innsbruck has carried out massbalance measurements at Hintereisferner since 1952 and at Kesselwandferner since 1965. The Munich based Comission for Glaciology of the Bavarian Academy of Sciences has been in charge of a long term monitoring project at Vernagtferner since the early 1960s, with a particular focus on glacier discharge.

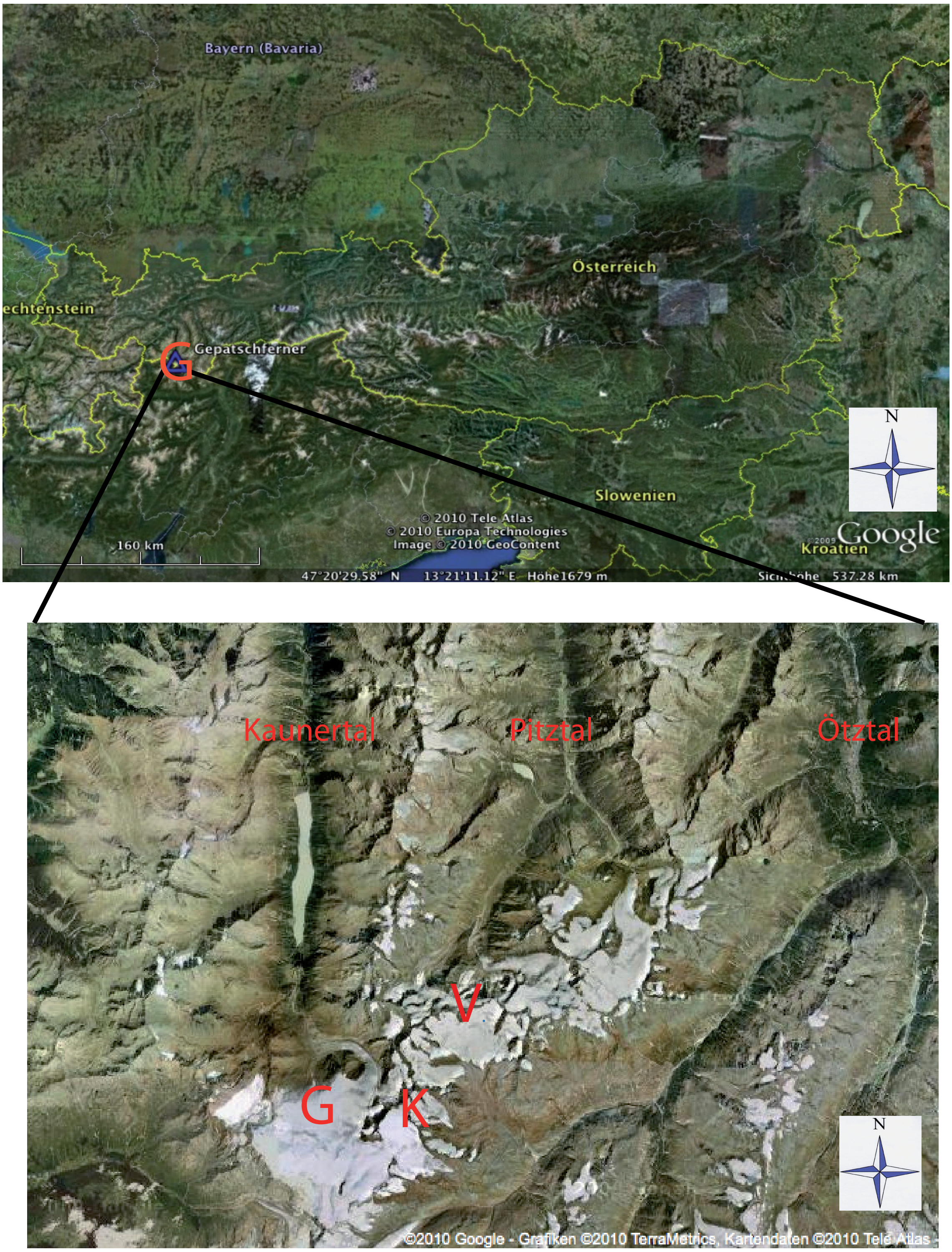


Figure 1.1: Position of Gepatschferner in Austria. Gepatschferner marked with G, Kesselwandferner with K and Vernagtferner with V in close up. (Google Earth Images)

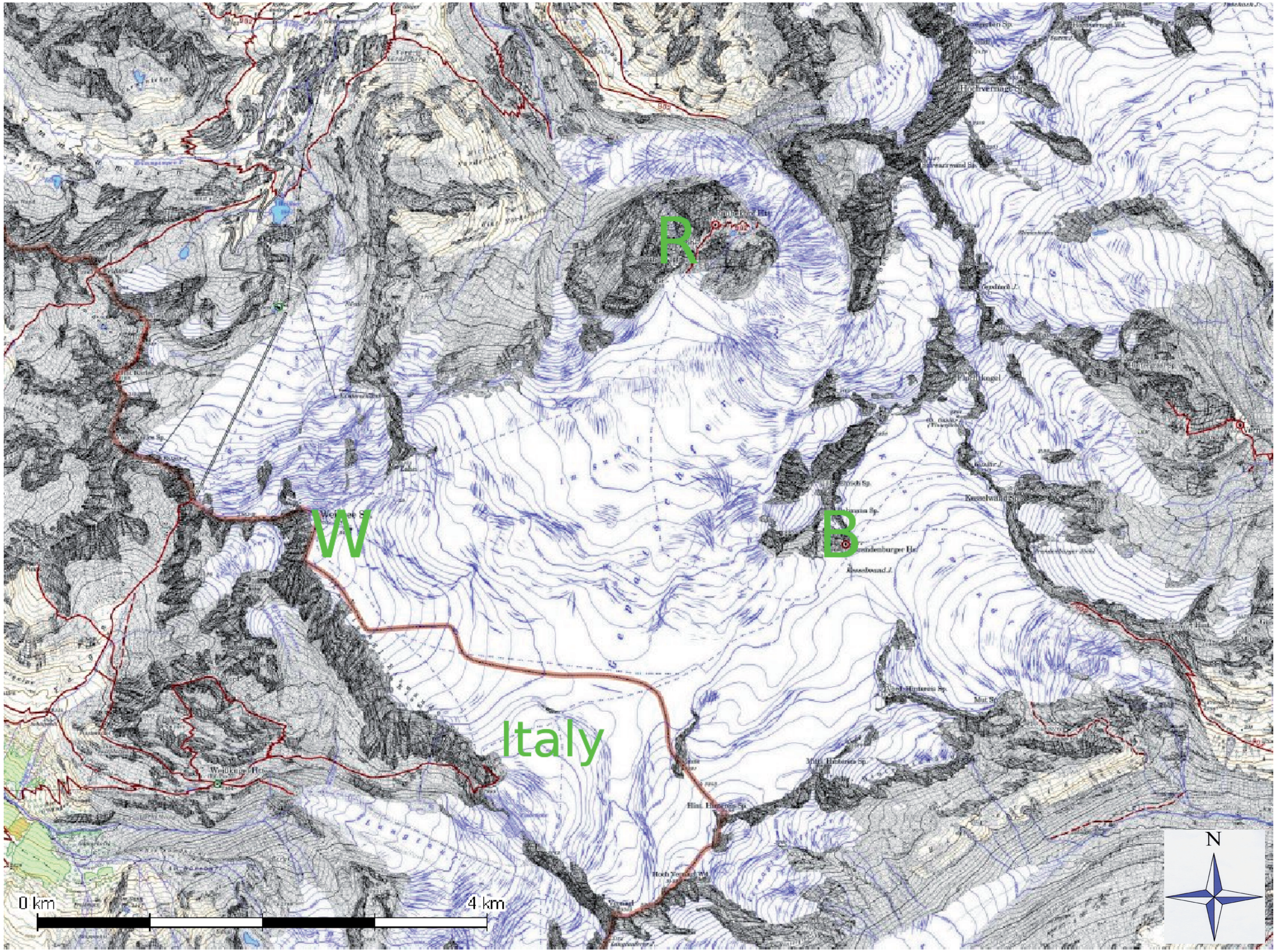


Figure 1.2: The Gepatschferner as shown in AV map Nr. 30/2 Ötztaler Alpen, Weißkugel from 2003, glacier extent is that of 1997 (Alpenvereinskartographie 2006). Weißseespitze marked with W, Brandenburgerhaus with B, Rauher Kopf with R.

Chapter 2

Methods

2.1 Software

- ***Matlab 7.1***: Matlab, short for "Matrix Laboratory", is a fourth generation programming language developed by *The Mathworks*. It has many possibly applications, particularly in numerical computing, and among many other things allows for matrix manipulation and creating user interfaces. In this study Matlab was used to process and visualise data.

- ***GLEDIFF***: GLEDIFF is a script by R. Würländer, which was used in this study to calculate absolute changes of volume in elevation increments of 50 vertical meters throughout the glacier. GLEDIFF is based on a paper by Finsterwalder (1953) where he develops the following equations for elevation and volume change in a specified elevation zone between two time steps (see also Figure 2.1):

  $$dh = \frac{\Delta F_1 + \Delta F_2}{F_1 + F_2} \cdot \Delta h$$

  Where dh = elevation change of the elevation zone, Δh = difference in elevation between upper and lower border of the elevation zone, F_1 = Area of the elevation zone at the bedrock, F_2 = Area of the elevation zone on the glacier surface

  and

  $$dV = \frac{\Delta F_1 + \Delta F_2}{2} \cdot \Delta h$$

  Where dV = volume change of the elevation zone, Δh = difference in elevation between upper and lower border of the elevation zone, V = volume, F_1 = Area of the elevation zone at the bedrock, F_2 = Area of the elevation zone on the glacier surface.

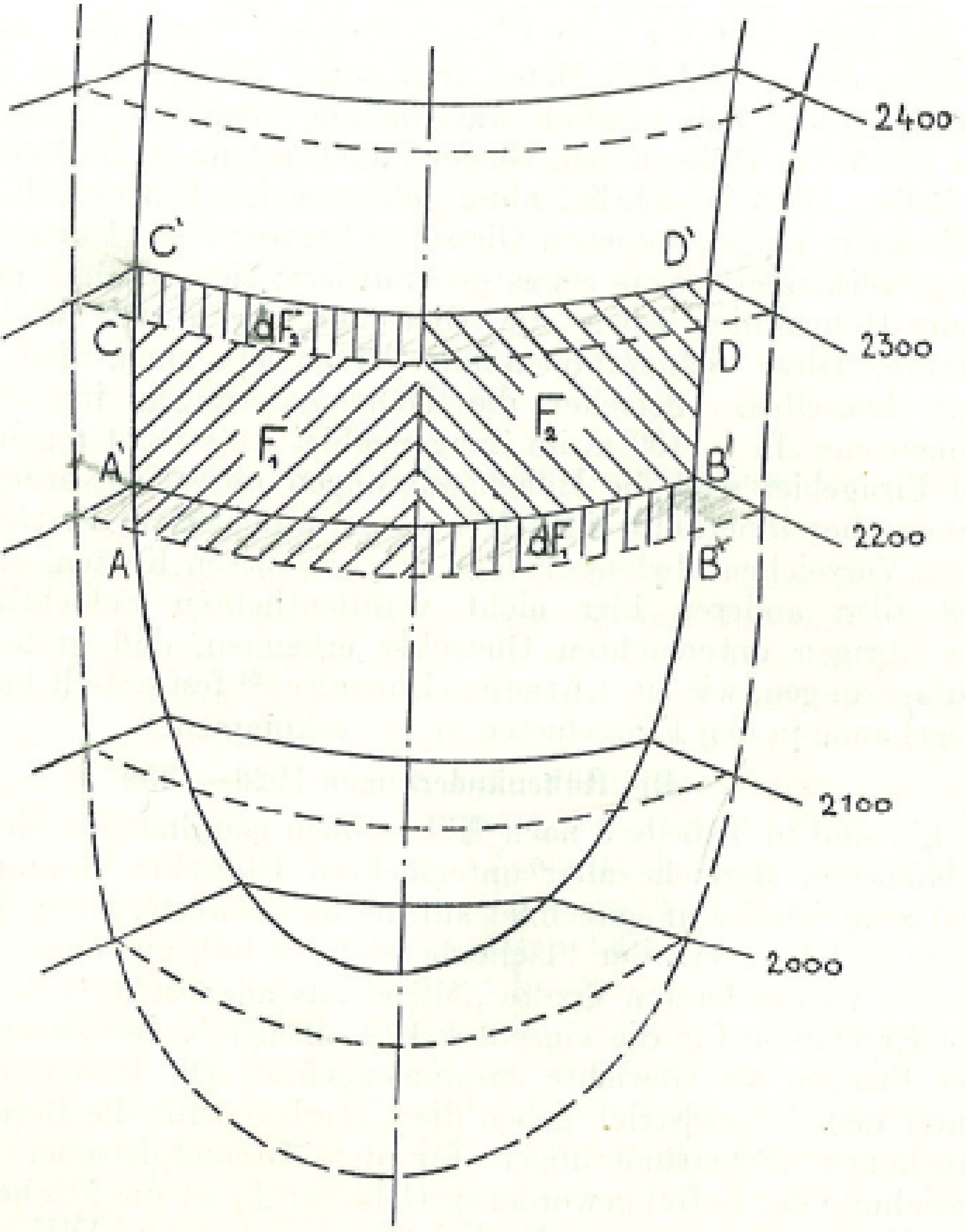


Figure 2.1: Diagram reproduced from Finsterwalder (1953) showing the shift in elevation zones on a glacier bewteen two time steps. The earlier stage is shown in broken lines, the later in full lines.

Dr. Mayer at the Comission for Glaciology of the Bavarian Academy of Sciences and Humanities was very helpful in this context and applied Würländer's script to data from this study, which had been accordingly prepared.

- ***ArcGIS 9.3***: ArcGIS is produced by *ESRI* and consists of a package of geographic information system (GIS) software products. It is is a powerful tool to generate, structure and analyse spatial data. ArcMap allows the creation of features in user defined or pre programmed coordinate planes. Data can be rectified and shown graphically. It is possible to spatially analyse various kinds of features and data, for example a shapefile of the glacier boundaries in one year can be directly and quantitavely compared to one of another year. Similarly, it is possible to perform calculations on raster data, such as substracting a digital elevation model (DEM) of the bedrock from one of the glacier surface. With the Topo to Raster function ArcGIS provides an interpolation tool designed to work with contour data.

  For this study, maps of the glacier from 1922 and 1971 were scanned and geo-rectified according to available and previously rectified orthofotos from the 1997 glacier inventory project (Lambrecht and Kuhn 2007), as well as prominent, recognisable terrain features. Contour lines in the maps were digitally traced and assigned values to create two DEMs, in which the glacier boundaries were then marked, also according to the maps.

  To create a DEM of the Gepatschferner in 1850, the glacier boundaries were located as well as possible using geomorphological terrain features (i.e. moraines). Then, contour lines were interpolated from ice free surfaces over the area of the glacier. This was done by hand in accordance with what can generally be observed in glacier topography, as well as the behaviour of the Gepatschferner as it was found to be in this study. The DEM was created using the Topo to Raster tool.

  To break down the glaciated area in each of the available DEMs into increments of 50 vertical meters, the ArcMap shapefile of the entire glacier area was intersected with the contour lines of the respective year to create a shapefile for each increment and calculate a value for each area, as well as the changes during each time step at different altitudes.

  Breaking down the glacier volume into 50 m increments proved more complicated due to the three dimensional nature of the ice body in question. In the calculations for the volume-altitude distribution for each of the discussed years, a simplification was used and conceptually rectangular, rather than trapezoid, ice bodies were assumed. I.e., the volume value for the 2500 m-2550 m increment would be the volume of the ice straight down from the 2500 m and 2550 m contour lines at the ice surface, rather than from the contours at the surface to the corresponding, uphill shifted contours on the bedrock. Volume changes for each time step were calculated using the Würländer script, which does not employ such a simplification.

2.2 Ice depth measurements

The ice depth measurements on which the volume calculations are based were carried out via radio echo sounding in 1996 by Massimo for his diploma thesis (Massimo 1997). Radio echo sounding is similar in principle to reflection seismology and sonar. A transmitter sends a high frequency pulsed signal into the ground, where it spreads, depending on dielectric characteristics of the ground, which in turn depend mainly on water content. The reflected signal reaches a receiver where it is digitised and saved.

Massimo used a transmitter developed by Narod and Clarke Narrod and Clarke (1994) in a slightly modified version, which transmits a 550 V signal at a central frequency of 512 Hz. The receiver was a digital oscilloscope (Type 28200 by Clock Computer Coporation) with a scale reading precision of ± 0.03 μs or ± 5 meters of ice, connected to a laptop.

Soundings were carried out at 355 points on 18 different profile lines in 3 surveys between April and September 1996 (see Figure 2.2). Massimo found radio echo sounding to be a generally well suited method for ice depth measurement, but not entirely without limitations: Zones of crevasses and seracs cause refraction and multiple reflections of the signal to the point where only a very weak or even no echo at all was picked up by the receiver. Measurement was only possibly up to a minimum ice depth of 30 metres. Anything less and the reflected signal became lost in the oscillations of the system.

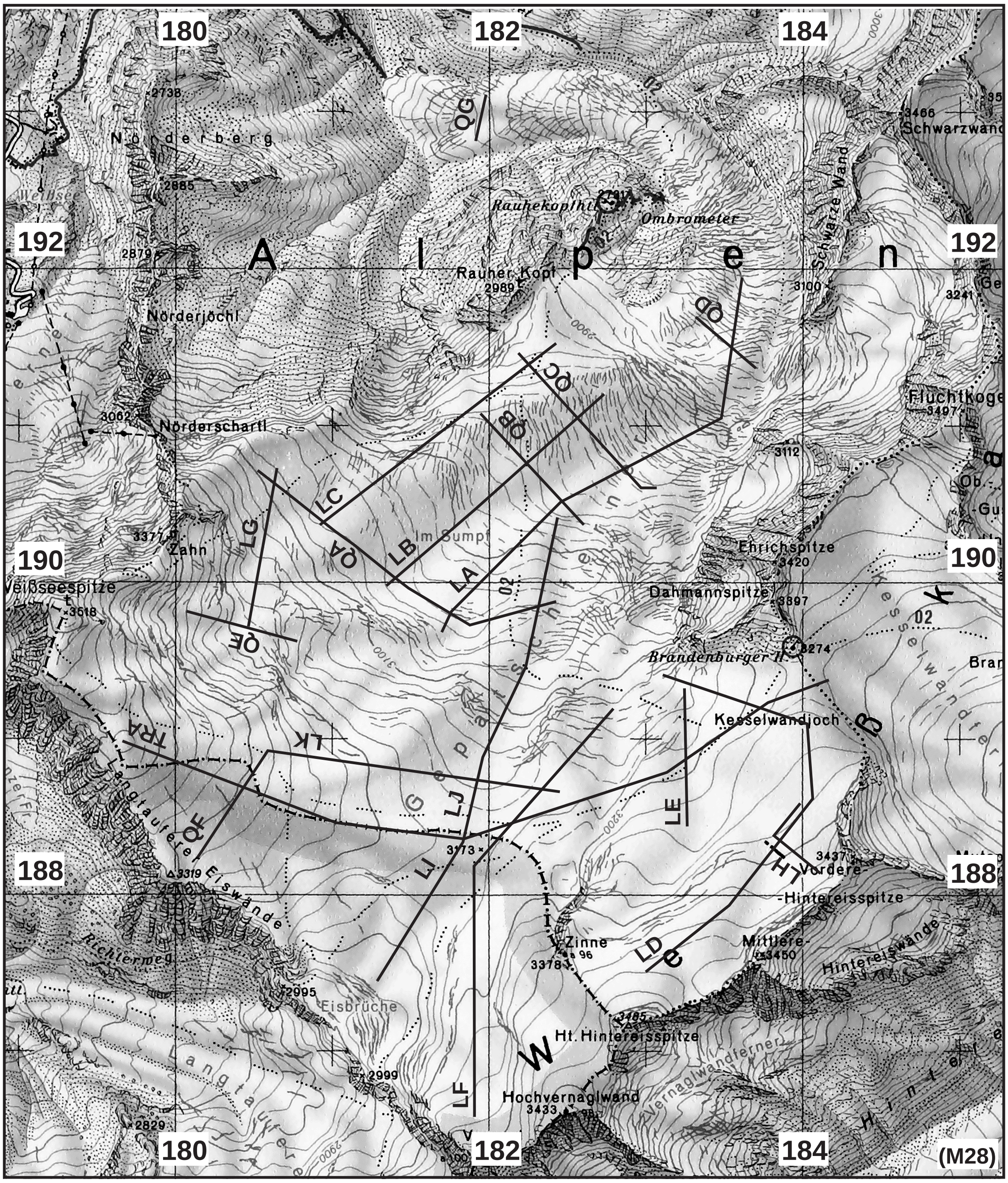


Figure 2.2: Measurement profiles by Marius Massimo, reproduced from Span et al. (2005).

Chapter 3

Data

3.1 Historic cartography

A milestone of early cartography in Tyrol and Austria was Peter Anich's and Blausius Huber's *Atlas Tyrolensis*, published in 1774. At a scale of 1:103 800 it shows Tyrol as a copperplate etching. A paper version, the so called "Reduzierte Karte von Tirol" ("Reduced map of Tyrol"), includes sketched lines marking the maximum extent of certain glaciers as well as regions where periglacial lakes developed and in some cases later caused glacier floods (Brunner 2005). The *Atlas Tyrolensis* also contains the first rendering of the outlines of Gepatschferner (Figure 3.1).

In 1860 the Austrian military geographer Karl Sonklar published 8 coloured maps of glaciers in the Ötztal Alps based on results of Austria's second national mapping campaign from 1817 (Sonklar 1860). Among these maps is one of Gepatschferner ("Die Karte des Gepaatschgletschers im Kaunertal") at a scale of 1:28 800. The map shows the glacier's extent in the 1850s quite well. The small tongue between Rauher Kopf and Nöderberg is still connected to the main tongue and Wannetferner is separated from the main ice body only by a small moraine.

A map of the entire Austro-Hungarian Empire (*Die neue Spezialkarte der Österreich-Ungarischen Monarchie und des Okkupationsgebiets*) published in 1890 at a scale of 1:75 000 contains contour lines (unlike Sonklar's work) but is inexact in many of the relevant mountainous areas.

Specific maps for glaciological purposes were not produced until the late 19th century, when the need for such maps was expressed in 1879 at the *Alpine Tagung* in Geneva (Brunner 1987). In 1888 S. Finsterwalder and Schunk published a map of the tongue up to an altitude of 2450 m, which marks the result of the first exact tacheometric survey of Gepatschferner by Finsterwalder, Schunk and Blümke two years previously (Finsterwalder and Schunk 1888). They were the first to use tacheometry for glacier mapping; the technique had previously been used only for

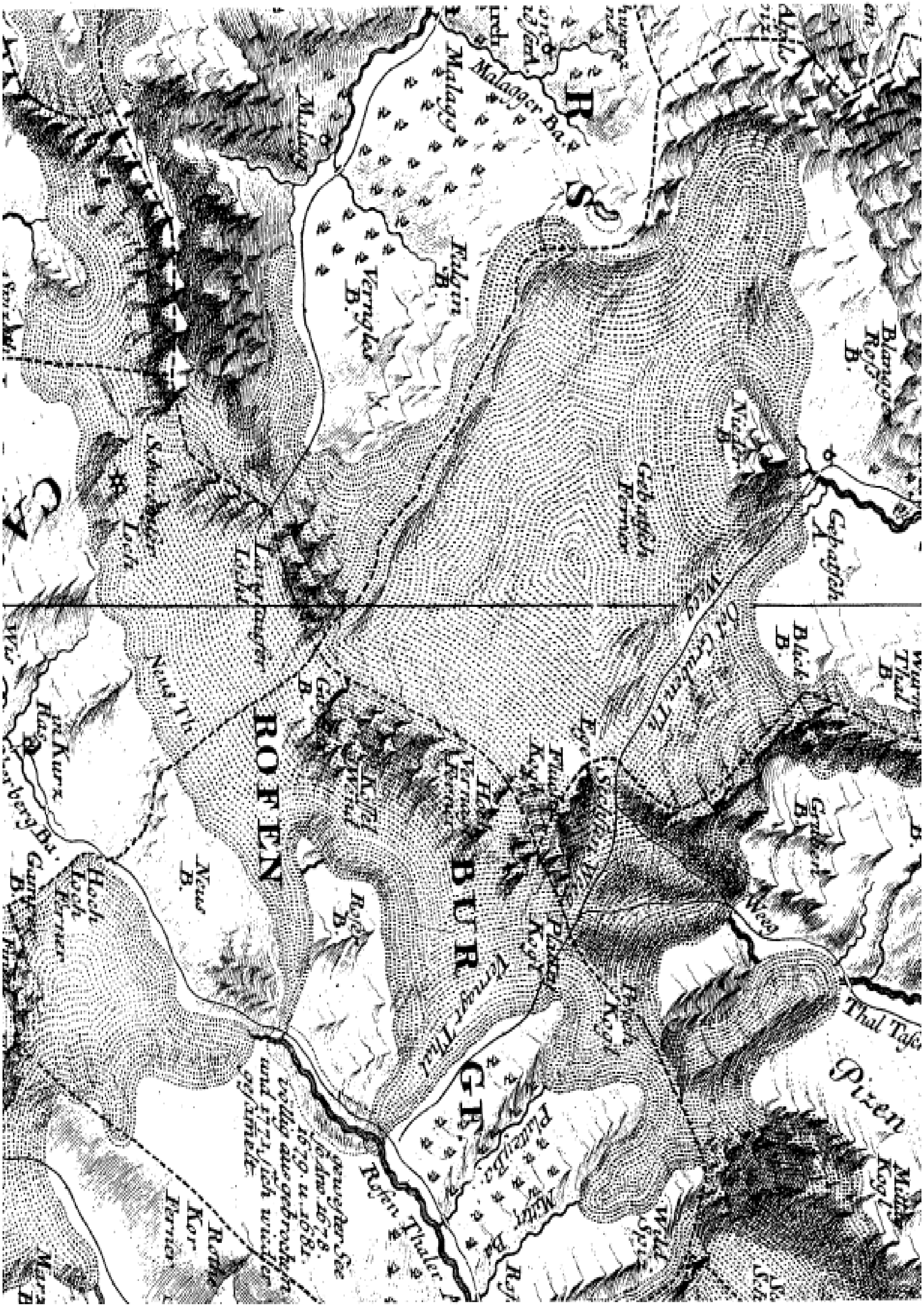


Figure 3.1: Gepatschferner in *Atlas Tyrolensis*, reproduced from Brunner (1987).

engineering purposes (Brunner 2000). Two remeasurements were carried out by Finsterwalder and others in the following years. S. Simony's map for the Austrian Alpine Club (AV) from 1893 (DÖAV 1893) uses this data and also reproduces some of its errors.

After a forced break during the First World War, study of Gepatschferner resumed in 1922 when Sebastian Finsterwalder, his sons Richard and Ulrich as well as J. Sartorius, a survey specialist and alpinist from Munich, embarked on a field trip with the goal of mapping the entire glacier by means of terrestrial photogrammetry. After transporting supplies and survey instruments by bicycle from the town of Landeck in the Inn-valley to the Gepatschhaus, an AV hut in the Kaunertal, they stayed for 17 days completing the survey. Finsterwalder mentions paying for their return fare and stay in part with their spare food after an economic crisis during their trip rendered any remaining cash worthless. He also expresses regret at not being able to access the now Italian part of the glacier (Finsterwalder 1928). The 1:20 000 map resulting from these efforts was published in 1928 and was used to create a DEM of the Gepatschferner in 1922 for this study.

In 1939 E. Schneider completed a new survey, which was later used by the Alpine Club for a a new map (DÖAV 1951). This was the last survey before the Second World War again prevented further study.

Since 1953 observations and surveys of Gepatschferner have been more continuous, in part also due to the more convenient and now routinely used technique of terrestrial photogrammetry. There are inventories of 1953, 1956 and 1958 as well as detailed plans of the tongue from 1957, 1959, 1961 and 1962 (Massimo 1997).

In 1971 the Regional Government of Tyrol commissioned an aerial survey, the results of which were a 1:7500 orthophoto map (Brunner and Rentsch 1977) and a 1:10 000 topographic map of Gepatschferner (Brunner 1978, 1985), which was also used as basis for a digital elevation model in this study.

With the publication of the first Austrian glacier inventory in 1980 (based mainly on aerial photos from 1969), Gepatschferner became part of a database of a total of 925 Austrian glaciers (Patzelt 1980). The second Austrian glacier inventory from 1997 provides us with a detailed digital elavation model of Gepatschferner based on othophotos aquired on 11 September 1997 (Lambrecht and Kuhn 2007).

In 2006 the Tyrolean governement again carried out flights to document the state of Tyrol's glaciers and this brought forth an even more detailed DEM based on high resolution LIDAR data.

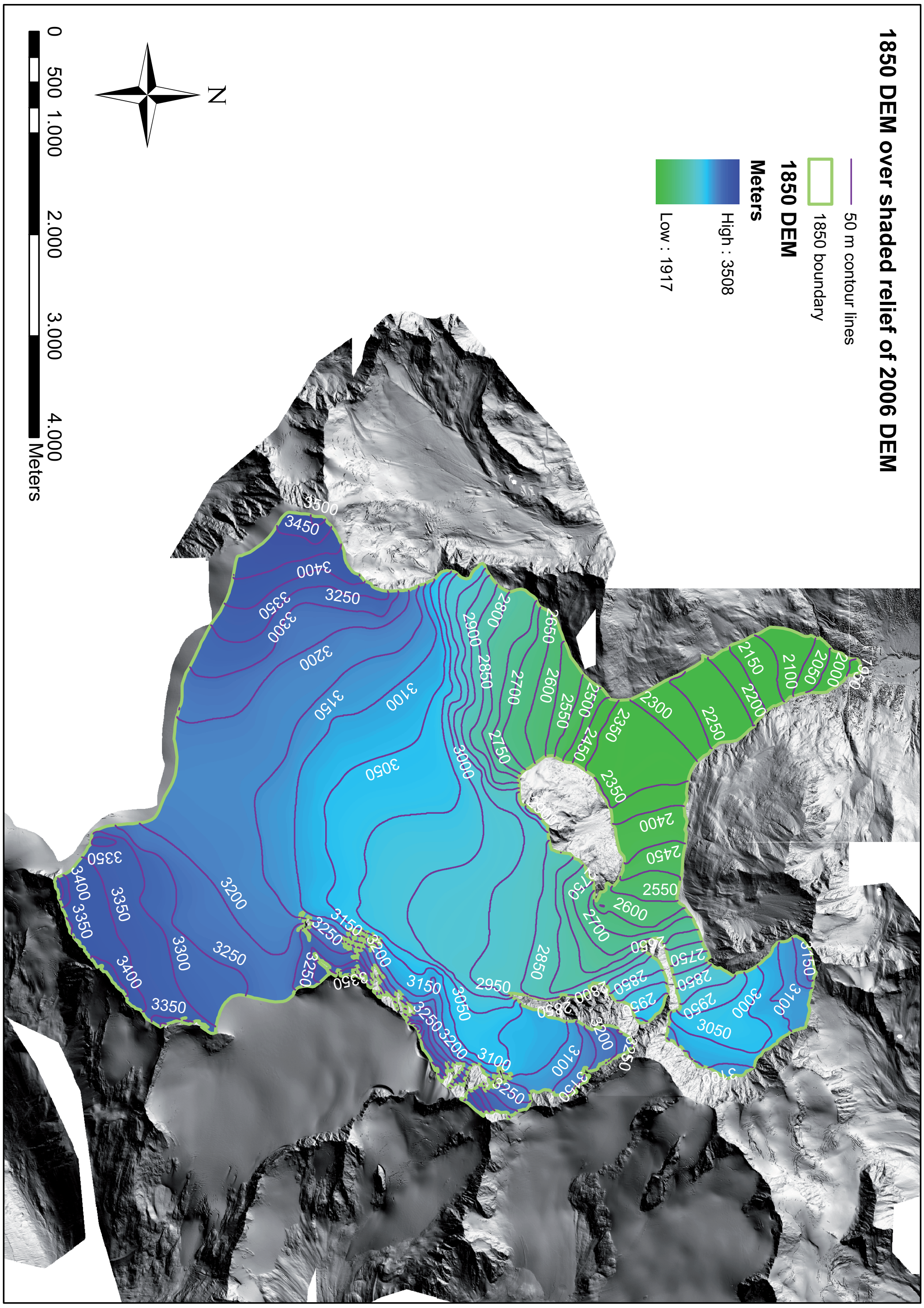


Figure 3.2: 1850 DEM shown over a shaded relief image of the 2006 DEM

3.2 The 1850 DEM

Previous estimates of the 1850 glacier boundaries (Gross 1987; Nicolussi and Patzelt 2001) were corrected and adjusted using detailed LIDAR images (see section 3.6), which were not available to Gross and Nicolussi. Even so, determining the exact location of the appropriate moraines and areas of detersion proved difficult due to erosion of the relevant topographic features. Nonetheless, the 1850 boundaries were located with reasonable accuracy given the available means and a DEM was created using ArcGis (shown in figure 3.2).

3.3 The 1922 DEM

Finsterwalder's 1922, 1:20000, map of the Gepatschferner was digitised using ArcMap (See Sections 2.1 and 3.1). Figure 3.3 shows a scan of the original map with the glacier boundaries as used in this study.

Going with half the line width as a measure for the accuracy of the map yields an inherent uncertainty of ±4 m. Add to that an estimated meter of uncertainty gained during the digitisation process and we have to assume a vertical and horizontal uncertainty of ±5 m in the 1922 DEM. The DEM is shown in Figure 3.4 and has a resolution of 5 m x 5 m.

3.4 The 1971 DEM

The 1971 DEM is based on the 1971 map of Gepatschferner (Brunner 1978) mentioned in section 3.1 and was otherwise created in the same way as the 1922 DEM. With the smaller scale of 1:10 000 the uncertainty inherent in the map decreases and a total uncertainty of ±3 m (2 m inherent, 1 m from the digitization process) is assumed for the 1971 DEM. Figures 3.5 and 3.6 show the 1971 map and the resulting DEM (resolution 5 m x 5 m).

3.5 The 1997 DEM

The creation of the DEM of the glacier in 1997 was part of the project to build a modern Austrian glacier inventory and is based mostly on data gathered during survey flights carried out by the Austrian Army, which was processed with digital photgrammetric methods (Lambrecht and Kuhn 2007). The resulting DEM has a cell size of 5 m x 5 m. Figures for the vertical accuracy of this data in general differ between better than ±1.9 m (Lambrecht and Kuhn 2007) and better than ±0.7 m (Würländer and Eder 1998). The 1997 DEM is shown in Figure 3.7.

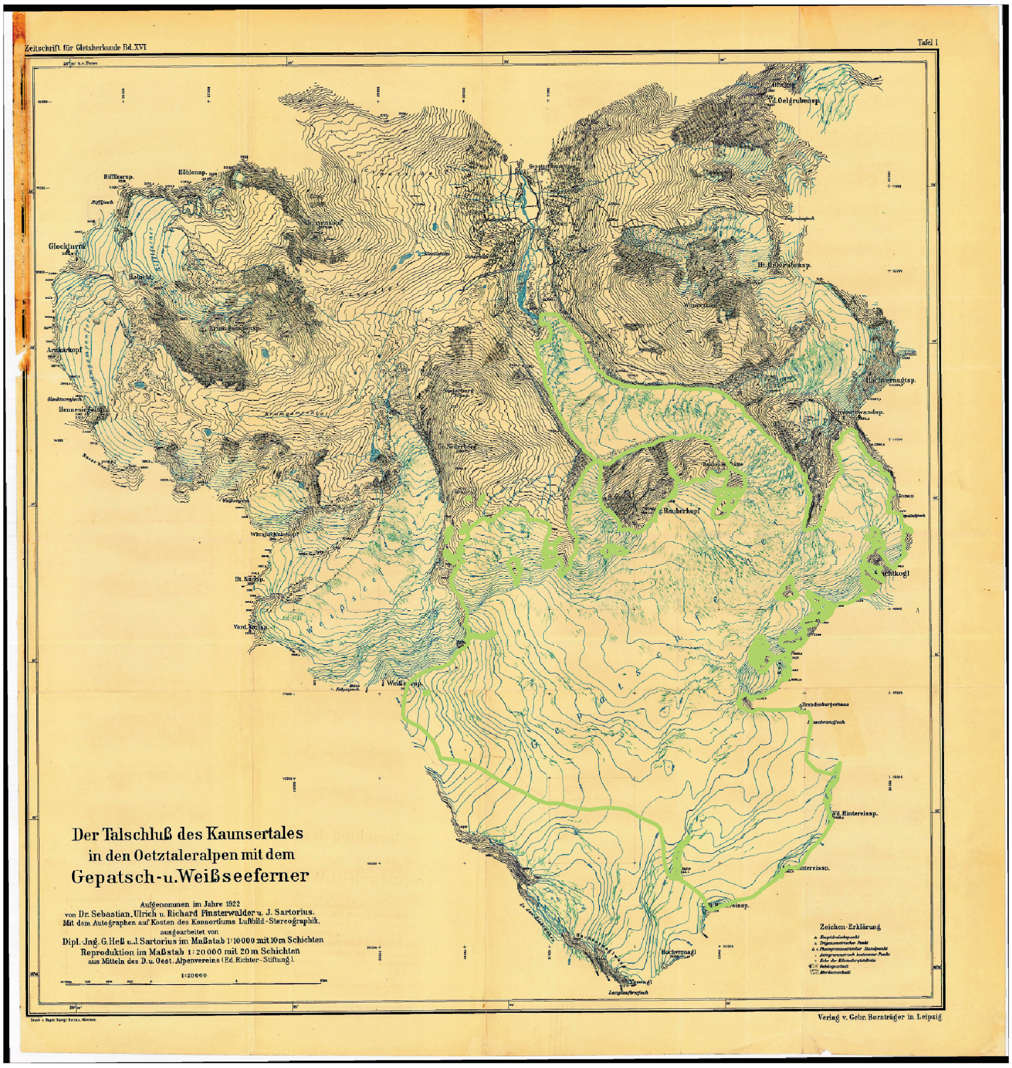


Figure 3.3: The 1922 map (Finsterwalder 1928) with glacier boundaries in green.

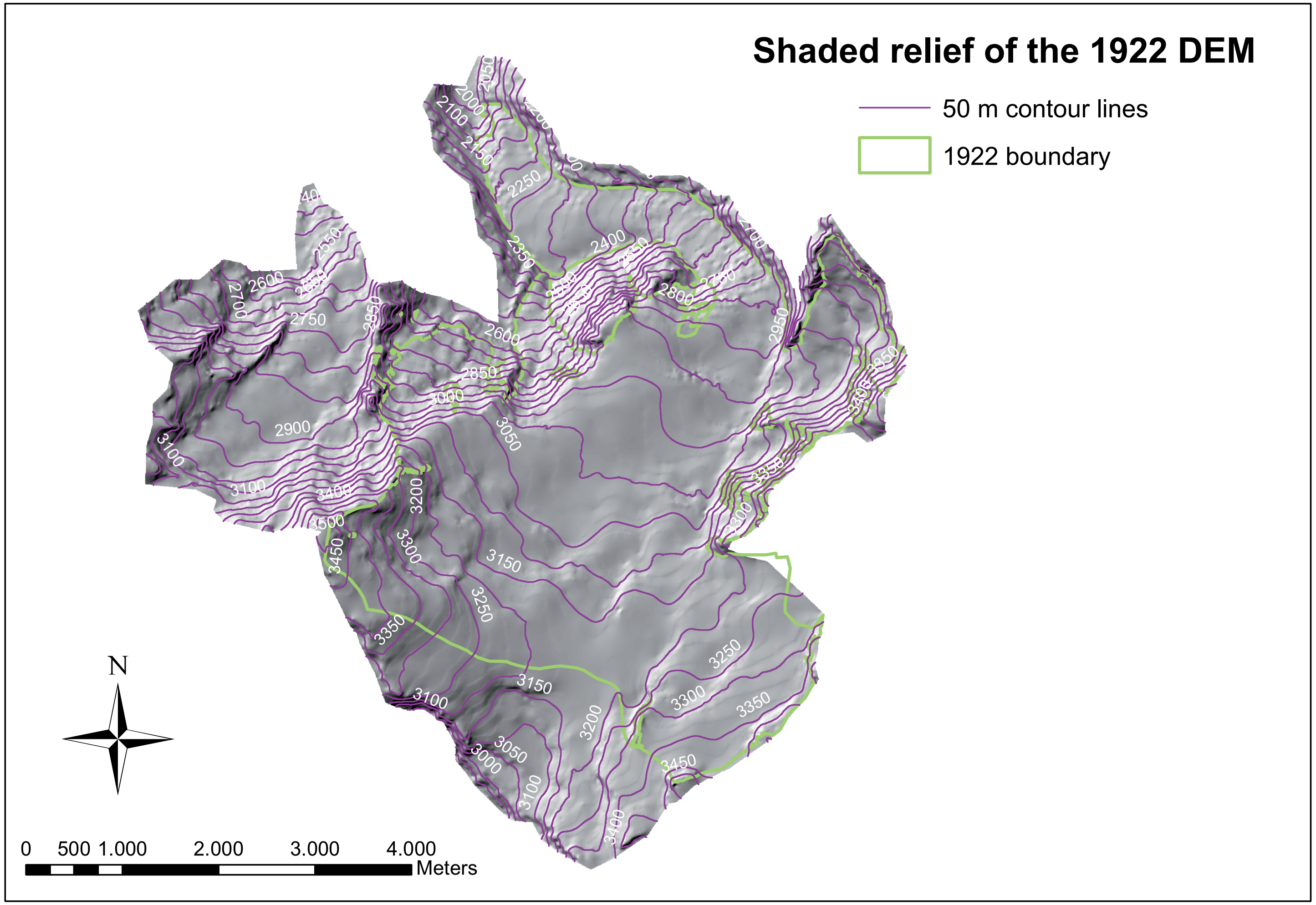


Figure 3.4: Shaded relief image of the 1922 DEM with contour lines and glacier boundaries.

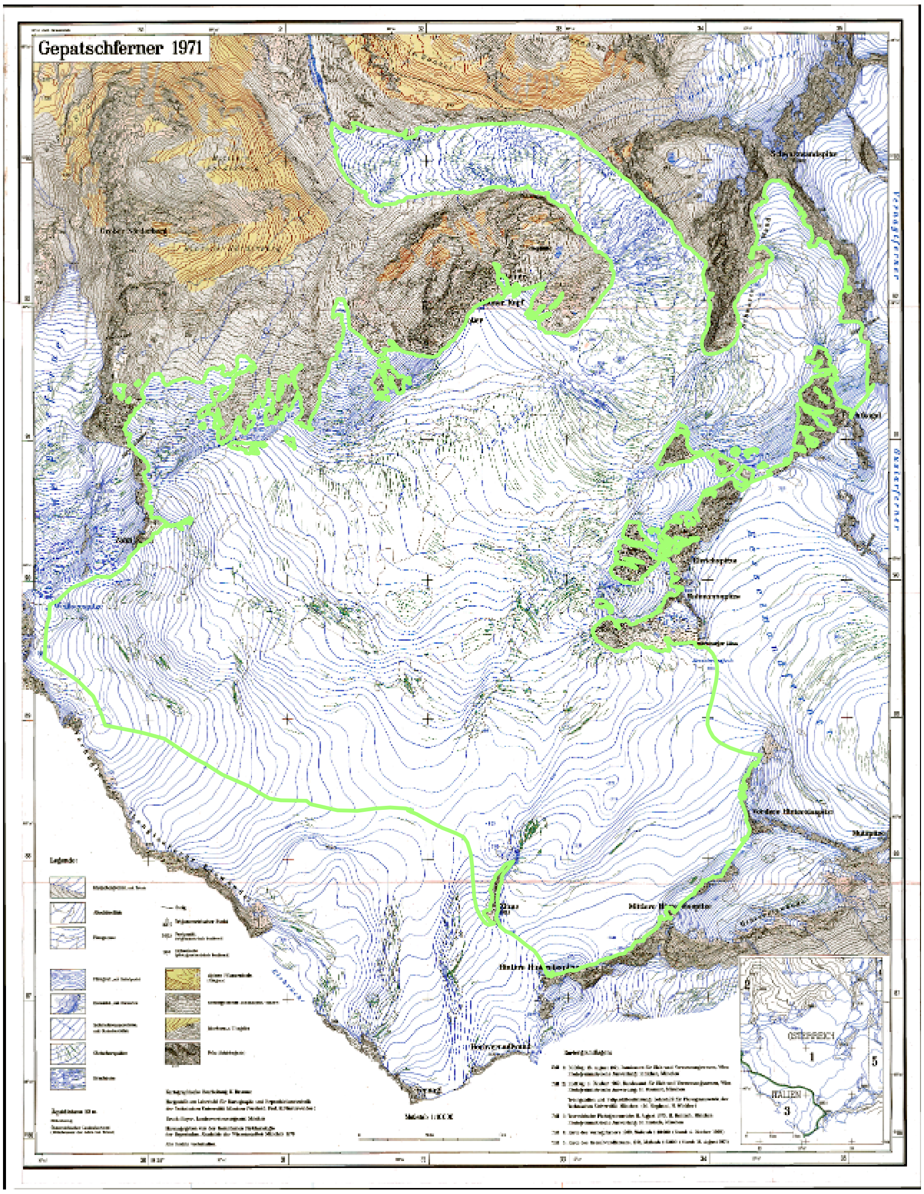


Figure 3.5: 1971 map (Brunner 1985) of the Gepatschferner with glacier boundaries as used in this study.

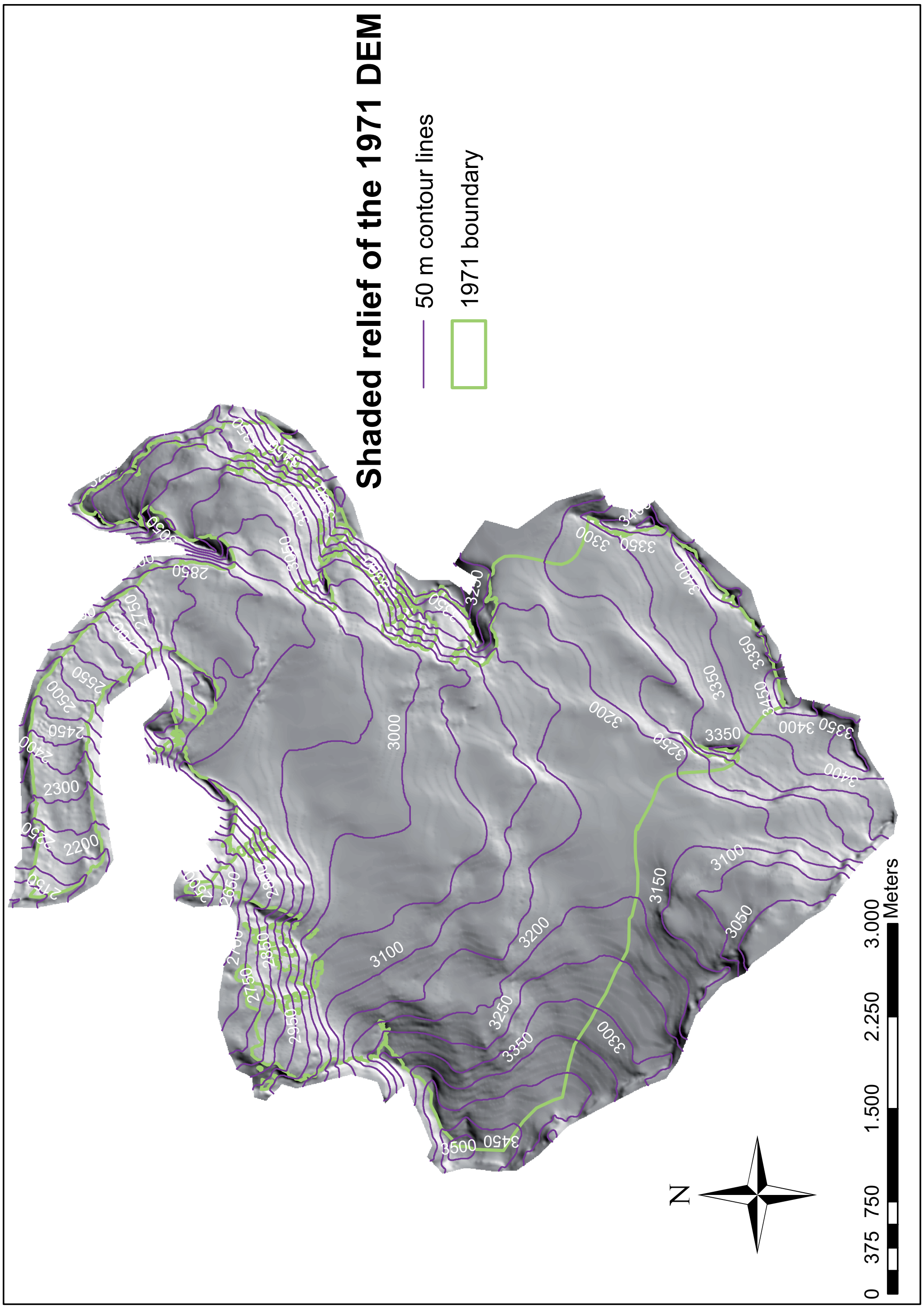


Figure 3.6: Shaded relief image of the 1971 DEM with contour lines and glacier boundaries.

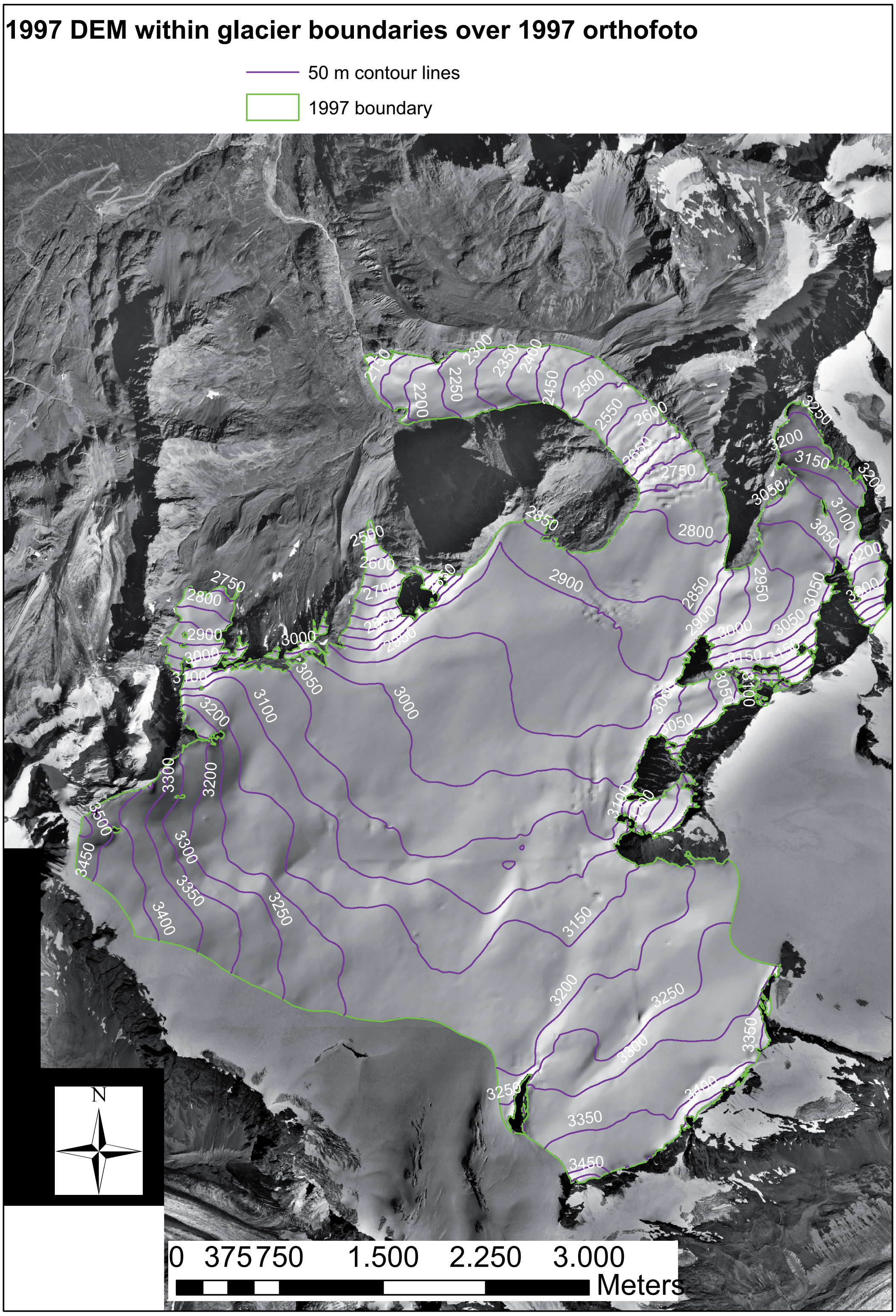


Figure 3.7: Shaded relief image of the 1997 DEM with contour lines and glacier boundaries over orthophotos from the same year.

3.6 The 2006 DEM

The 2006 DEM (Figure 3.8) is based on high resolution airborne LIDAR data aquired by the Government of Tyrol in flights between 23 August and 9 September 2006 and is vertically accurate to ±0.1 m (Abermann et al. 2009).

3.7 Ice Depth Data

In order to analyse the total volume of the glacier for a given year as well as volume changes in select elevation zones over time it was neccessary to create a DEM with bedrock elevations for areas currently covered with ice. This was achieved using ice depth measurements from 1997 by Massimo (Massimo 1997). A resulting map of the bedrock is shown in Figure 3.9.

Radio echo sounding measurements were carried out along one traverse, 11 profiles along- and 7 profiles across the glacier during the time periods 16.- 21. 04. 1996, 05.05.-07.05.1996 and on 24.10.1997. This resulted in a digital elevation model with 10 m raster size of the ice depth at an accuracy of ±5 m. The ice depth could not be determined below a minimum of 30m due to the technical specifics of the sounding arrangement used (see section 2.2).

There is no ice depth data available for the side glacier south of Schwarzwand Spitze, which connects to the upper part of the tongue in the north-east (see section 1.2). The ice in this area can be assumed to be thin, especially in the steep areas on the sides, and contributes only a small percentage to the entirety of the ice body. The side glacier is not included in any of the following calculations of glacier volume.

3.8 Length Change Measurements

The Austrian Alpine Club annually measures variations of glacier length on several glacier tongues, including that of the Gepatschferner. These measurements are published every year in the club magazine *Bergauf*, previously *Mitteilungen des Österreichischen Alpenvereins*, (eg. Patzelt (2006)). For Gepatschferner, measurements for the overall length change exist for the time periods 1856 - 1886, 1886 - 1896, 1896 - 1919, 1919 - 1922, as well as 1923 - 1928. Since then there are annual measurements, with the exceptions of 1939 and 1945 when the Second World War prevented trips to the glacier.

Patzelt calls the data collected by the Alpine club *“often erroneous and sometimes misleading”* but states that despite the variability in the quality of the data, it gives a valuable overview of the behaviour of the selected glaciers (Patzelt 1970). Gepatschferner has a small tongue compared to the rest of the glacier and length

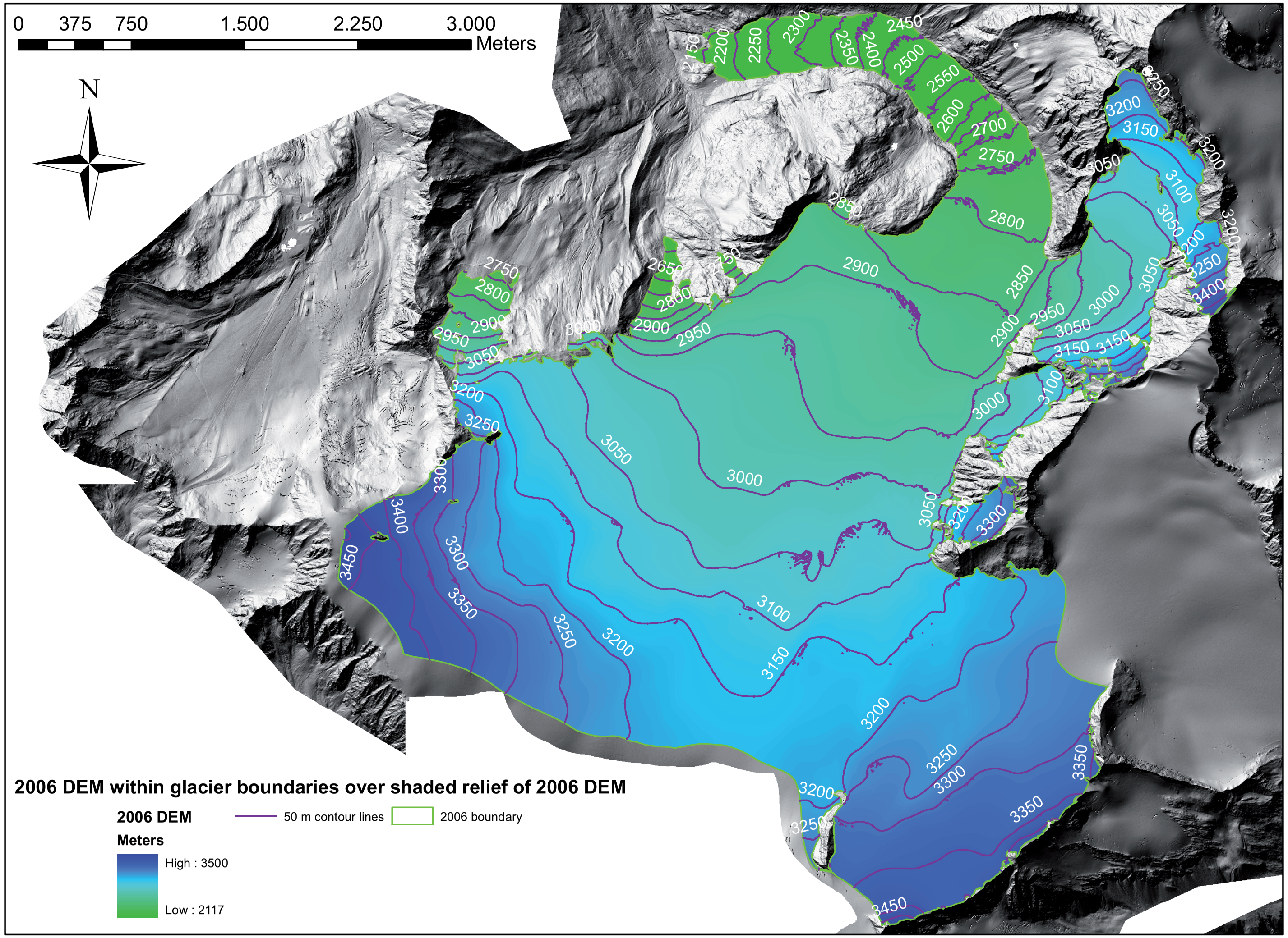


Figure 3.8: The 2006 DEM of the Gepatschferner with contour lines and glacier boundaries over a shaded relief image of a DEM of the surrounding region (also from 2006).

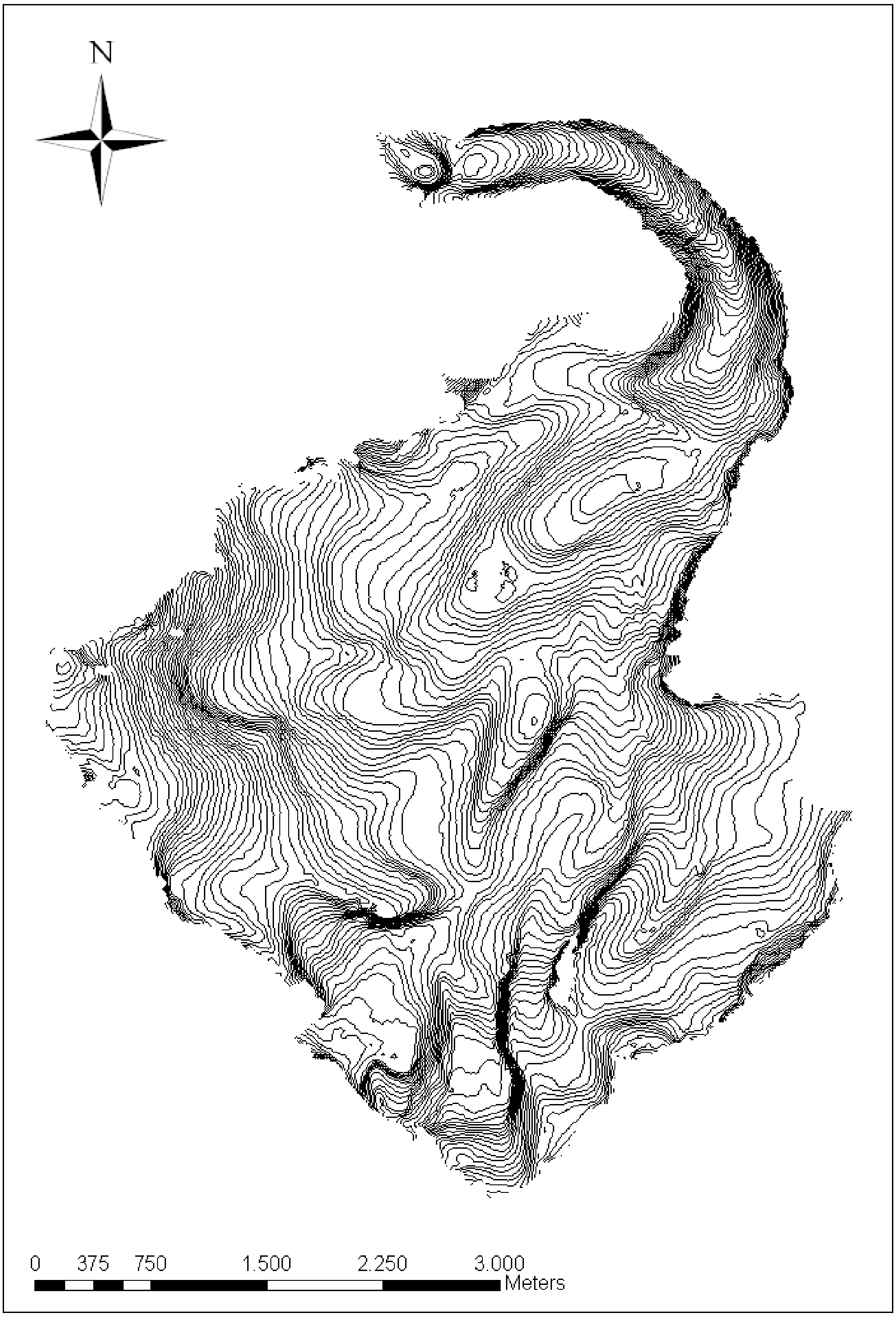


Figure 3.9: Map of the bedrock of Gepatschferner from Massimo (1997).

changes in this case naturally reflect the behaviour of the entire glacier less well than they would at a valley glacier with a large tongue, like for example Hintereisferner.

Chapter 4

Results

4.1 Advances and retreats of the tongue

Advances and retreats of the tongue can be seen as indicators of growth and shrinkage of the glacier as a whole and can provide us with a first general overview of how Gepatschferner has changed since the 1850s.

The long, if somewhat in-homogenous, time-series of length measurements of the tongue (see section 3.8) is shown in Figure 4.1. Both the net values as measured and the cumulative values are shown.

Values between 1856 and the start of the yearly time series show losses of over a kilometer in length. The overall retreat of the tongue is substantial, with a total loss of over two kilometres. No period of growth can be determined in the 1910s. It is hard to say whether this is due to the sporadic measurements or whether the growth seen during this time at many glaciers in the eastern Alps (Patzelt 1970) was less pronounced at Gepatschferner, which might well have only experienced a period of stagnation.

From the early 1920s to the early 1970s the retreat happens at a fairly steady rate. A few years of stagnation in the 1970s are followed by an advance of the tongue in the 1980s and renewed retreat from the 1990s until 2006, at slightly higher rates than before the stagnation. The bar graph of the net change shows quite clearly that even though the tongue grew in length for a few years, it grew less than it retreated before and after.

Table 4.1 lists the mean length change of the tongue per year for the time periods discussed in this paper as defined by the available DEMs. In accordance with Figure 4.1, the loss per annum averaged for the 1922-1971 period is nearly double that of 1850-1922; there is only very little loss per annum from 1971-1997 due to the advance in the 1980s and the retreat of the tongue is fastest in the most recent years.

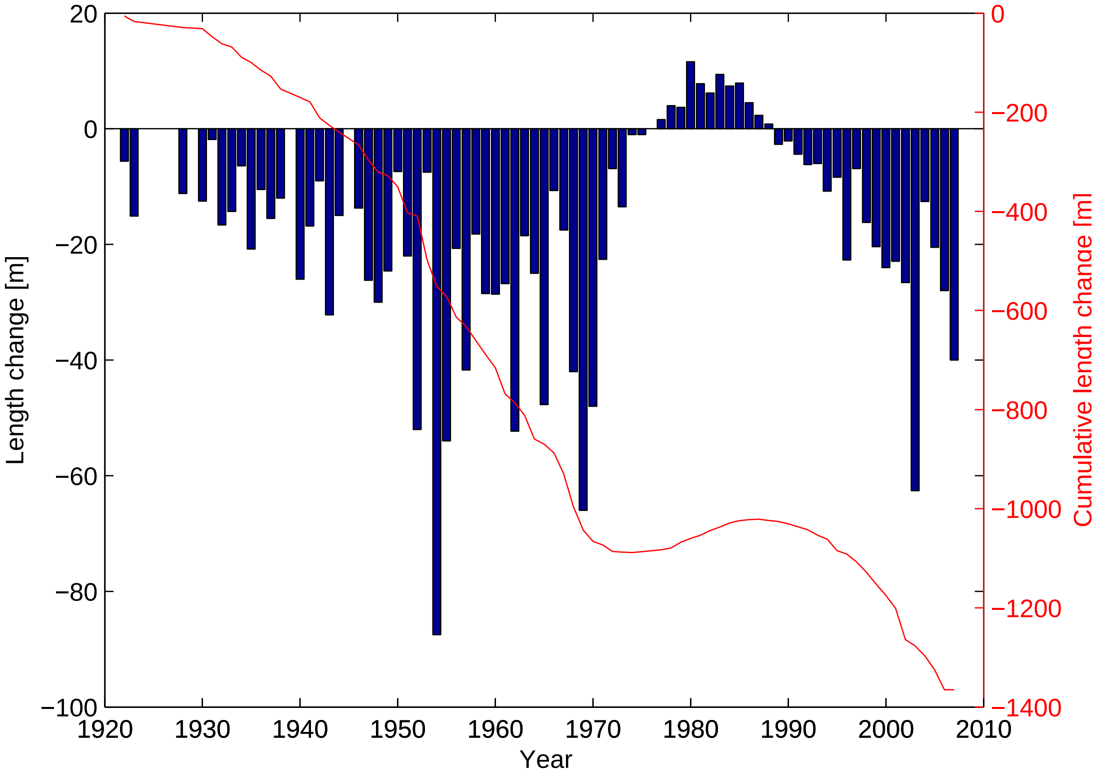


Figure 4.1: Change of tongue length in meters for the Gepatschferner (1922-2006), cumulative as red line, net as black bars.

In conclusion, the data from the tongue tells us that the Gepatschferner has been shrinking for most of the last 150 years, interrupted by a period of stagnation from about 1900 to 1920 and some years of growth in the 1980s. The increasingly fast retreat of the tongue in recent years suggests an increase in overall mass loss of the glacier, which will be further investigated in the following sections.

Table 4.1: Annual changes in length (m), area (m^2) and volume (m^3) (1850-2006)

Time period	1850 - 1922	1922 - 1971	1971 - 1997	1997 - 2006
ΔL/y (m)	-11.3	-21.9	-1.0	-26.0
ΔA/y ($m^2 \cdot 10^4$)	-6.05	-4.49	-2.83	-9.01
ΔV/y ($m^3 \cdot 10^6$)	-5.56	-3.72	-5.59	-9.24

4.2 Changes in Area and Volume

In this section changes in glaciated area and glacier volume are discussed in detail and separately for each time period (1850-1922, 1922-1971, 1971-1997 and 1997-

2006).

4.2.1 1850-1922

From 1850 to 1922 the Glacier lost about 18% in both volume (0.4 km^3) and area (4.3 km^2). In 1928, Finsterwalder calculated 1.095 km^2 of area- and 0.1428 km^3 of volume lost between 1856 and 1922 (Finsterwalder 1928) at the tongue.

As can be seen in Figure 4.2, losses are greatest at the tongue where a substantial amount of terrain became ice free during the 1850-1922 period. The small gain at the very tip of the tongue can only be explained by errors in the 1850 DEM.

Östlicher Wannetferner no longer connects to the Gepatschferner in 1922 and is included in the volume calculations for the glacier in 1850 only. This leads to greater absolute losses in the data than actually occurred, since anything not connected to the main glacier is not considered in the study, yet of course the side glacier did not completely melt when the connection with Gepatschferner was severed. In fact, it exists much diminished to this day.

Noteworthy is also the behaviour of the eastern side arm of the glacier, which completely encircled the central rock island of Rauher Kopf in 1850 and has split up into two distinctly separate tongues by 1922.

It can be observed that losses are smaller in steeper areas, such as the pronounced drop west of Rauher Kopf where the formerly connecting side glacier splits off from the main ice body. The same can be said for higher elevations - there are even some gains at the high points of Weisseespitze and Hintere Hintereisspitze, although it is debatable whether this result is significant, given the possibly large error in the 1850 DEM. Between 2900m and 2950m losses are also comparatively small. Since this is not the case for the other time periods, errors in the DEM are probably to blame.

Both the volume- and area altitude distribution graphs for 1850 are markedly shifted against later years (Figure 4.10). The percentage of total volume and area contributed by the tongue is higher in 1850 than at any later time. However, the opposite is true for a region around and slightly below 3000m of altitude. This suggests that the low lying areas of the glacier, i.e. its long, thin tongue, are suffering greater losses than the large firn basin and that this discrepancy is large enough for a noticeable upwards shift in mass distribution to develop, rather than just a general decrease in mass by a uniform scale factor.

Figure 4.3 shows the greatest absolute changes in area occurring at an altitude of about 3100 m to 3200 m, where the graph has two distinct peaks. In this elevation zone, an area just north of Brandenburgerhaus was ice covered in 1850 and ice free in 1922 (see Figure 4.2). Area losses due to Wannetferner breaking off and the separation of the main and secondary tongue are far more significant but do not produce peaks as prominent because they are spread out over several of the 50m elevation increments.

Volume change correspondingly peaks at around 3200m of altitude. Apart from this main peak, volume losses are fairly large at the tongue and almost non existent in the highest regions. In general, changes are greatest in the region of the large plateau where area and volume are greatest (Figure **??**figure:22-50av).

Gains in both volume and area as suggested in the respective graphs are assumed to be false and ascribed to the problems of the 1850 DEM.

4.2.2 1922-1971

Between 1922 and 1971 the Gepatschferner lost 0.19 km^2 in area and 2.2 km^3 in volume, 10% and 11% respectively.

The large area of equally small loss in the upper regions of the glacier is noteworthy (Figure 4.4). Loss is slightly higher at the high points of Weissseespitze and Hintere Hintereisspitze where wind drift likely plays a more important role due to the more exposed nature of the terrain.

Losses on the tongue increase continuously with decreasing altitude except for the very tip of the tongue where there will have been only very little ice available to melt in the first place and losses are therefore small. The two secondary tongues west of Rauher Kopf further recede. While the easterly one still just touches the main tongue in 1922, it has retreated about 300 vertical meters in 1971 and almost lost its “tongue like” shape.

Area and volume distribution in 1922 lie between the 1850 graph and those of the later years on the tongue (Figure 4.10). In the region around 3000 m (discussed previously in Section 4.2.1) the shift appears to have fully occurred by 1922 as the graphs for both 1922 and 1971 are very similar to those of the following years.

During the 1922- 1971 period, peaks in change of area and volume are less distinct than in the previous time step. Area changes are large below 3000m, generally smaller above. There is a prominent peak around 2300 m, however losses appear greatest between 2700 m and 2900 m when considering the sum of several elevation zones (Figure 4.5).

The distribution of volume change also shows a peak in losses on the tongue at 2300 m, this corresponds with a peak in the 1850-1922 graph and can be attributed to the rapid retreat of the secondary tongues east of Rauher Kopf. There are two positive peaks between 2700m and 3000m, also corresponding to the 1850-1922 graph. This suggests an error in the 1922 DEM, although a possible shift of mass from the region of largest volume downwards may also play a role.

Mean annual losses of volume are markedly lower than in any of the other time steps, while annual area losses are similar to the 1850-1922 values (Figure 4.13).

4.2.3 1971-1997

Between 1971 and 1997, 4.5% (0.8 km^2) of area and 8.4% (0.14 km^3) of volume were lost.

Overall yearly losses between 1971 and 1997 (Figure 4.6) are smaller than in any other time period discussed, due to the growth of the tongue from 1976 to 1988. However, it can be noted that losses at higher elevations and on the main ice body are mostly higher than in the 1922-1971 period. While losses increase on the tongue, they do not do so continuously.

Figure 4.7 shows that both area and volume change hover at or around nought up to an altitude of around 3000 m, where losses increase to the point where they exceed those of previous years. However, losses at the tongue are far smaller compared to previous years than they are greater at higher elevations.

Figure 4.13 correspondingly shows generally smaller mean annual changes in volume (and area) in lower regions and changes as high or higher than in the other time steps at the upper elevations. This sheds light on why volume losses from 1971 to 1997 are large, while area and length losses are at a minimum (see Table 4.1): Area and length losses take place mainly at the tongue, which retreats fast in most years. Ice thickness is small in this region to begin with, so substantial area can be left ice free over the course of one time step. In the upper regions the ice is thick and losses there do not as quickly affect the area of the glacier, let alone length changes at the tongue. Between 1971 and 1997, losses in the upper regions continue yet almost cease at the tongue. Had the losses we see in this time step taken place at the tongue or generally in areas of low ice thickness, rather than at elevations where the ice thickness is at a maximum, we would see area losses similar to those of the other years.

4.2.4 1997-2006

From 1997 to 2006, 2.9% (0.5 km^2) and 5.9% (0.1 km^3) of area and volume respectively were lost.

In the most recent years, changes at higher elevations remain similar in pattern to the 1922-1971 and 1971-97 periods (Figure 4.8). In contrast, losses at the tongue dramatically increase by up to 40% at the tongue over the greatest losses of previous time steps (-3.4 m per year in 1922-1971, -5.7 m per year in 1997-2006).

In connection with the high losses at the tongue, one should consider the now almost due westerly exposition of the lowest regions of the tongue, compared to when it extended further down the valley and was entirely north facing. This may contribute to the faster retreat along with rising temperatures. Figure 4.9 seems to confirm this with slightly elevated values of absolute and annual losses at around 2200 m to 2400 m of altitude where the tongue faces due west. The exposition of the tongue further increases losses where they have already been highest in most of the previous years.

Overall mean annual losses of volume between 1997 and 2006 exceed mean annual losses of area by a factor of 2.3. While absolute losses at the tongue and therefore in area, as well as the elevation changes seen particularly at the very end of the tongue, may seem dramatic, this suggests that the loss of volume at higher elevations is even more so.

A peak in area change between 3050 m and 3100 m (see Figure 4.9) appears to be an error in the data, as no sufficiently large loss of glaciated area can be determined in comparing the glacier boundaries for 1997 and 2006 at this elevation. There is no corresponding peak in either the absolute or annual mean volume changes.

4.3 Summary

Figure 4.10 shows the distribution of glacier area and volume over the range of elevation of Gepatschferner for the years discussed. It can be seen that a maximum in area and volume remains almost unchanged at an altitude of 3200 m. Over the years, the distribution graphs in general change little in the regions above this maximum but do so increasingly below the maximum.

Absolute changes in area and volume for each time step are shown in Figure 4.11. Losses in area around 2400 m and 2800 m are markedly larger during the time steps before 1971 than in the more recent years. This can not be observed in volume change. The 1850-1922 graphs have a far greater range than those of the other time steps in both cases. This reflects the greater length of this time step, as well as the inaccurate nature of the 1850 DEM. In general, changes are largest around 3000 m and at the tongue.

Mean annual changes in area and volume during the time steps can be seen in Figure 4.13 which shows that net losses are highest around 3000 m and at the tongue. The tongue lost up to over 10% of its mass between 1997 and 2006, compared to under 2% in all previous time steps (Figure 4.12). Nonetheless, higher elevations at around 3000m contribute most to overall losses and do so increasingly in more recent years.

Table 4.2 shows the total area and volume of the glacier for the respective years. The decreasing trend in both is obvious. Since 1850, the Gepatschferner has lost 32% of its area (roughly 7.8 km^2) and about 36% of its volume. In Table 4.1 it can be seen that annual losses are largest in the most recent time period. This corresponds with the increase of losses in length at the tongue. Noteworthy is the fact that volume losses from 1971 to 1997 are comparatively large, whereas area and length losses are at a minimum during this period.

Table 4.2: Area and volume of the Gepatschferner (1850-2006) as absolute values and as percentage of the area and volume in 1850.

Year	1850	1922	1971	1997	2006
Area(km^2)	24.4	20.1	17.9	17.1	16.6
Area (% of 1850)	100	83	73	70	68
Volume(km^3)	2.26	1.86	1.67	1.53	1.44
Volume (% of 1850)	100	82	74	68	64

4.4 Estimation of errors

A horizontal- and vertical uncertainty $u_{x,y}$ and u_z was defined for each DEM based on the following possible error sources or values given in literature where applicable (e.g. : Abermann et al. (2010), Würländer and Eder (1998), Lambrecht and Kuhn (2007))

- inaccuracies during the manual digitisation process
- inaccurate georeferencing
- errors inherent in the map used as basis of the DEM (or due to limited resolution orthofotos where such were used)

As is to be expected, errors decrease with increasingly recent DEMs. The 1850 DEM is by far the most problematic, seeing as it was derived solely from geomorphological data. While moraines are clearly visible in lower lying areas and allow for a reasonable determination of the 1850 glacier boundaries at the tongue, the same cannot be said for many sections of the boundary at higher elevations. However, the resulting errors remain within tolerable range as boundary changes in the upper regions are very small compared to those at the tongue. Compared to the value for glacier area, the value for volume has to be seen as more uncertain, as all contour lines were interpolated and considerable errors may have occurred during the interpolation.

The 1922 DEM is based on a map created using terrestrial photogrammetry data, which produces a greater (and very inhomogenous) horizontal error compared to aerophotogrammetry. In this case the topography of Gepatschferner is beneficial as its main body is only very gently inclined and wide expanses are almost flat. Horizontal errors may be large but still produce only a small vertical error.

The 1971 map is based on an aerial survey, as is the 1997 DEM which is based on orthophotos rather than a map. With improving technology accuracy greatly improves.

Errors in the laser scanning data for the 2006 DEM may be due to atmospheric parameters at the time of the survey flight and vary in relation to ground roughness. Errors generally increase at the edges of the area scanned and the horizontal error is smaller than the vertical error.

Taking into account inaccuracies in the ice depth data, the uncertainty values for area u_A and volume u_V given in Table 4.3 were calculated according to the Gaussian law of uncertainty propagation, where u_y is the uncertainty of y and x_i are independent variables.

$$u_y = \sqrt{(\frac{\delta y}{\delta x_1} u_1)^2 + (\frac{\delta y}{\delta x_2} u_2)^2 ...}$$

Errors in area range from 0.4 to 0.01%. Errors in volume are estimated to not exceed 10%.

Table 4.3: Horizontal and vertical mean errors ($u_{x,y}$ and $u_z(m)$) in the DEMs as well as calculated errors in volume and area in the respective years.

Year	1850	1922	1971	1997	2006
$u_{x,y}(m)$	±10	±5	±3	±1	±0.3
$u_z(m)$	±15	±5	±3	±1.9	±0.1
Area(km^2)	24.4	20.1	17.9	17.1	16.6
$u_A(km^2)$	± 0.098	0.040	0.021	0.007	0.002
$u_A(\%)$	0.40	0.20	0.12	0.04	0.01
Volume(km^3)	2.26	1.86	1.67	1.53	1.44
$u_V(\%)$	10	7	5	3	1

It should be understood that the values in Table 4.3 are estimates based on assumptions about the DEMs. They give an idea about the range of uncertainty in area and volume but there is no way to determine the "error in the error".

4.5 Conclusion

The glacier has been analysed for the whole of the studied time span (1850 -2006), as well as separately over the course of time steps as mentioned. Central points of this investigation are as follows:

- Absolute losses for the time steps as a whole were greatest from 1850 to 1922. Mean annual losses were greatest from 1997 to 2006. In the most recent time period, annual losses in length are larger by a factor of 1.2 than in the time period with the next highest losses (1922-1971). Annual area losses are greater by a factor of 1.5 over the next highest value (1850-1922). Annual volume losses have increased by a factor of 1.7 over those of the 1971-1997 period.

- The rate of loss of volume is double that of the rate of loss of area in the most recent years and has steadily increased with time, starting from equal losses in area and volume from 1850 to 1922.

This leads to the conclusion that losses in the upper regions of the glacier are affecting the Gepatschferner as a whole more strongly in recent times than they have in the past, when losses took place mostly at the tongue. While losses in the lowest regions of the glacier are extreme for a comparatively small number of 50m elevation increments with low overall volume and area, the smaller losses on the large firn basin combine to far greater losses, which appear to be continuously rising. During the 1971-1997 time period there was a small surge of the tongue when it increased in length and hardly any area or volume was lost in the lower regions of the glacier. That the loss of volume in the upper regions continued unchecked during this period and was larger by a factor of 1.9 than the overall loss of area is a strong symptom of the phenomenon described above.

A previous study states a loss of 0.9% of glacier volume for a period from 1971 to 1990 and also mentions that the tongue mainly gained in surface elevation during this time, whereas the changes were more inhomogenous in the accumulation zone (Keutterling and Thomas 2004a,b). This matches the results of this study well.

Length change measurements at the tongue of Morteratsch Glacier in Switzerland, a glacier similar in size and exposition to Gepatschferner, show similar trends to those shown in this study, although no periods of advancing are recorded. Total losses are about the same at around 2 km (Oerlemans 2007). Palü Glacier, in the same area but less than half the size of Morteratsch Glacier, shows the same trends, including advances in the 1910s (period of stagnation likely at Gepatschferner) and 1970s, but total length losses are smaller at around 1300 m.

Hallstätter Glacier in the Dachstein area lost 63% of its volume since the last glacier maximum (Helfricht 2009), Mullwitzkees, a glacier of southern exposition in the Venediger Group lost 73%. The neighbouring Zettalunitzkees lost 55% of area and a total of 1600 m in length since 1890 (Stocker-Waldhuber 2010). It would be interesting to further investigate what role the topographic characteristics of different glaciers play in their melting and then compare large glaciers with relatively small tongues like Gepatschferner to glaciers with long tongues (Hintereisferner) or cirque glaciers.

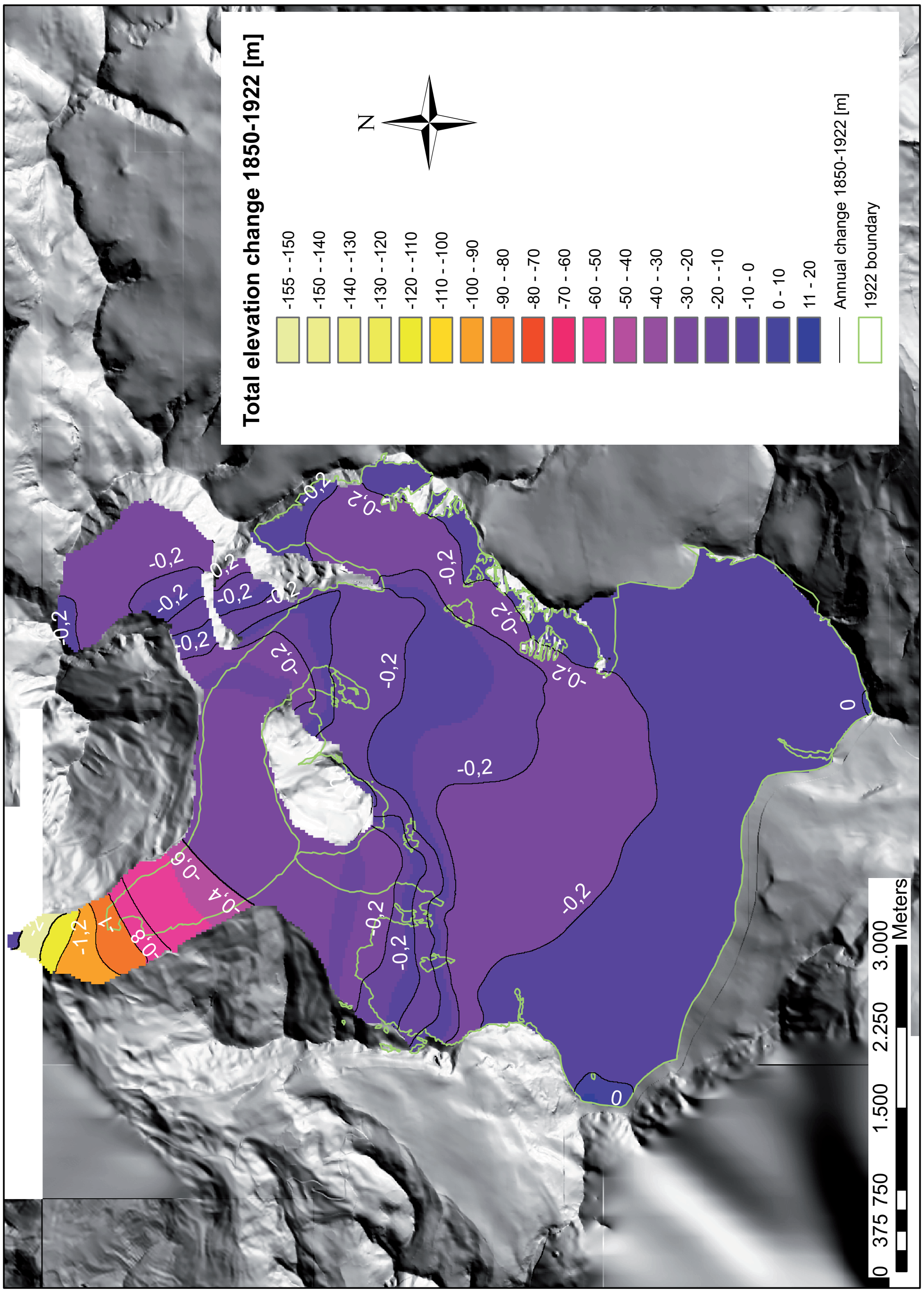


Figure 4.2: Changes in surface elevation in meters from 1850-1922 with mean annual changes in this period as contour lines. 1922 boundaries in green.

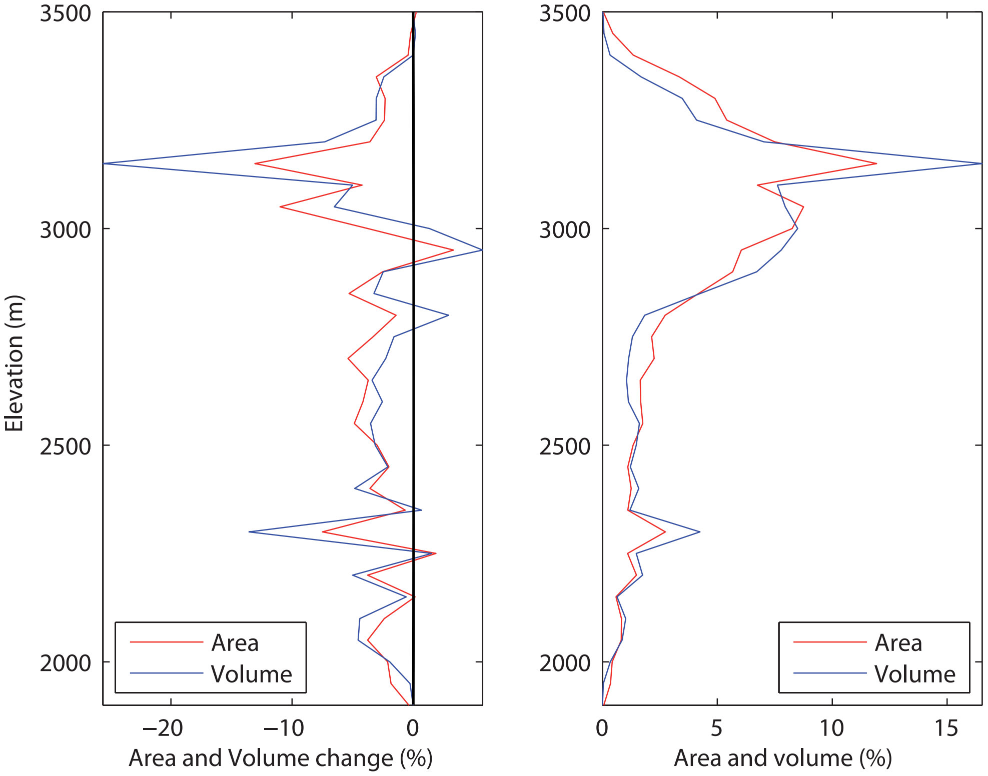


Figure 4.3: Mean annual changes in area and volume from 1850-1922 as percentage of the total mean change on the left, area and volume - altitude distribution of 1850 on the right.

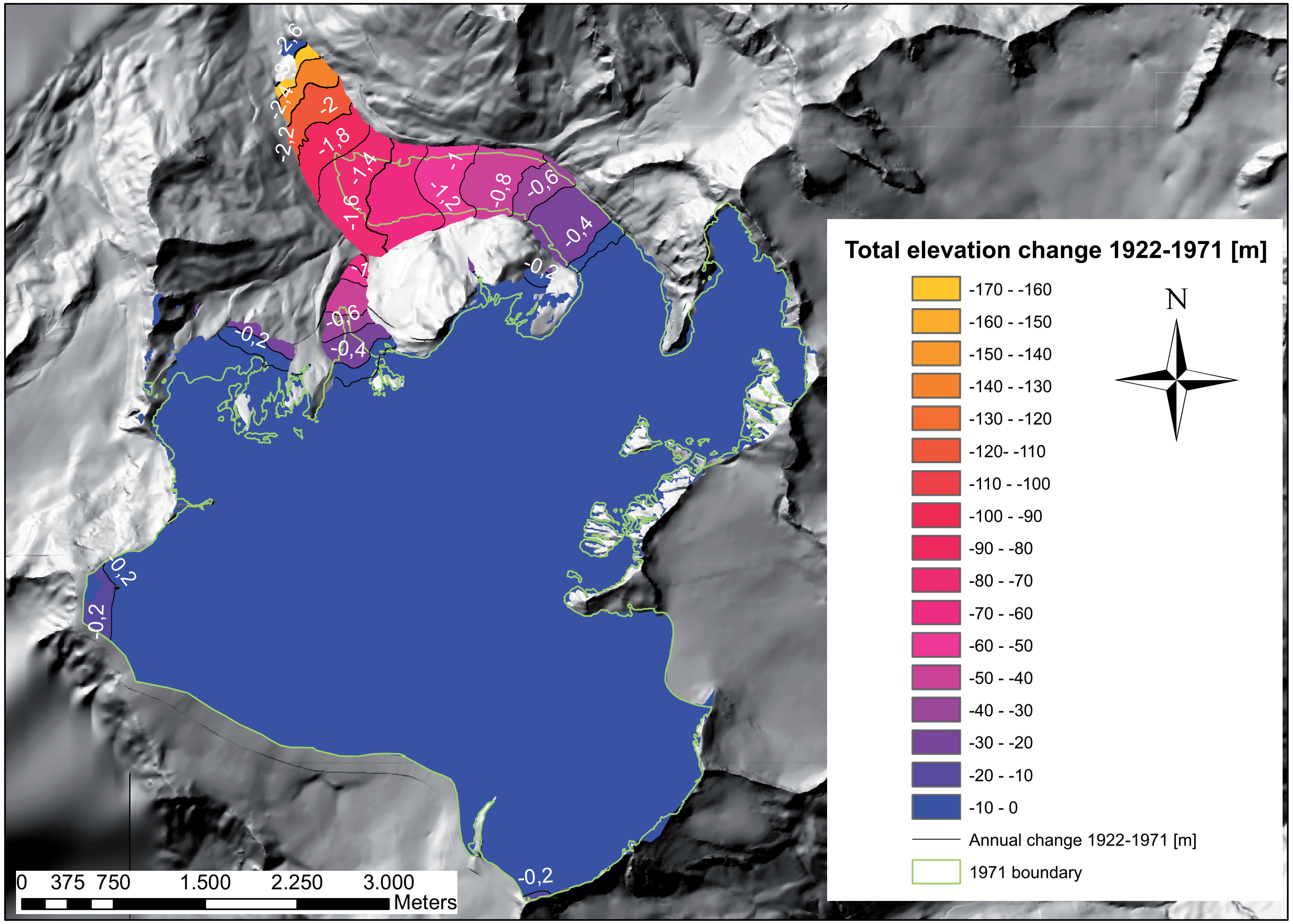


Figure 4.4: Changes in surface elevation in meters from 1922-1971with mean annual changes in this period as contour lines. 1971 boundaries in green.

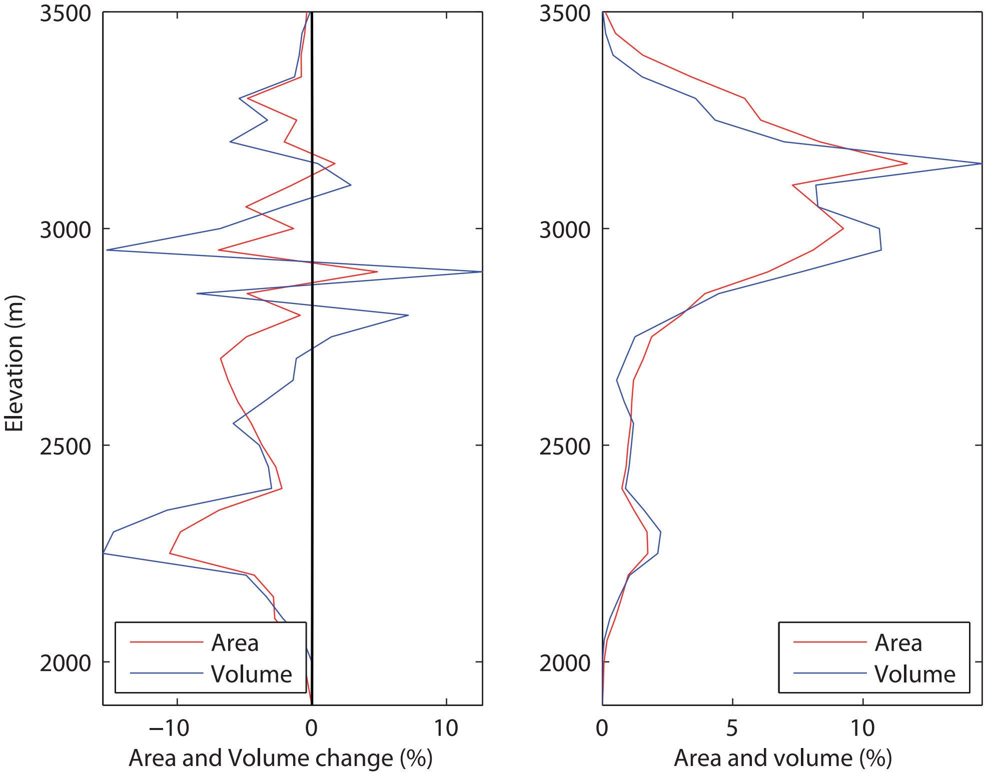


Figure 4.5: Mean annual changes in area and volume from 1922-1971 as percentage of the total mean change on the left, area and volume - altitude distribution of 1922 on the right.

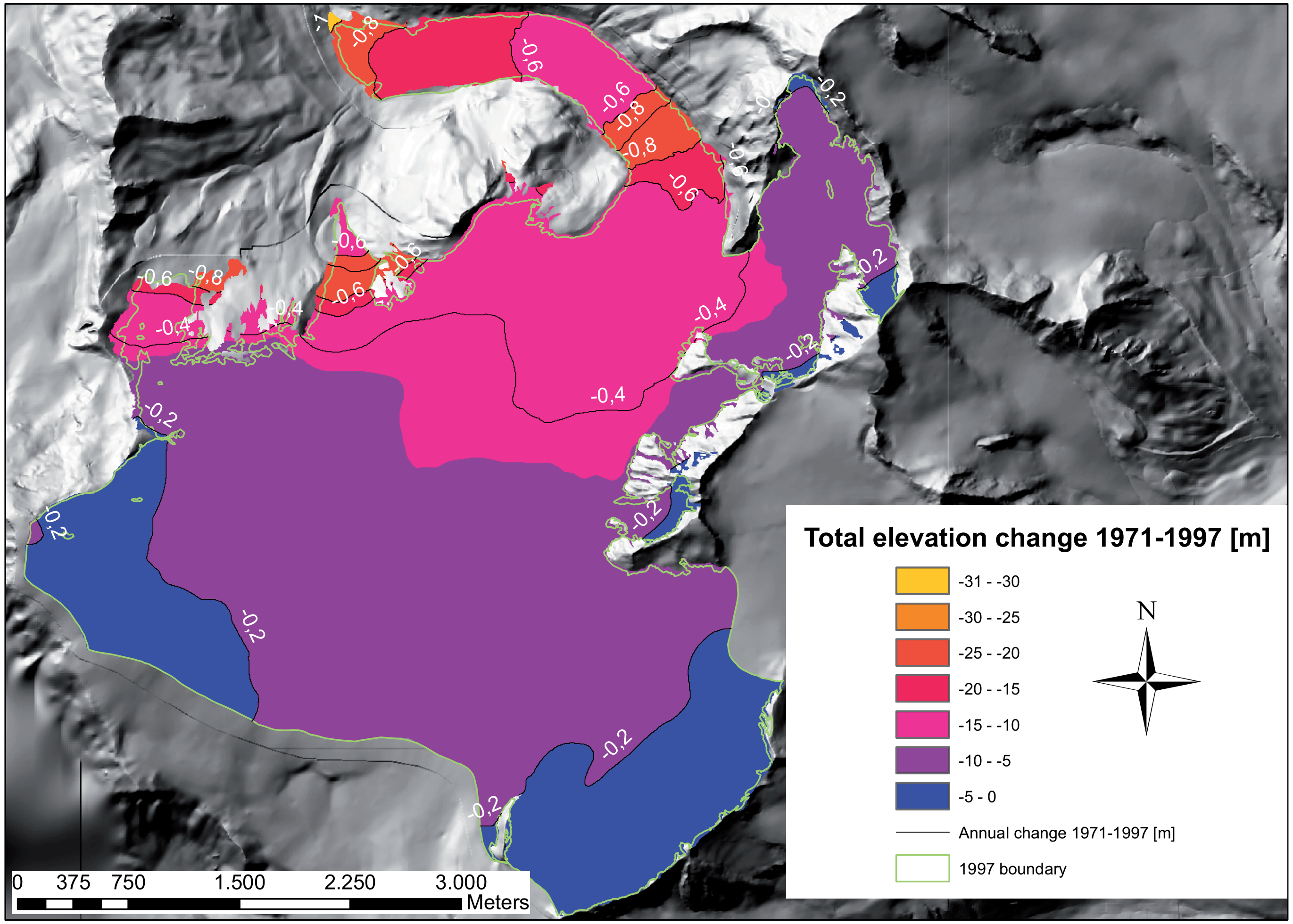


Figure 4.6: Changes in surface elevation in meters from 1971-1997 with mean annual changes in this period as contour lines. 1997 boundaries in green.

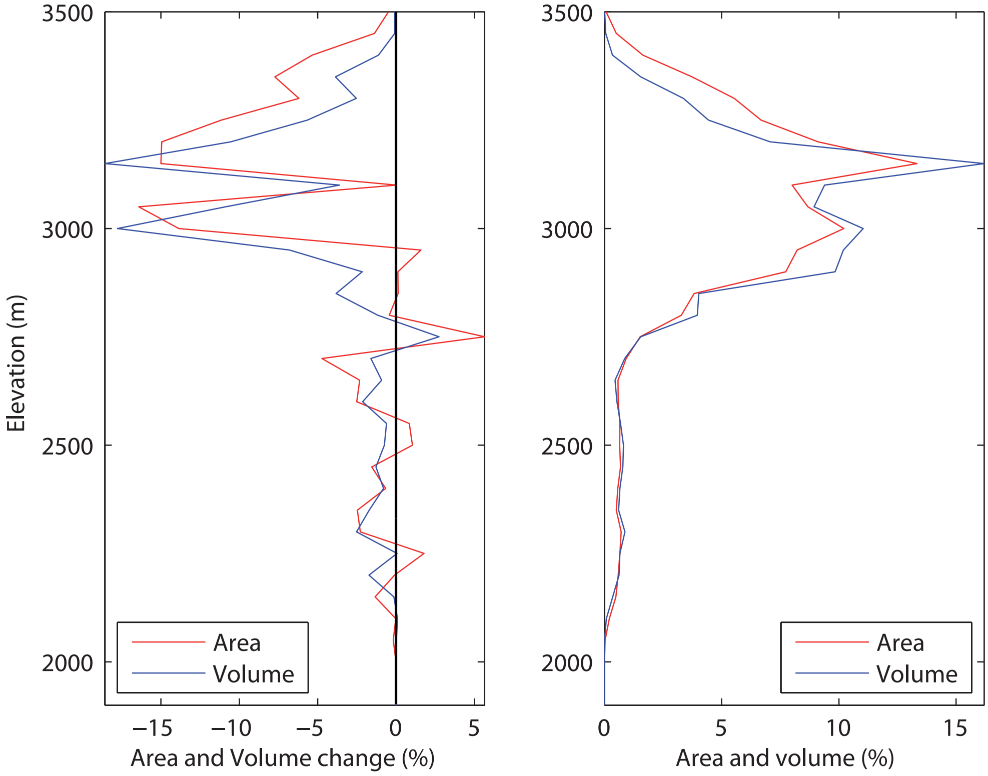


Figure 4.7: Mean annual changes in area and volume from 1971-1997 as percentage of the total mean change on the left, area and volume - altitude distribution of 1971 on the right.

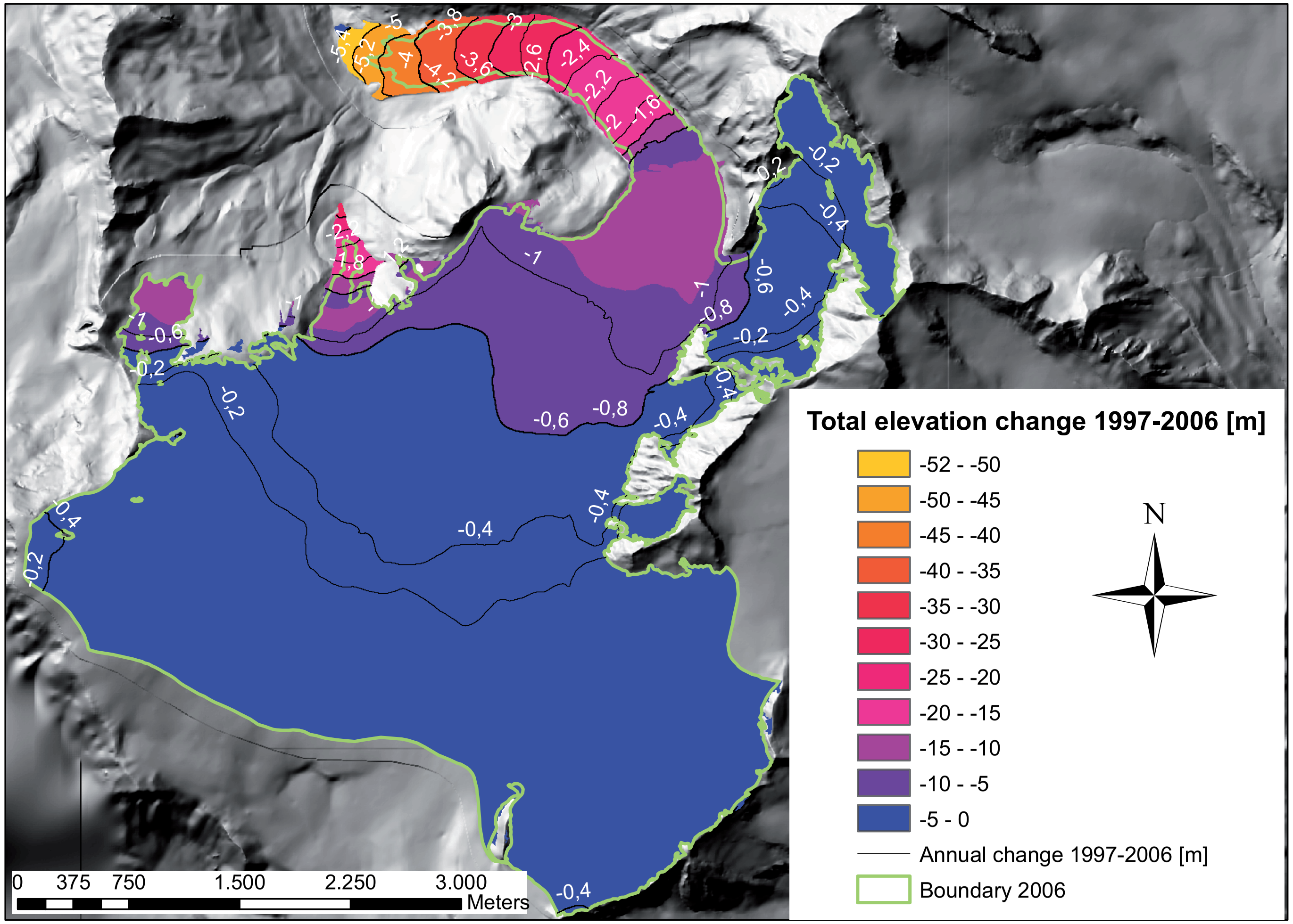


Figure 4.8: Changes in surface elevation in meters from 1997-06 with mean annual changes in this period as contour lines. 2006 boundaries in green.

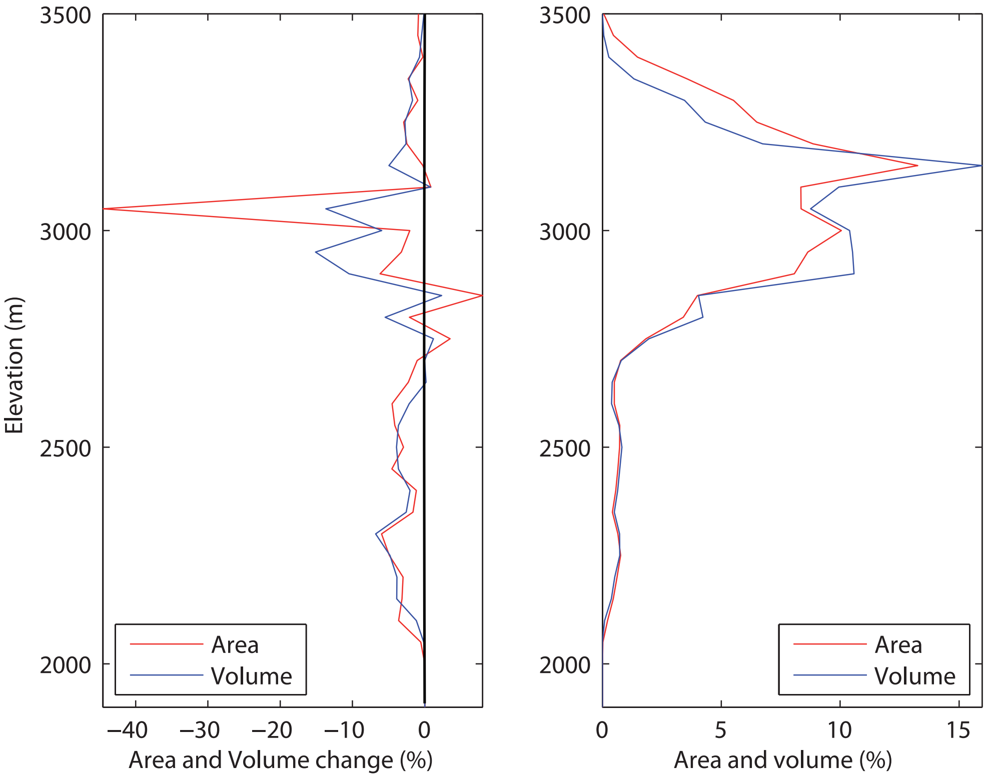


Figure 4.9: Mean annual changes in area and volume from 1997-2006 as percentage of the total mean change on the left, area and volume - altitude distribution of 1997 on the right.

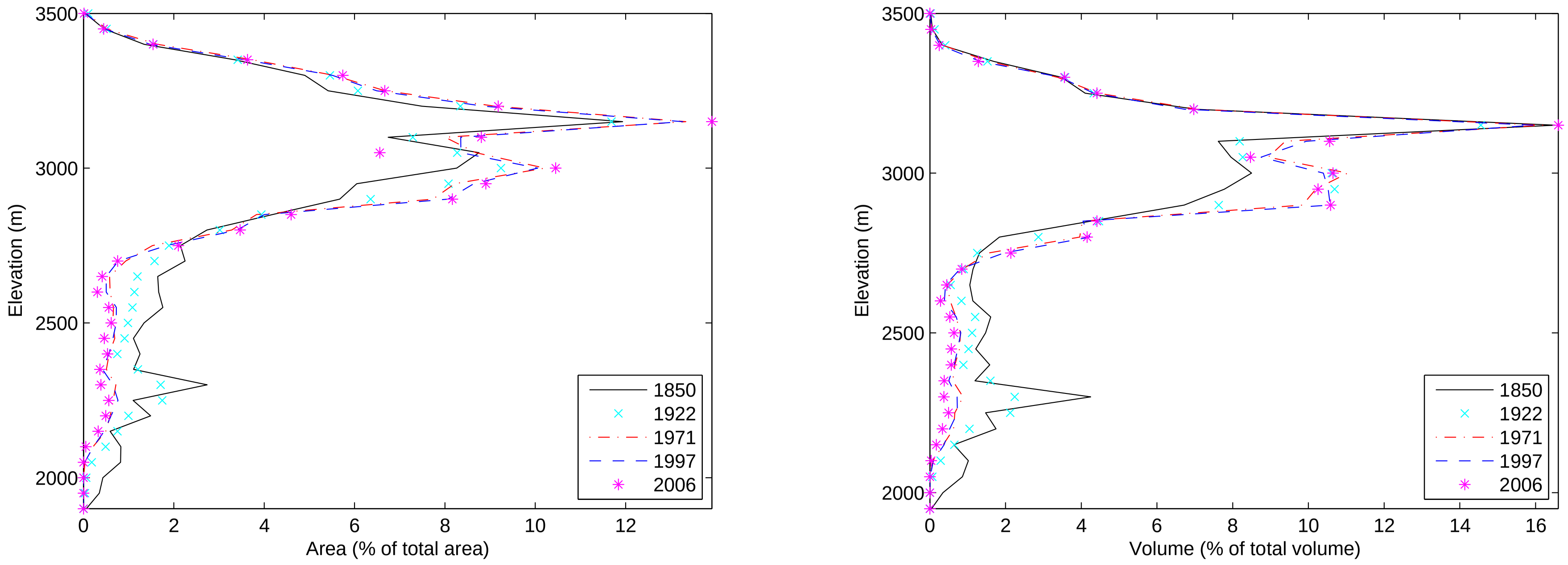


Figure 4.10: Area- and volume altitude distribution of the Gepatschferner in m^2 for increments of 50 vertical meters for the years 1850, 1922, 1971, 1997 and 2006

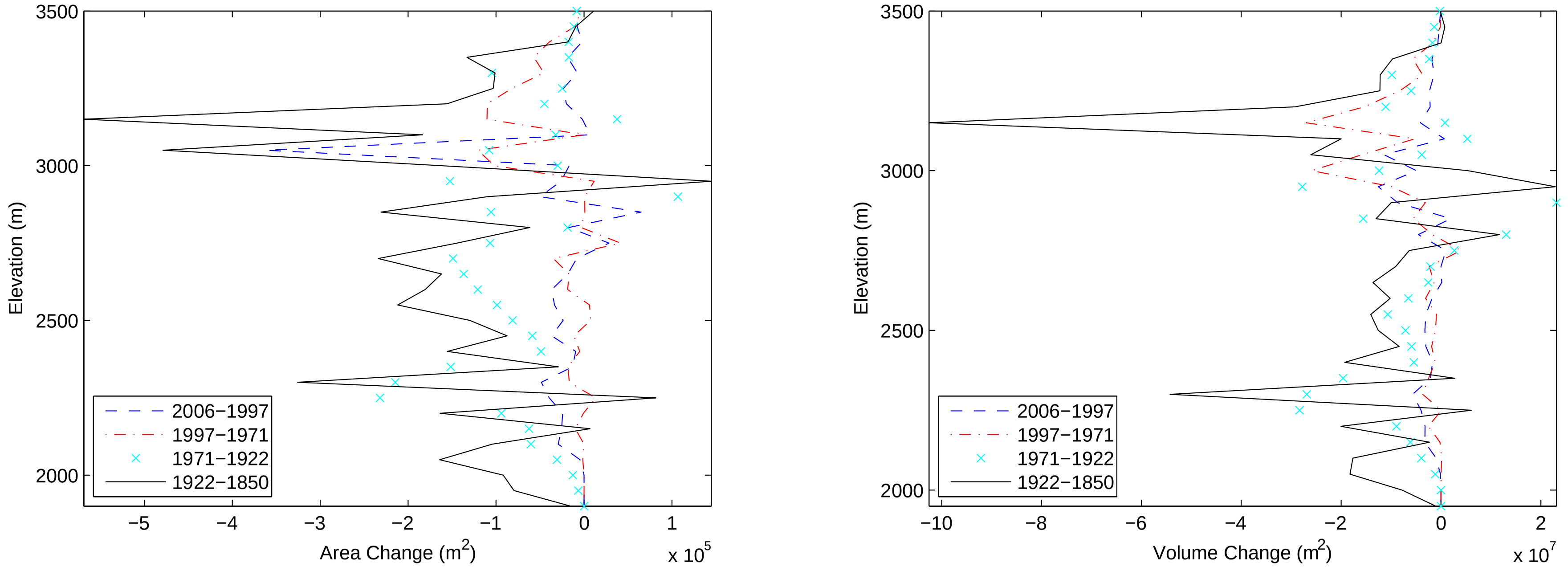


Figure 4.11: Area- and volume change distribution of the Gepatschferner in m^2 for increments of 50 vertical meters during the time periods 1850-1922, 1922-1971, 1971-1997 and 1997-2006

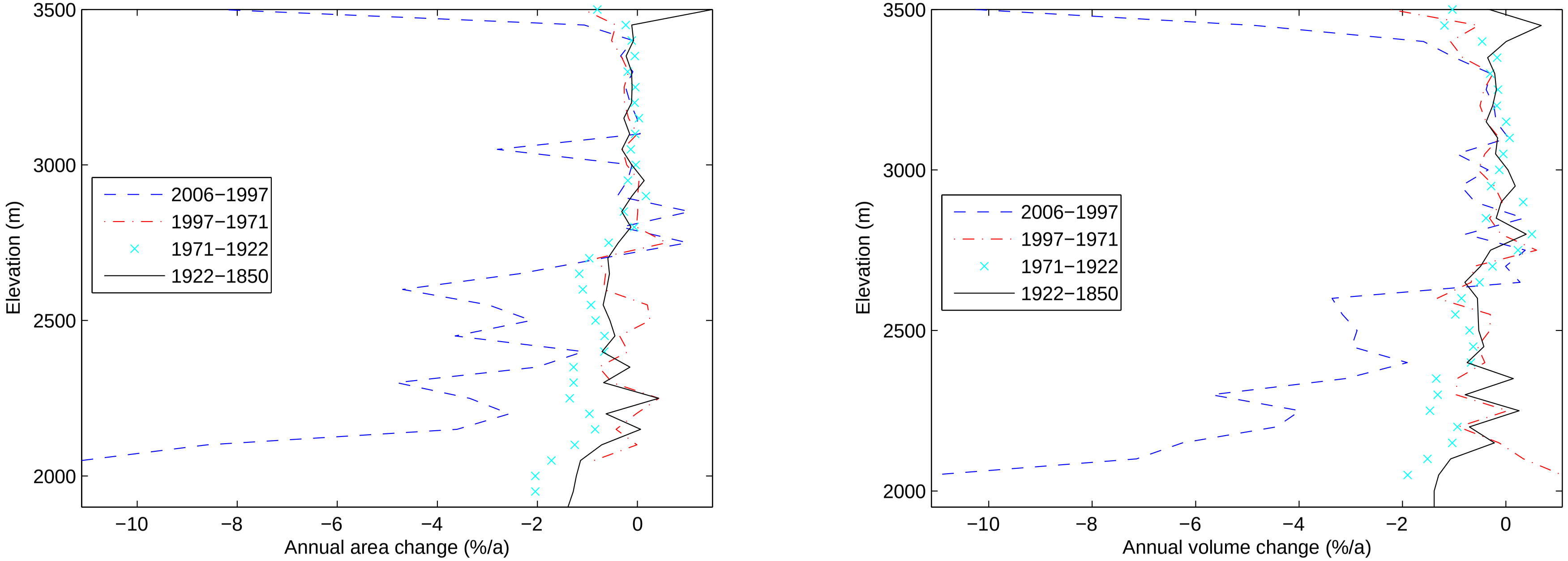


Figure 4.12: Area- and volume change per year as percentage of the previous year for increments of 50 vertical meters during the time periods 1850-1922, 1922-1971, 1971-1997 and 1997-2006

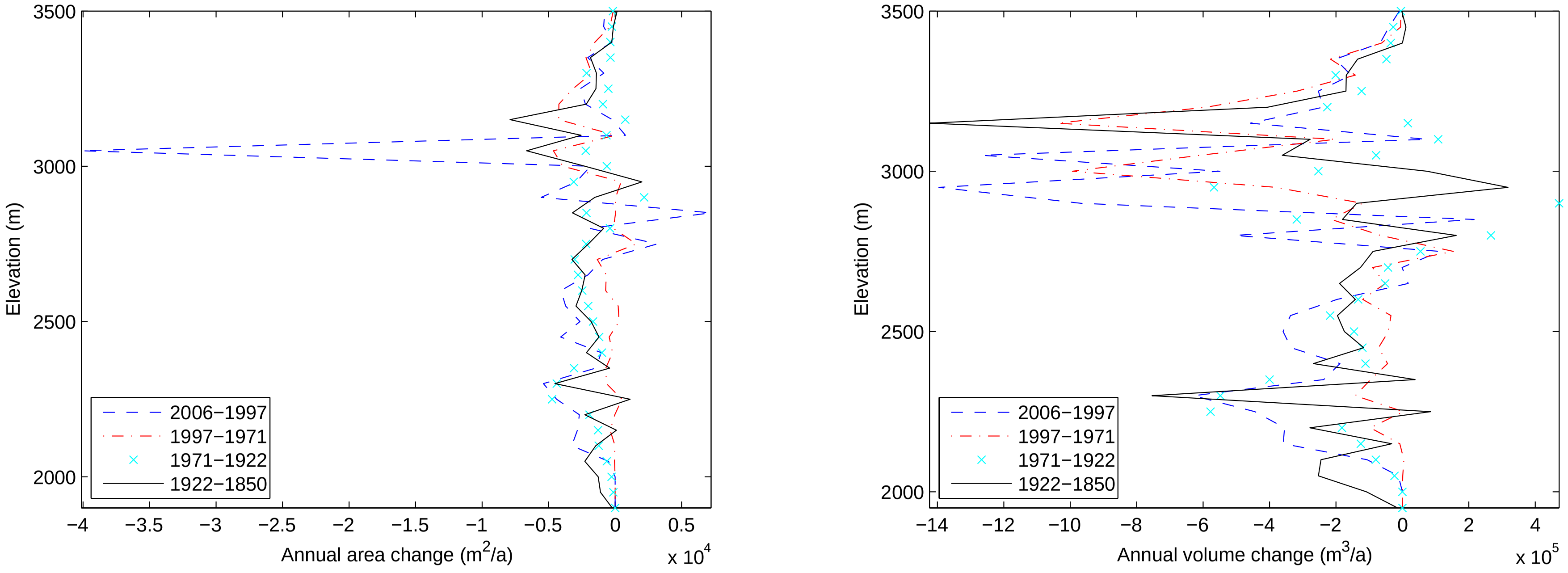


Figure 4.13: Area- and volume change per year in m^2 for increments of 50 vertical meters during the time periods 1850-1922, 1922-1971, 1971-1997 and 1997-2006

Chapter 5

Discussion

In this chapter the changes at Gepatschferner are considered in relation to climate data. Temperature and precipitation data from the HISTALP project is described and shown in the first section. In light of this, changes at the glacier are then discussed in the second section.

5.1 Climate data

HISTALP (Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region) is a publicly available database of long term climate series in the so called Greater Alpine Region (GAR), between 4° and 19°E and 43° and 49°N, hosted by the Austrian weather service ZAMG (http://www.zamg.ac.at/histalp/). Since the early 1990s the HISTALP database has developed from a first collection of climate data in Austria to a variety of data sets from seven countries for several climatological parameters that are:

- Longterm
- Spatially dense
- Quality improved
- Homogenized
- User Friendly

The datasets are available in station mode, i.e. homogenised and quality improved (outlier detection etc.) monthly series of data from weather stations in the GAR, as well as in gridded form. Grid-mode-1 presents anomaly series at a grid size of 1° latitude and longitude, whereas CRSM-mode (coarse resolution subregional means) shows anomalies for 5 principal subregions of the GAR (Auer et al. 2007).

For the parameter of precipitation a 10 minute resolution grid has additionally been developed (Efthymiadis et al. 2006).

Temperature and precipitation are the climate parameters mainly relevant to the mass balance. The respective data is shown and discussed in the following.

5.1.1 Temperature

Gepatschferner lies within a rectangle spanned by four grid points in the grid-mode-1 dataset, two of which are on the southern side of the main alpine ridge (46°N, 10°E and 46°N, 11°E) and two which are in the north (47°N, 10°E and 47°N, 11°E). Grid point 47°N, 11°E is the closest to Gepatschferner (30 km).

The two grid points that lie south of the main Alpine Ridge are not only 100 km of distance away from Gepatschferner, they are situated in low lying areas of Brescia and Trentino province in Italy and do not share the climate of the high alpine regions around Gepatschferner.

The two closest station-mode data sets are from Innsbruck (575 m) and Vent (1900 m). Vent is located at the end of the Ötztal, roughly 13 km from Gepatschferner.

Figure 5.1 gives an overview of stations and gridpoints.

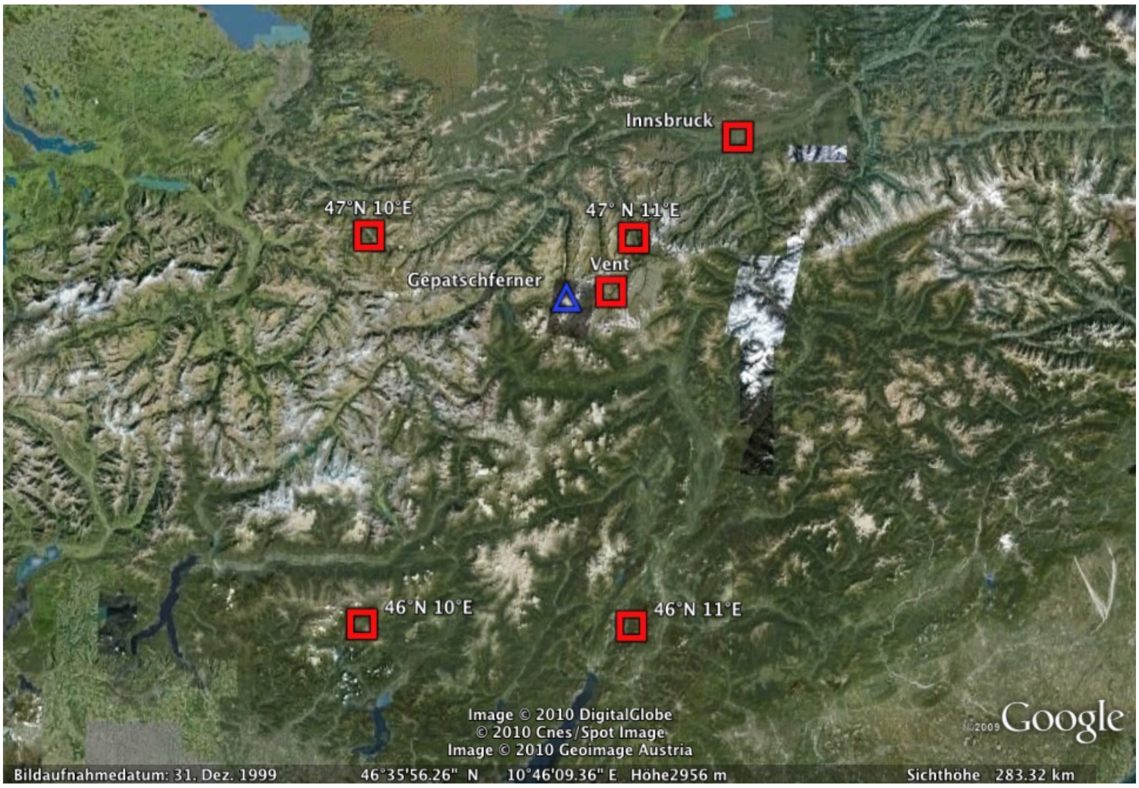


Figure 5.1: Position of relevant temperature grid points, Innsbruck and Vent stations (red squares) and Gepatschferner (blue triangle).

There are two gridded temperature sets, one for high elevations, based on summit stations and generally stations at higher elevations and one for lower elevations. The latter is available throughout all of the GAR, the former only in mountainous regions.

Figure 5.2 shows 20 year mean temperature anomalies at all of the four grid points mentioned above. The curves show no significant differences for grid points on either side of the main alpine ridge. From the beginning of the time series until the 1890s, the anomalies are slightly more negative south of the Alps. This trend does not continue, however.

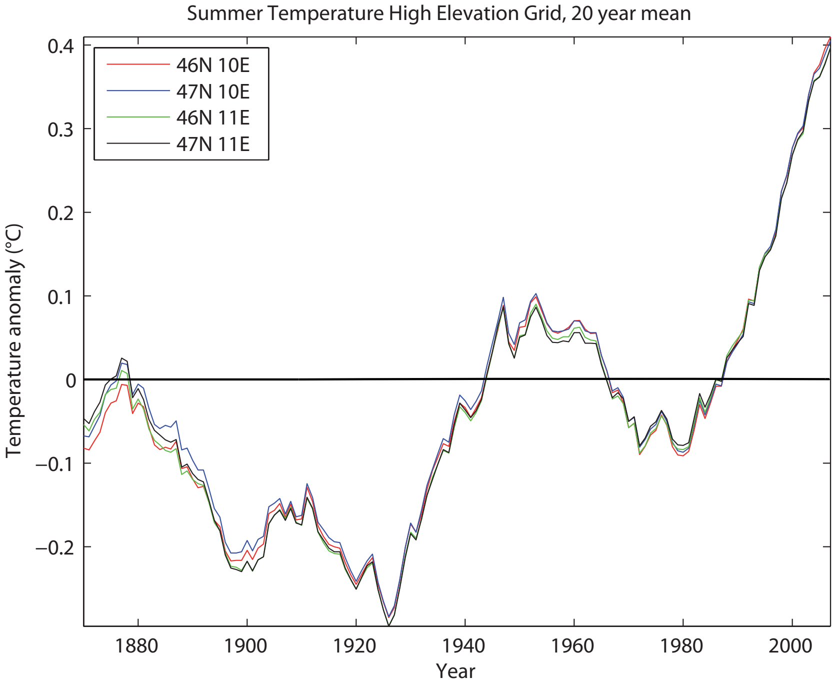


Figure 5.2: 20 year mean of high elevation gridpoint temperature anomalies at all four grid points.

In Figure 5.3 temperature anomalies at the gridpoint closest to Gepatschferner are shown at high and low elevations. Little difference in anomalies can be seen, however both positive and negative peaks seem slightly more pronounced at high elevations.

The 20 year means show no discernible pattern of consistent differences in trend between the high and low elevation anomalies for the entirety of the time series. The curves up to 1950 could be interpreted as showing the high elevation values to be farther below the mean than the low elevation values during an overall cooling trend (from around 1880 until the early 1920s) and higher above the mean during the following warming trend. After 1950 differences in the means appear negligible.

To compare station and grid mode data, temperature anomalies for Innsbruck

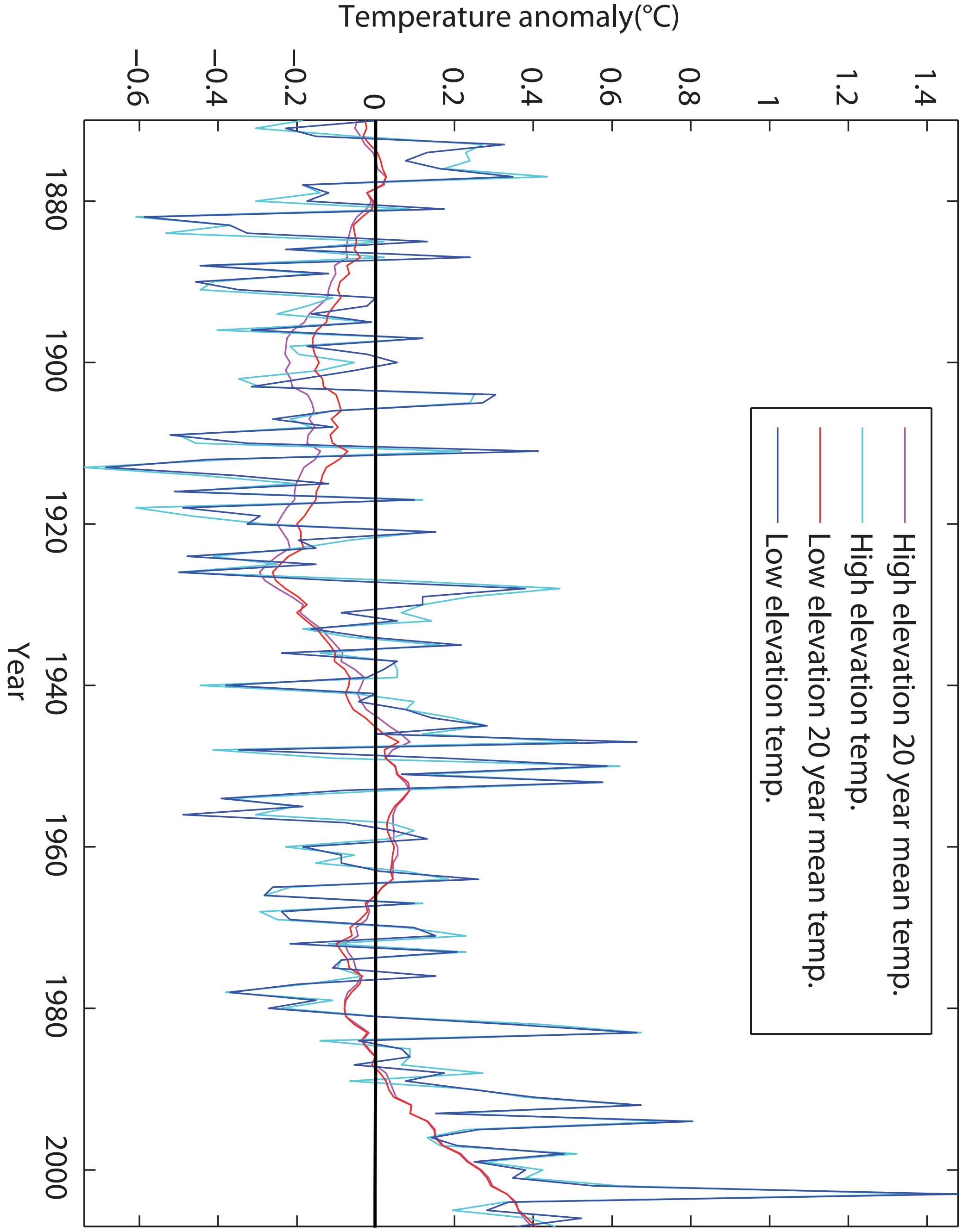


Figure 5.3: High and low elevation gridpoint temperature anomalies and 20 year mean of the anomalies at 47°N 11°E

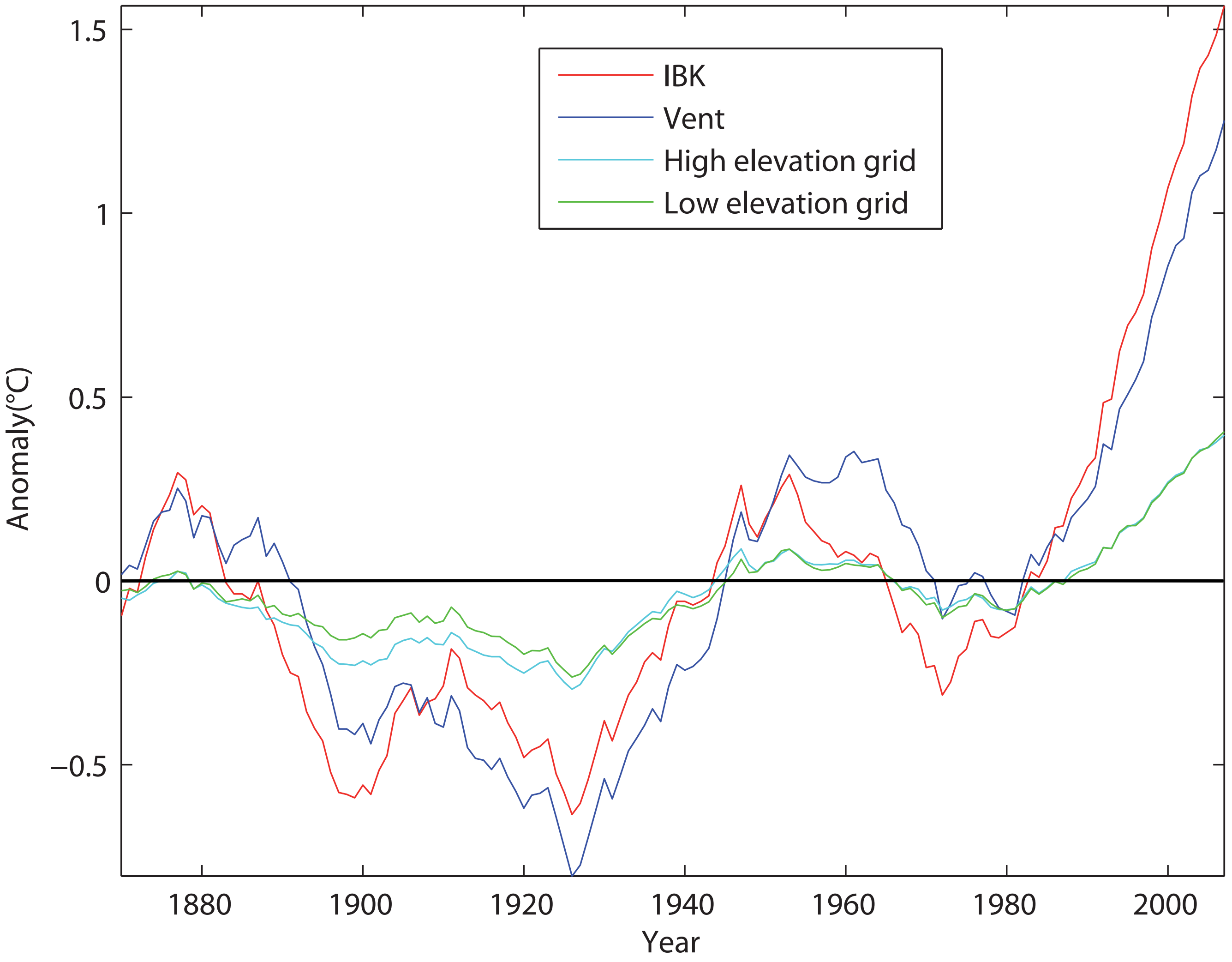


Figure 5.4: 20 year mean of high and low elevation gridpoint temperature anomalies at 47°N 11°O and at Innsbruck and Vent stations.

and Vent were calculated with respect to a mean over the entire time series. As can be seen in Figure 5.4, while overall warming and cooling trends are consistent in both modes, they are far more pronounced in the station data. Other than that, a warming period in the 1910s is hardly noticeable in Vent but quite strong in Innsbruck. However, Vent reaches a strong positive maximum in the early 1960s, where Innsbruck is already showing a distinct cooling trend.

Both gridded and station data reach their absolute anomaly maxima in the most recent years with 1.5°C above the long term average in Innsbruck and Vent and roughly 0.4°C at the high and low elevation grid points.

In conclusion, both the gridded temperature data and the station data show the same warming trends particularly in recent years, although these trends are more pronounced in the station data.

5.1.2 Precipitation

Gepatschferner lies at 46° 50'N and 10° 45'E, putting it in between grid points 46° 45'N; 10 45'E and 46° 55'N; 10° 45'E on Efthymiades' 10 minute grid (Figure 5.5). The mean of these two points was used in the following discussions. The grid shows anomalies expressed in percent with regard to the 1971-1990 monthly mean. No elevation is given for the grid, however data from unreliable summit stations was not used for its interpolation and a "low" elevation should be assumed.

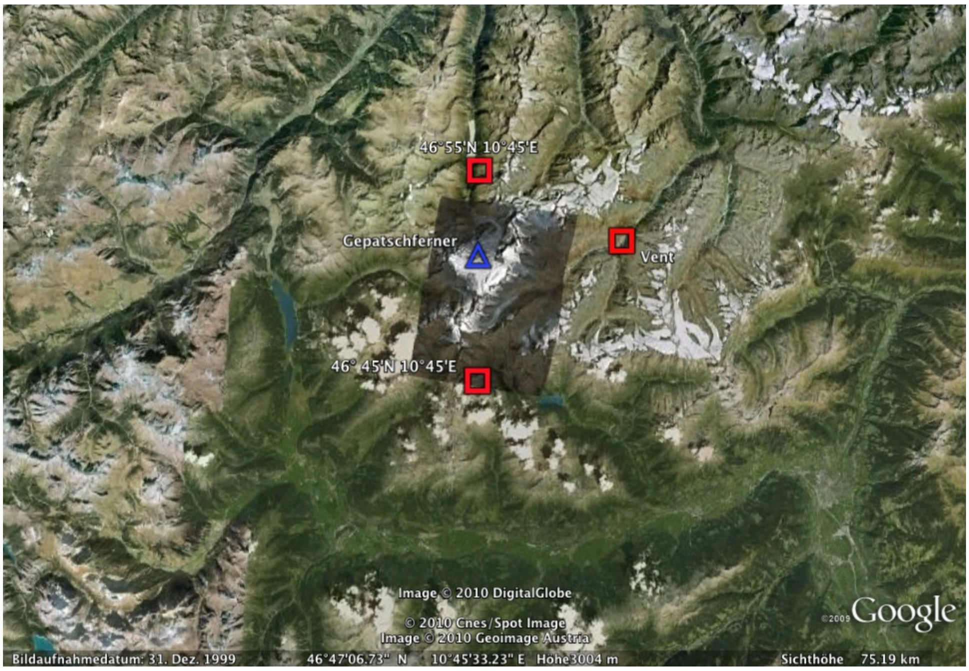


Figure 5.5: Position of relevant precipitation grid points, Innsbruck station (red squares) and Gepatschferner (blue triangle).

Monthly precipitation totals are available for Innsbruck station (shown in Figure

5.6) and anomalies were calculated for better comparability with the gridded data with regard to the 1970-2000 mean. Innsbruck averages around 800mm precipitation per year with some fluctuation until a positive trend appears to begin around 1950. At the end of the time series, the absolute maximum of the entire graph, the yearly precipitation values reach 900mm.

Figure 5.7 shows anomalies of average monthly precipitation from January to December at Innsbruck station and in grid mode. The 20 year means of the anomalies show an upward trend in the station data which rose from about 90% to close to 100% over the course of the time series. The gridded precipitation data reaches its absolute minimum in the late 1950s at under 90% and appears to be increasing since then, however it is currently only just approaching the level of its last high point of just under 100%, whereas the values in Innsbruck are several percentage points above any previous maxima.

From the beginning of the time series to the 1950s the mean gridded anomalies lie about 5 percentage points above the Innsbruck values. The curves are approximately parallel until they intersect in the 1950s. From there on the Innsbruck data shows a stronger positive trend than the gridded data and the earlier situation is reversed with the Innsbruck values consistently several percentage points above the grid values.

Figure 5.8 shows 20 year means of summer and winter precipitation anomalies in Innsbruck. Notable are the high precipitation values during the winters of the late 1910s until 1930. From about 1940 to 1980 there is a series of negative peaks in an overall positive trend. Winter precipitation in 1943 was extremely low at only 83%. In some cases there appears to be a lag of 5-10 years between summer and winter peaks. The increasing upwards trend in the years since 1980 is due mainly to above average precipitation during the winter months.

As with the temperature data sets, gridded and station mode precipitation appears to be comparable within reason, however the significant increase in precipitation measured at Innsbruck station is not as clearly reflected in the grid data.

5.2 Evaluating glacier change in relation to climate data

In order to understand the relevance of the available climate data, it is important to briefly look at the main weather patterns at Gepatschferner and at the respective weather stations and grid points. Situated on the main Alpine Ridge, Gepatschferner receives most of its precipitation from the south. Innsbruck on the other hand lies in an East-West aligned valley north of the main Alpine Ridge and is almost

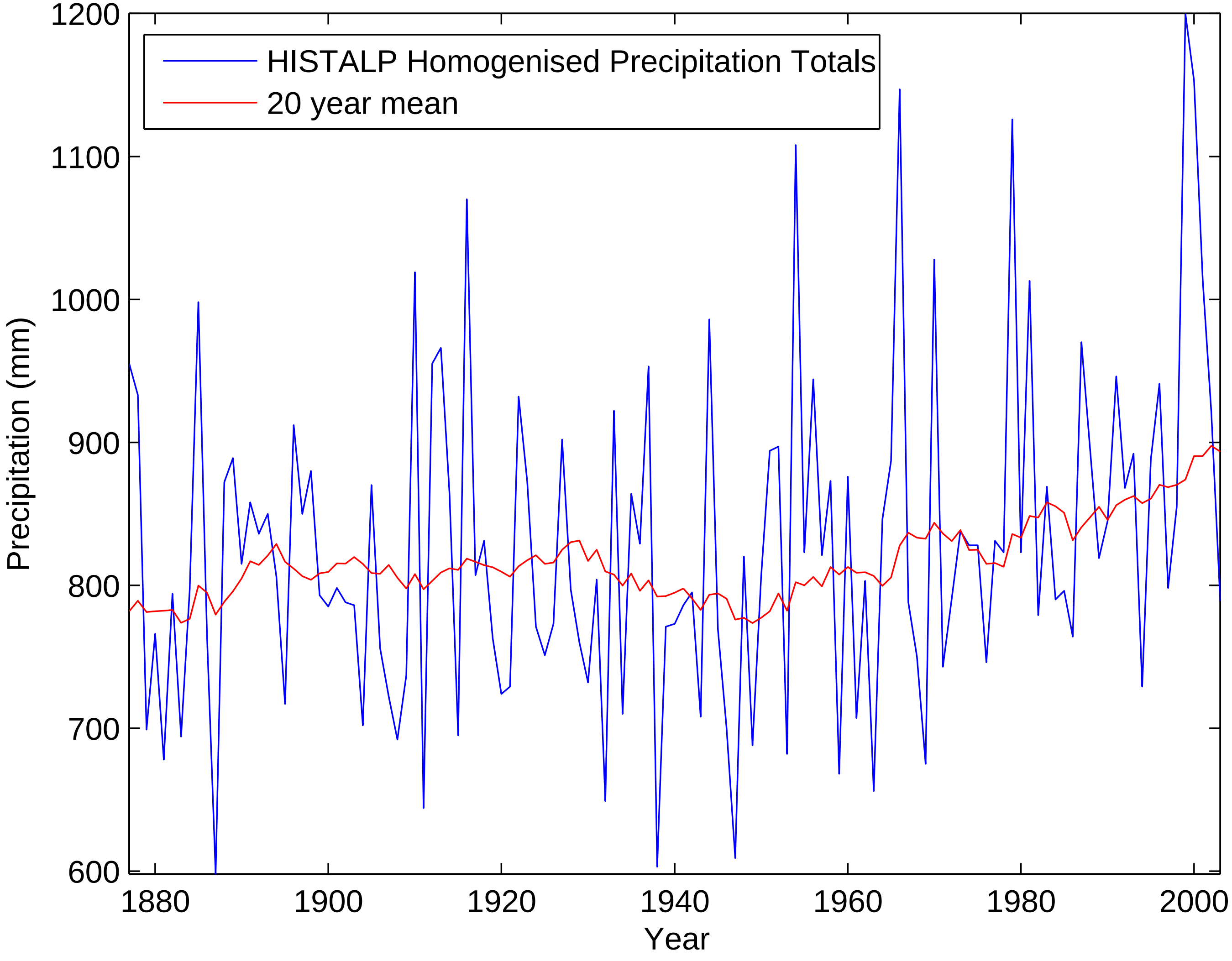


Figure 5.6: Average yearly precipitation at Innsbruck station.

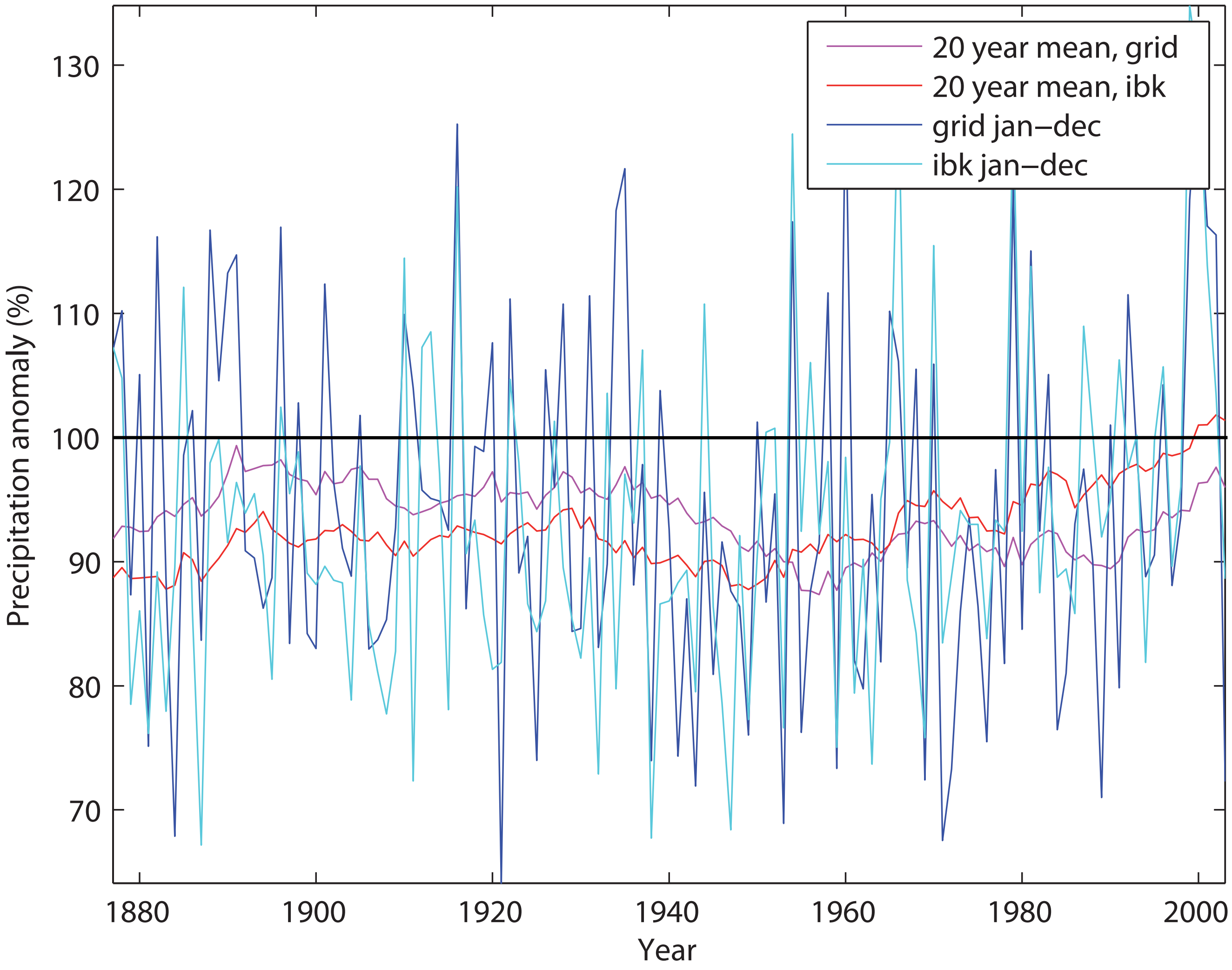


Figure 5.7: yearly average precipitation anomalies with regard to the 1970-2000 monthly mean at Innsbruck station and as grid data.

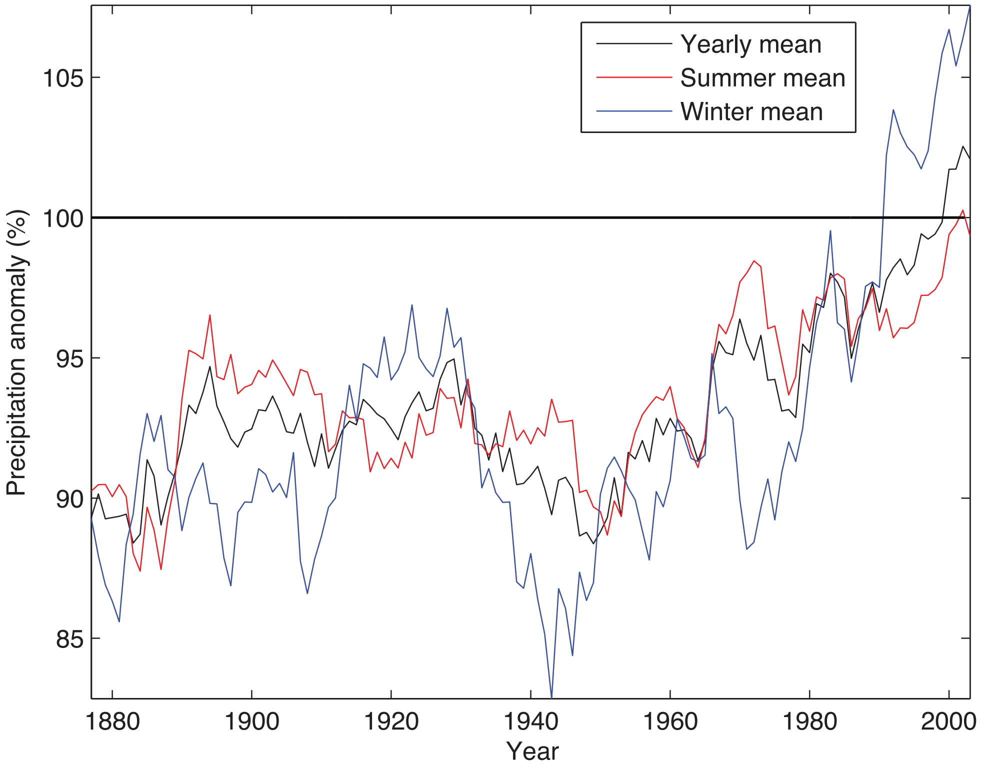


Figure 5.8: Precipitaion anomalies with regard to the 1970-2000 monthly mean in Innsbruck as yearly average, for April -September and for October - March.

entirely blocked from precipitation from the south. Orographic lift can play an important role in Innsbruck during north-westerly flow and lead to large amounts of precipitation, while conditions at Gepatschferner are dry or nearly so. Precipitation data from Innsbruck therefore does not necessarily provide a very accurate indication of precipitation patterns at Gepatschferner.

Nonetheless, it is of interest whether the trends shown in climate data are reflected in the behaviour of the glacier and the following main questions arise:

- Does the rise in temperature in recent years result in increasing mass losses at the glacier?
- Are effects of increasing precipitation discernible at the glacier?
- In light of this, can a conclusion be reached regarding the usefulness of gridded climate data for glacier reconstruction?

Table 5.1 lists summer temperature anomalies in Innsbruck and Vent, as well as at the closest grid point during each time period and also shows the corresponding volume losses per year. As expected, the largest losses in the most recent years coincide with the highest temperatures. However, comparatively large losses also occur from 1850- 1922, the coolest time period. During the 1922-1971 and 1971-1997 periods volume losses and temperature seem to correlate again nicely.

Table 5.1: Temperature anomalies at Innsbruck and Vent stations (in reference to the mean of the entire time series) and anomalies at 47°N 11°E during the summer months, as well as average annual volume loss at Gepatschferner during the time periods.

Time Period	1850 -1922	1922 - 1971	1971 - 1997	1997 - 2006
Anomaly IBK (°C)	-0.4	-0.1	0.5	1.9
Anomaly Vent (°C)	-0.3	0.0	0.4	1.6
Anomaly High Elev. Grid (°C)	-0.1	0.0	0.1	0.5
Anomaly Low Elev. Grid (°C)	-0.1	0.0	0.1	0.6
Annual volume loss (m^{3}x10^6)	-5.56	-3.72	-5.59	- 9.24

The length change measurements at the glacier tongue are of great value as they provide a year by year indication of what is happening at the glacier, rather than just a long term overview, as do the area and volume values that were gained from the DEMs. Figure 5.9 shows length change plotted against the mean temperature anomaly of high elevation gridded data. Advances and retreats of the tongue coincide well with cooling and warming periods, suggesting a strong correlation. The period of low temperatures in the 1970s is followed by an advance of the tongue 3 to 4 years later, giving some indication as to the response time of the glacier.

In 5.4 it is interesting to note that the temperature difference between station- and grid data has been increasing to up to a degree in recent years. While the warming trend is the same in both data sets, it is much more pronounced in the station data. A 1 degree difference would naturally have a significant impact on the glacier in terms of freezing level and equilibrium line altitude.

A connection between precipitation and length change can not easily be determined from Figure 5.10. Increased winter precipitation as suggested by the Innsbruck station data would have greater effects in the accumulation area of the glacier and might be discernible in a hypothetical yearly time series of volume change in the firn basin or a long term mass balance series.

Lacking such things it is impossible to say, whether the station- or grid precipitation data are more useful for glacier study and reconstruction. In contrast, the gridded temperature data clearly reflects the same trends that the Innsbruck and Vent stations show and appears consistent with length changes at the tongue.

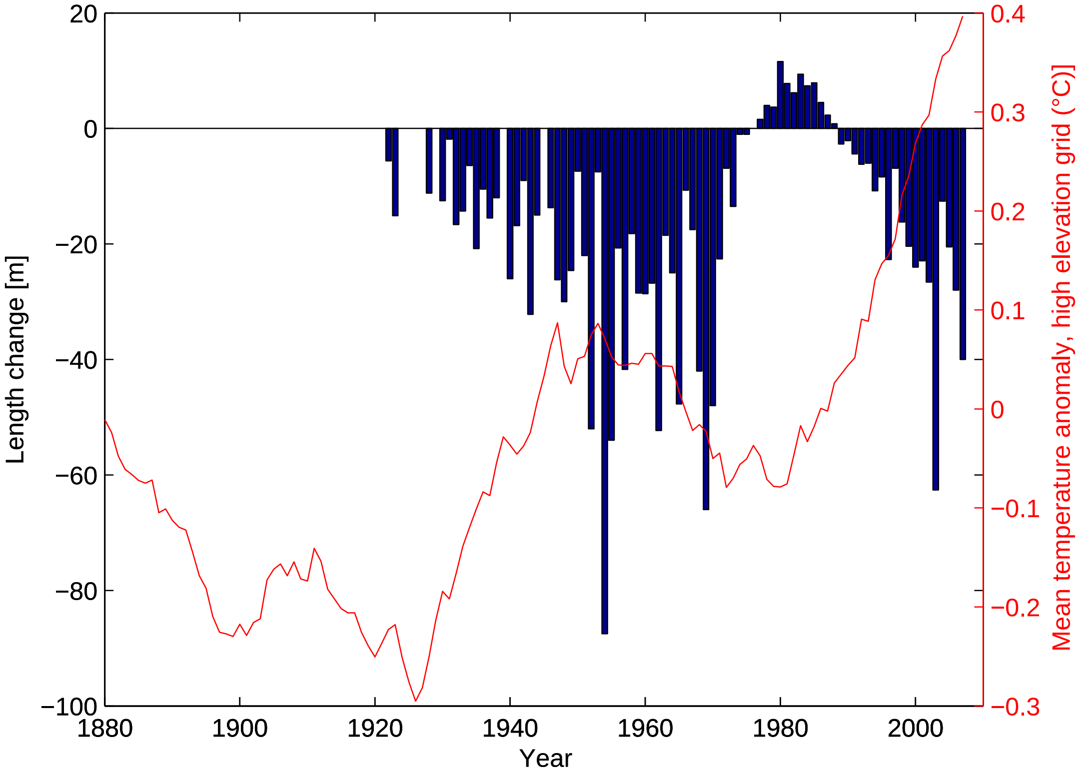


Figure 5.9: Mean temperature anomaly at 47°N 11°E and length change at the tongue.

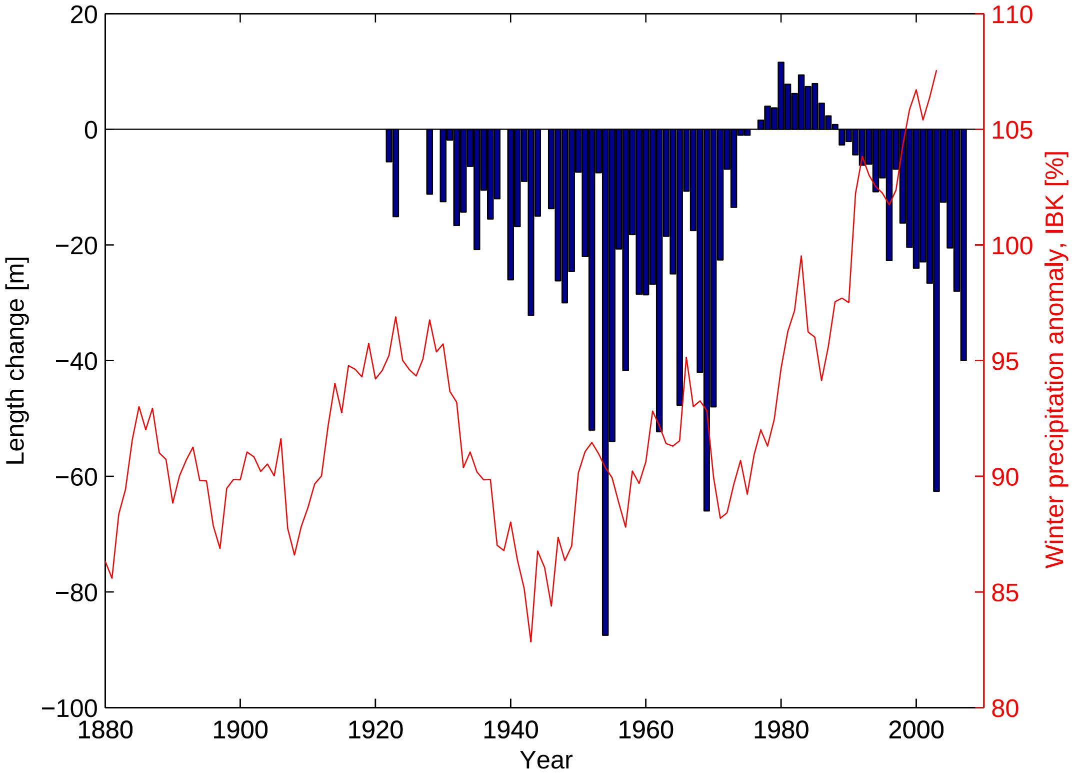


Figure 5.10: Mean winter precipitation anomaly (in reference to 1970-2000 mean) at Innsbruck station and length change at the tongue.

Chapter 6

Final Conclusion and Outlook

Looking back at our initial research questions of how Gepatschferner has changed since 1850 and whether gridded climate data is useful for glacier reconstruction, the following can be said:

- The Gepatschferner between 1850 and 2006

  Gepatschferner is retreating in length, area and volume. Apart from a brief advance of the tongue in the 1980s this trend is continuous. The rate of loss of volume is increasing faster than the rate of loss of area and losses in the upper regions of the glacier are becoming increasingly more important to overall losses. The largest losses per 50 m elevation increment occur in low elevations at the tongue. These losses are greatest in the most recent time period studied, 1997-2006, and exceed previous values by 40% and more.

- Gridded climate data and glacier study

  The conclusions that can be drawn about the usefulness of the HISTALP data in this study are limited. The gridded temperature data shows the same trends as station data in the area of the Gepatschferner although they are less pronounced. These trends correlate well with length changes at the tongue and the overall impression that the glacier is shrinking increasingly fast in the most recent years, which also mark the highest temperatures of the entire time series in both gridded and station data.

  In the case of the other most important climatic parameter in relation to the growth and shrinkage of glaciers - precipitation - the answer is not so simple. The precipitation grid, while of a higher spatial resolution than the temperature grid, does not distinguish between high and low elevation sites. The data from Innsbruck station shows a distinct increase of total yearly precipitation due mainly to an increase of precipitation during the winter months. The gridded data shows similar trends to the station data, again slightly dampened.

The increase in recent years is not reflected as clearly.

An increase in winter precipitation would affect the glacier most in its upper regions, i.e. the accumulation zone. Accordingly, no particular correlation can be determined between precipitation and changes at the tongue, the only variable regarding glacial changes of which a sufficiently long yearly time series exists. If yearly changes in volume at high elevations or mass balance data was available for a comparable time span, chances are that more satisfying results could be achieved.

Unfortunately there is no precipitation data available for Vent station in the context of HISTALP and accordingly it is not possible to say whether the gridded data might be a better representation of conditions at Gepatschferner by comparing it to a data set from a high elevation site close to Gepatschferner. Even with this option, regional topography and precipitation resulting from orographic lift would remain hard to quantify and complicate any spatial interpolation of precipitation data.

For future studies at Gepatschferner the generation of a degree-day model or similar would be of interest to see how well the behaviour of the glacier can be reproduced using the HISTALP grid data. Ideally, such a project would be able to fall back on several years of mass balance measurements to calibrate the model and carry out control runs for single years. Gepatschferner seems a good candidate to join its neighbours Hintereis-, Kesselwand- and Vernagtferner in becoming a regular subject of intense study and measuring campaigns.

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