Glacier-friendly weather? Sub-daily pressure and temperature data from the city of Bern around the mid-19th century

Master's Thesis

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1. Introduction

Over the past few decades, the influence of human activities on global climate change has raised public concerns and thus stimulated research in the scientific community. A detailed understanding of present and past climate variability and climate change is crucial to quantify and attribute the anthropogenic effects on climate. The reconstruction of past climates is dependent on a spatially and temporally dense network of past weather data. Each small piece of elapsed weather data helps to increase the understanding of the past climate and therefore to quantify and attribute the anthropogenic effects on climate. Therefore, one goal of the master thesis at hand is to contribute to a better understanding of the past climate by digitizing and validating an instrumental time series from the mid-19th century, which was measured by Daniel Gottlieb Benoit (1853) in the city of Bern, Switzerland.

The choice of the period is motivated by the fact that it lies on the boundary of the time for which no sub-daily instrumental data exists for the city of Bern. Hence, the digitized series will extend the time for which sub-daily instrumental data exists at this location. Another reason why the period was chosen is its coincidence with the last maximum extent of the glaciers in the Bernese Alps. Once processed, the series will allow the study of the weather conditions from the mid-19th century and connect them with the last maximum extent.

Additionally, the time series chosen is based upon sub-daily observations. In contrast to average data, high temporal resolution data "provide[s] the basis [for] detailed analysis of trends and variability in the mean climate and in climate extremes and the possibility to study atmospheric processes and deliver[s] insight into mechanisms that cannot be detected and addressed in average data." (Auchmann, 2012, p. 1)

This leads to the second goal of the work at hand: the study of the weather conditions which caused the mid-19th century maximum glacier extent. The reconstructed glacier length fluctuations of the Lower Grindelwald Glacier will serve as the basis for the analysis. (Zumbühl, 2016, p. 45-114) Low solar activity during the Dalton Minimum until the late 1830s and especially the major volcanic eruptions of the Unknown Volcano in the winter of 1808/09 and the Tambora in 1815 led to cold and wet conditions in Europe. A lot of work has been done to understand the relation between solar activity, the volcanic eruptions in 1808/09 and 1815 and the weather in Europe at the beginning of the 19th century. (e.g. Anet et al., 2014;

Brugnara et al. 2015) Furthermore, the relation between the Lower Grindelwald Glacier and the central European climate is well understood and analysed into detail. (e.g. Schmeits and Oerlemans, 1997) Steiner et al. (2008, p. 428) were able to show that the unusual weather conditions induced by the low solar activity and the volcano eruption leading to glacier growth via low summer temperatures and high autumn precipitation. However, the question remains, which factors led to the persistence of the extent and even additional growth of the Lower Grindelwald Glacier during the 1840s and 1850s.

A possible explanation could be a southward shift of the storm track during that period, leading to positive precipitation anomalies during the cold season and negative temperature anomalies during the warm season. By using the results of the digitized and validated pressure series from the first part of the work at hand, the weather conditions at the Bernese Alps during the years of the latest maximum extend of glaciers in the Bernese Alps will be studied. For that purpose, the digitized pressure series, together with other pressure series on a transect from northern to central Europe will be used to model the path of the storm track during the period of our measurement series, similarly as Brugnara et al. (2015, p. 1037-1039) for the years from 1815 to 1817 had. Furthermore, anomalies of the reconstructed CAP7 weather types by Schwander et al. (2017) will be used to draw additional inferences about the weather conditions in the middle of 19th century in central Europe.

Hence, the main research questions are:

– How precise were Benoit's measurements and which measurement errors did he commit?

– How well fit Benoit's measurements into the overall picture of other contemporary measurements and of the reanalysis data?

– Did certain weather conditions prevail above Switzerland during the decades before the mid-19th century maximum glacier extent?

– Can the mid-19th century maximum glacier extent be explained by the weather conditions during the 1830s and 1840s?

To answer these questions, in chapter 2.1. a brief summary of the state of thermometry and barometry during the first half of the 19th century will be given, the common measurement errors will be discussed and methods to correct these errors will be explained. Since there was only few meta data available for Benoit's measurements, a secondary well documented measurement series, measured simultaneously only a few meters away by Johann Friedrich Trechsel (Wolf, 1844a; Wolf, 1844b; Wolf, 1845a; Wolf, 1845b; Wolf, 1845c; Wolf, 1845d; Wolf, 1846a; Wolf, 1846b; Wolf, 1846c; Wolf, 1846d; Wolf, 1847; Wolf, 1848a; Wolf, 1848b; Wolf, 1848c; Wolf, 1849a; Wolf, 1849b; Wolf, 1849c), will serve as a reference to compensate for the missing meta data. Hence, in chapter 2.2. the measurements of Benoit and Trechsel will be discussed in detail; then they will be compared to each other, to additional contemporary measurements, to reanalysis data and to the outcome of the literature research from chapter 2.1.. In chapter 2.3. the methods of the weather analysis and their connection to the length of the Lower Grindelwald Glacier will be discussed. In addition, the history of research of the Lower Grindelwald Glacier and its climate sensitivity will be examined. The weather conditions at the Lower Grindelwald Glacier and patterns of European weather during the years before the glacier's maximum extend will be discussed in chapter 3. as well as the relation of the weather and the glacier. Finally, the results of the different chapters will be summarized in chapter 4. and will be put into relation to the important literature.

2. Data and Methods

The data consists of two pressure and temperature series from Bern, one main series and one reference series. Furthermore, other observations made in several locations in Switzerland and Europe will be used for the validation of the main series, as well as for the analysis of the relation between weather and glacier length fluctuations. Hence, in order to identify common sources of error, a brief overview will first be given about pressure and temperature measurements in the first half of the 19^{th} century. In a second step, since the two Bernese series were digitized for the master thesis at hand, they will be discussed comprehensively in order to validate and to assess the quality of Benoit's measurements. Finally, the history of research of the Lower Grindelwald Glacier and its climate sensitivity will be examined and the methods used to investigate the relation of weather and glacier fluctuations will be explained and discussed.

2.1. Historical temperature and pressure measurement, its correction and data processing

Böhm et al. (2008, p. 47) wrote that the introduction of national meteorological services "caused a fundamental reorganization […] from sparser individual activities typically at astronomical observatories to well organized, spatially dense and internationally coordinated networks." Nevertheless, scientific networks such as the Royal Society or the Naturforschende Gesellschaft introduced or at least suggested measuring standards and uniform instruments long before the introduction of national meteorological services. (e.g. Allgemeine Schweizerische Gesellschaft für die Gesammten Naturwissenschaften, 1823, p. 18) Hence, there already were common standards and knowledge about temperature and pressure measurements in the first half of the 19^{th} century. Therefore, in the following, the development of temperature and pressure measurements and the most common types of measurement instruments during the first half of the 19^{th} century will be introduced and discussed. In addition, common errors typical to each of the two different instruments will be discussed. For more details on the history of the barometer, the reader is referred to Middleton (Middleton, 1964). Readers interested in an exhaustive history of the thermometer and temperature measurement are referred to Chang or Middleton. (Chang, 2004; Middleton, 1966)

2.1.1. Historical length and temperature units

Although one result of the French Revolution was the adaptation of the metric system, for a good part of the 19th century, the *foot* has persisted as a unit of length. It was divided into twelve inches, which in turn were divided into twelve lines. In some cases, inches were divided into tenths or into sixteenths. Unfortunately, the length of the foot differed from country to country. Since the values of historical barometers are often given in inches, Table 1 gives an overview of the lengths of the different inches (Middleton, 1964, p. 172-174).

Since the ° Celsius and the ° Fahrenheit scale were already in use, the main difference to today's temperature units was the use of the ° Réaumur scale. Nevertheless, the conversion from ° Réaumur to ° Celsius only requires a division by 0.8 of the value in ° Réaumur.

NAME	VALUE IN MM	SUB-UNITS
SWEDISH INCH	29.69	1/10 to 1/100 inch
PARIS INCH	27.07	Lines (1/12 inch) and Points (1/4 to 1/16 line)
VIENNA INCH	26.34	Lines (1/12 inch) and Points (1/4 to 1/16 line)
RIJNLAND INCH	26.15	Lines (1/12 inch) and Points (1/4 to 1/16 line)
ENGLISH INCH	25.40	1/10 to 1/100 inch
CASTILIAN INCH	23.22	Lines (1/12 inch) and Points (1/4 to 1/16 line)

Table 1: Length of inches in different countries and their sub-units (Middleton, 1964, p. 172-174)

2.1.2. Observation Times

For certain comparisons of different locally and temporally distributed measurements, a common unit of time was necessary. The Gregorian calendar had already been adopted during the first half of the 19th century in the countries where the measurements took place.

Nevertheless, day times were measured in local solar time and therefore needed to be converted into a time that enables comparison with each other, model and reanalysis data, as well as data from the more recent past. Hence, if necessary, the time information was translated into UTC with the formula:

$$t_{UTC} = t_{loc} - \lambda \cdot \frac{24}{360}$$

wherein λ is the longitude of the station in degrees east, t_{loc} is the local time and t_{UTC} is the UTC time.

2.1.3. Thermometers during the first half of the 19th century

At the beginning of the 19th century, two things were required to build a thermometer that functioned correctly: two fixed points with a constant temperature and a thermometric substance that expanded with temperature in a linear manner.

By the end of the 18th century, there was a strong consensus on the temperature of the freezing point of water and the steam point as fixed points, though over the course of the first half of the 19th century, both remained under discussion with regard to the methods of how to reach the exact points when calibrating a thermometer. (Chang, 2004, p. 47-56)

The correct thermometric substances also remained under discussion. Mercury, atmospheric air and ethyl alcohol were the three contenders in the quest for a substance indicating the true temperature. By mixing different shares of melting ice and boiling water, the Genevan Jean-André De Luc in 1772 was able to show that mercury expanded more linearly than any other liquid he had tested. De Luc also experimented with alcohol thermometers but came to the conclusion that alcohol does not expand as linearly as mercury. Furthermore, the alcohol-water emulsion expands dependent on its alcohol concentration, which in De Luc's day was hard to measure precisely. Therefore, it was difficult to produce temporally and geographically separate alcohol thermometers that were comparable to each other. De Luc's conviction that mercury was by far the best thermometric substance had gained wide acceptance around the year 1800. However, De Luc's method was attacked by representatives of the Caloric Theory, which was the underlying theory of chemistry and physics in the decades around that time.[1] De Luc's assumption that the amount of heat needed to warm the same body of matter by 1 degree was constant independent of its temperature was especially questioned. However, Calorists assumed that the action of heat was most purely manifested in gases. Chang therefore concluded in his book that the experiments of Henri Victor Regnault, who was able to prove that in contrast to mercury thermometers, air thermometers were more comparable to each other, eventually led to the prevailing of the air thermometer in 1840s over the mercury thermometer because "the spirit thermometer had been discredited beyond rescue" (Chang, 2014, p. 79) before. Middleton, on the other hand, stated in his monography

[1] The reader interested in the history of the caloric theory is referred to R. Fox or S. Lilley. (Fox, 1971; Lilley, 1948)

from 1966 that mercury and alcohol remained the standard thermometric substances in meteorology until well into the 20th century, whereby mercury was much preferred due to De Luc's experiments. (Chang, 2014, p. 60 – 84; Middleton, 1966, p. 124-132)

Another reason for inaccurate temperature measurements was the location of the thermometer and its inaccurate protection from exposure to direct or reflected radiation. In his book on the history of the thermometer, Middleton stated that from the 1760s onwards, the question of where to site a thermometer was led between those who believed the thermometer should be located at some distance to any building and those who were in favor of hanging the thermometer near the northern wall of a house. Different experiments over the course of the centuries before had made it clear that the exposure of the thermometer to direct sunlight, or its location inside a building, led to a distortion of the results of meteorological temperature measurements. Furthermore, in 1817, Jean Baptiste Joseph Fourier published an exposition of the effect of radiating surroundings on a thermometer. Although during the first decades of the 19th century there was increasing awareness of the thermometer's need to be sheltered from a radiation-emitting environment, the idea that thermometers are affected by radiation only if the object is located close enough cropped up throughout the 19th century. Therefore, the first documented examples of protective constructions for the thermometer from the 1830s and 1840s mainly served to protect the thermometer from direct sunlight and precipitation (Middleton, 1966, p. 208-215).

In a talk that he gave in 1859, Heinrich Wild said that contemporary meteorology textbooks only stated that the air temperature is best measured by hanging the thermometer 10 feet above the ground at a northwards open space in the shadow. Wild criticized such directives as too vague to achieve comparable results and listed the sources of inaccuracy: the heat exchange between the thermometer and its surroundings via radiation, the heat conductivity of the supporting structure, the circulation of the air around the thermometer and the construction thermometer itself. (Wild, 1860, p. 92-101) This contemporary attempt to improve meteorological temperature measurements reinforces the assumption that in the first half of the nineteenth century, thermometers in general were not protected sufficiently enough from indirect and scattered radiation, even though awareness of the problem was already present.

2.1.4. Error of the thermometer

If the contemporary observer has not stated what kind of thermometer they have used for their measurements, the standard for the first half of the 19th century is assumed. This means that the two fixed points for calibrating the thermometer were water at the freezing point and the steam point both estimated correctly. Since around 1800, De Luc's view that mercury was by far the best thermometric substance we assume that in general mercury thermometers have been used.

De Luc's original results from 1772 indicated that the mercury thermometer tends to underestimate the real temperature the closer the reading gets to 50° C. According to De Luc's experiments, the error at 50° C occurred around 1.75° C. In the negative spectrum of the Celsius scale, mercury thermometers tended to overestimate the true degree of heat according to De Luc. (De Luc, 1772, p. 301)

Furthermore, De Luc's experiments showed that according to the alcohol concentration, alcohol thermometers underestimated the true temperature value even more than mercury thermometers. At 50° C on the mercury thermometer, for example, the different alcohol thermometers tend to underestimate the mercury thermometer up to 6.25° C. (De Luc, 1772, p. 326)

Other, more recent studies show different departures from linearity of mercury and alcohol in thermometers. I. Rivosecchi, for example, stated in his paper that combined with the irregular expansion of glass, the overall deviation for some types of mercury thermometers only underestimates the real value by 0.11° at 40° C and overestimates it by 0.17° at -20° C. (Rivosecchi, 1975)

In accordance with the literature concerning the location and protection of the thermometers during the first half of the 19th century, we assume that thermometers measuring the air temperature were protected from direct sunlight, but were exposed to indirect or scattered radiation to different extents. This means that the thermometer was directly attached to a north-facing wall, attached to a suspension device a few centimeters from a north-facing wall or standing on its own several meters away from the nearest building, protected from direct solar radiation and precipitation.

Böhm et al. had the opportunity to compare a historical temperature measurement station from Kremsmünster, located in an unheated meteorological observing oriel with a modern TAWES[2] station located a few meters away in the garden of the building. Since the historical thermometer was not located outside at a north-facing wall, as Benoit's and Trechsel's thermometers presumably did, we cannot consider their results for estimating quantitative deviation values. However, we can observe trends for thermometers attached to north-facing walls at different times of the day, depending on the alignment of the building. According to Böhm et al., thermometers located at or close to north-northeast facing walls tend to overestimate the real temperature in the morning. In particular, temperatures measured between 6 AM and 8 AM during the months of April to September are affected. Thermometers located at or close to north-northwest facing walls are affected the most during evening hours, with a peak at 4 PM to 6 PM during the same months. Thermometers located at or close to strictly north-facing walls show both deviation peaks – morning and evening – only less pronounced. Of course, these results are strongly dependent on the latitude of the station and the surrounding of the relevant building. (Böhm et al., 2010, p. 50-53)

With regard to seasonal deviations, Michael Chenoweth came to similar conclusions for unscreened thermometers. However, his findings leave aside the different effects of different daytimes of nonstandard thermometer exposure and only reflect seasonal averages. Chenoweth used various sources from Europe and North America to estimate the non-climatic effects of non-standard thermometer exposure. He showed that in comparison to free-standing screened thermometers, the maximum temperature deviation of unscreened thermometers with little protection from scattered and reflected radiation is at its highest during the summer months, reaching deviations of up to approximately +1.5° C. Unscreened but well-protected thermometers situated under an eave or a porch, on the other hand, tended to underestimate the temperature in comparison with free-standing screened thermometers. For minimum temperatures, Chenoweth found a difference between unscreened thermometers attached directly to a north-facing wall, which generally showed higher temperatures – up to approximately 1° C – than unscreened thermometers attached to a suspension device on a north-facing wall, which showed only minor deviations from a free-standing screened thermometer. This bias is most likely the result of heat stored by the wall the thermometer is attached to. A special case in Chenoweth's study points in the same direction: unscreened thermometers attached to a north-facing wall located under an eave or a porch overestimate

[2] TAWES stands for Teilautomatische Wetterstation and is the standard weather station in Austria at the present day.

the minimum temperature even more than without an eave or a porch, compared to thermometers under a free-standing screen. The eave or the porch apparently acts as a barrier for ascending warm air, warmed up by the wall which has stored the heat previously. Unfortunately, there is no winter data for this last category (Chenoweth, 1993, p. 1793-1795).

In summary, it can thus be said that we cannot calculate exact temperature deviations without knowing the exact circumstances of the historical measurements. We only can approximate the direction of the error dependent of the season and the time of day.

2.1.5. Barometers during the first half of the 19th century

In the first half of the 19th century, different types of mercury barometers were employed for stationary pressure observations. They can be divided into three different main categories: the fixed-cistern barometer, the Fortin barometer and the siphon barometer. (Brugnara et al., 2015, p. 1031-1032)

The fixed-cistern barometer is composed of a cistern filled with mercury, which is exposed to the air. A thin glass tube, closed at the upper end, where a vacuum is created, is vertically immersed into the mercury. Either on the glass tube itself or fixed externally to it there is a scale, from which – in some cases with the help of a Vernier – the pressure can be read off. Because of the hydrostatic equilibrium between the mercury and the air, a change of pressure in the air causes a change of the mercury in the tube and therefore a smaller change in the cistern as well. The dimension of the change in the cistern is dependent from the ratio between the diameter of the cistern and the tube. Therefore, a correction needs to be applied to readings made on the tube to take this level-change into account. (Brugnara et al., 2015, p. 1032)

In the case of the Fortin Barometer, this correction is not applied to the readings, but to the level of the mercury in the cistern itself. The mercury is set to zero (indicated by an ivory pin above the surface of the mercury) by a screw which pushes against a leather bag containing the mercury. Nicolas Fortin was one of the most important persons in the course of the development of the barometer. Around the year 1800, he invented the Fortin Barometer, which was a portable and precise barometer. Its design endured with almost no changes for the following 150 years (Brugnara et al., 2015, p. 1032; Turner, 1983, p. 234; Knowles Middleton, 1964, p. 210-211).

Rather than having a cistern, siphon barometers are u-shaped glass tubes with the closed vacuum-containing end on one side. On the other end, a shorter and open leg exposes the mercury to the air. The level of mercury in both ends is needed to obtain the pressure value. Owing to its rather impractical use, the siphon barometer was often criticized by contemporaries. (Brugnara et al., 2015, p. 1032)

Different corrections to the readings of the barometer are necessary due to thermal expansion of mercury and the change in gravity with latitude. Furthermore, for today's use, the measurement units need to be identified and converted into hPa. Additionally, the pressure values need to be reduced to mean sea level as pressure declines with altitude. In the following these adaptations will be discussed.

2.1.6. Correcting pressure values for temperature

As discussed above, J. A. De Luc has experimented with the thermal expansion of mercury, in the course of the mid-18th century research of barometric hypsometry. He came to the conclusion that if the barometer stood at 27 Paris inches, the difference in temperature between melting ice and boiling water would lead to a difference of exactly six lines (18.045 hPa). In comparison, using the modern standard formula for reduction to 0° C (see below), the difference between 0° Cand 100° C at a barometer stand of 27 Paris inches yields 17.735 hPa.
In 1817, P.L. Dulong and A.T. Petit made another huge step determining the thermal expansion of mercury. They came to the conclusion that the mean dilatation of the volume per degree Celsius was 1/5550. Translated into hPa, that yields a result of 17.393 hPa for the difference between 0° C and 100° C at a barometer stand of 27 Paris inches. The main difference between the results of De Luc and Dulong and Petit was the accuracy. While Dulong and Petit considered their results accurate for several one-thousandths, De Luc considered his results accurate for several tenths of the mean dilatation per degree Celsius. In 1847, H.V. Regnault refined these results and in 1883, O. Broche at the "Bureau International des Poids et Mesures" again made small adjustments, but the differences to the results of Petit and Dulang remained relatively small. (Middleton, 1964, p. 178-180).

Also debated was the effect on the measurements of the thermal expansion of brass and glass where the scale was written on most barometers at that time. F. Baily published a correct formula and tables in 1837. (Middleton, 1964, p. 180)

Another problem with regards to the correction for temperature was the assumption that the thermometer attached to the barometer was considered or hoped to show the average temperature of the mercury in the barometer. This assumption was particularly problematic in the case of sudden temperature changes. In 1902, R.T. Ormond was able to show that after a fire had been lit in a cold room, or a window opened in warm one, differences of up to 3° F occurred, which in turn translated in an error of 0.01 inches in the corrected height of the mercury column. Ormond warned that particularly morning readings at stations in colder climate might be biased (Middleton, 1964, p. 181).

In fixed cistern barometers, the mercury rises in the cistern when it falls in the tube and vice versa, so there are two ways to properly reduce the pressure to a standard-temperature. In one case, a standard-scale is used and afterwards, the correction is calculated. In that case, the point on the scale at which the barometer has initially been adjusted must be known. In the other case, an appropriately contracted scale is fit to the barometer. In both cases, the ratio between the cross section of the tube and the cistern must be known; however, the first sound attempt to correct fixed-cistern barometers for temperature was made by C. Jelinek in 1867 for a barometer without a contracted scale. The problem of the correction to a standard temperature for fixed-cistern barometers with contracted scales was not solved properly until 1914 (Middleton, 1964, p. 182-183).

Since all the pressure series used in the work at hand were at least partially measured before 1855, all the corrections of a fixed-cistern barometer to a standard temperature must have been biased. Jelinek, for example, has calculated that someone who first did the correction for temperature and then for the level-change in the cistern made a mistake of at least 0.075 hPa for -7.5° C and -0.534 hPa for 30° C, assuming the ratio between the cross section of the tube and the cistern was infinitely small. The closer to 1 the ratio between the cross sections gets, the bigger the room for mistakes gets. (Jelinek, 1867, p. 662)

Historical pressure series can be divided into three categories, each with its own problems. In the first case, the correction for temperature was done by the contemporary user of the barometer himself and has stated this. Since the meta data rarely reveals the formulas and tables employed by contemporary users to reduce the pressure values to 0°, the amount of the bias often remains uncertain.

In the second case, the contemporary user of the barometer wrote down the pressure values without stating whether the values were reduced to 0° or not. Since the time covered by the work at hand is decades after science began to deal with the problem of thermal expansion of mercury in barometers, it will be assumed that the values were reduced to a standard temperature. Often, 0° C was the temperature the pressure values were reduced to, but there is still uncertainty about the choice of temperature chosen by the contemporary user of the barometer.

In the third case, the contemporary user wrote down pressure values together with the temperature of the barometer. In this case, the pressure values were reduced by the writer with the formula

$$L_0 \;=\; (1-\gamma T)L_{mm}$$

where L_0 is the observation reduced to 0° C, γ is the thermal expansion coefficient of mercury at 0° C ($1.82\times10^{-4}K^{-1}$), T is the temperature of the barometer in ° C and L_{mm} is the original observation in mm of mercury. (Source: Teaching material from Climatology III: Cimate variability and change)

Today the reduction to 0° C is stated by international standards. However, since the thermometer which measured the temperature of the mercury in the barometer could have been biased, even these results do not necessarily represent the true temperature correction.

Additionally, there is an uncertainty for fixed-cistern barometers which grows the higher the temperatures are. If the ratio between the cross sections of the tube and cistern or the neutral point of the barometer are unknown, the error could not be estimated exactly.

2.1.7. Conversion of the pressure values to hPa

After the historical pressure readings were translated from inch to mmHg and corrected for temperature, they were converted from mmHg to hPa by using the hydrostatic equation

$$P_0 \;=\; \rho g_n L_0 \;\cdot 10^{-5}$$

where P_0 is the absolute pressure in hPa, ρ = 1.35951×10^4 kg m^{-3} is the density of mercury at 0°Celsius, g_n = 9.80665 m s^{-2} is the standard gravity acceleration and L_0 is the barometric reading in mmHg. (Source: Teaching material from Climatology III: Climate variability and change)

2.1.8. Correcting pressure values for standard gravity

Since gravity acceleration varies with latitude and altitude based on the geographical coordinates of the barometer, further correction for local gravity is needed:

$$P_n = \frac{g_{\phi,h}}{g_0} P_0$$

where P_n is the pressure corrected for local gravity, g_0 is once again the standard gravity acceleration and P_0 is the absolute pressure. $g_{\phi,h}$, the local gravity can be estimated with the formula:

$$g_{\phi,h} = [9.80620 \cdot (1 - 0.0026442 \cdot cos2\phi - 0.0000058 \cdot cos^2 2\phi) - 0.000003086 \cdot h]$$

assuming flat terrain around the station. ϕ stands for the latitude and h is the altitude of the station in meters above sea level. (Source: Teaching material from Climatology III: Climate variability and change)

2.1.9. Reduction to mean sea level

For comparability purposes, pressure values from different altitudes must be converted to a common altitude, the altitude of the mean sea level. The following formula was applied to the different pressure values:

$$SLP = P_n \cdot exp\left(\frac{\frac{g_{\phi,h}}{R} . h}{T_S + a \cdot \frac{h}{2}}\right)$$

where SLP stands for Sea Level Pressure, P_n is the station pressure with all the corrections applied from above, $g_{\phi,h}$ again stands for the local gravity, R = 287.05 J kg^{-1} K^{-1} is the gas constant for dry air, a = 6.5×10^{-3} K m^{-1} is the standard lapse rate of the fictitious air column below the station, T_S is the outside temperature at the station in degrees Kelvin and h again is the altitude in meters above mean sea level. (Source: Teaching material from Climatology III: Climate variability and change)

Even though it is a standard procedure to apply this conversion, it comes with difficulties. Just like the ocean, the atmosphere has its ebb and flow and produces rhythmic semidiurnal and diurnal pressure variations on the surface. This atmospheric tide is the strongest at low latitudes and decreases with increasing latitude (Blancq, 2011, 306-307). The red line in Figure 1 shows the diurnal pressure cycle for Bern using hourly averages of pressure measurements from the station Bern Bollwerk from February 26th 1991 to November 8th 2017 (Source: MeteoSchweiz). The range of the diurnal cycle in Bern is approximately 1.2 hPa and lies between 954.0 and 955.2 hPa. However, the problem becomes evident when looking at the black dotted line, which shows the same data only reduced to mean sea level using temperature measurements from the same station. The range of the SLP average values is with approximately 2.3 hPa between 1013.6 and 1015.9 hPa — almost twice as high as in the case of station pressure. Furthermore, the expansion of the scale is not uniform. The range of the curve becomes slightly compressed during the night time and expanded during the day time.

This problem must be considered when comparing values from different daytimes. Since early instrumental temperature measurements tended to overestimate the real temperature value during the day time the problem becomes even further enhanced.

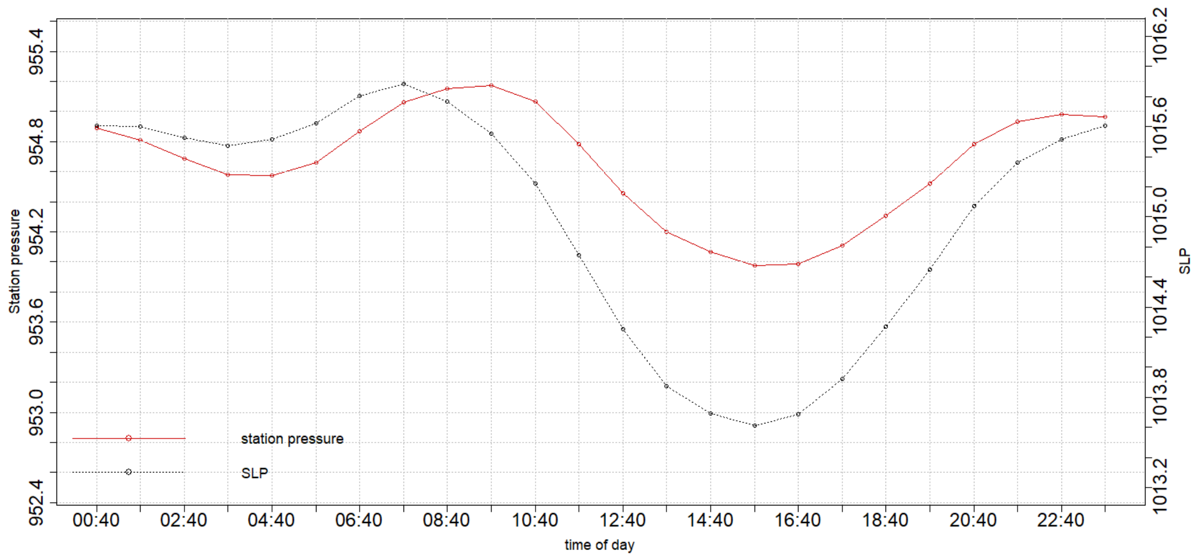

Figure 1: Comparison of hourly averaged station pressure and sea level pressure. Red line: Station pressure from Bern Bollwerk from February 26th 1991 until November 8th 2017 averaged over time of day; black dotted line: Sea level pressure reduced with outside temperature from the station Bern Bollwerk from February 26th 1991 until November 8th 2017. (Source: MeteoSchweiz)

2.1.10. Error due to capillarity

If a pipe is dipped into water, the surface of the water within the pipe will be higher up than the surface of the water around the pipe. Furthermore, the surface within the pipe will be concave. The opposite is true for mercury. The surface within the pipe will be convex and lower than the surface around the pipe. The reason for this phenomenon is called capillarity and is described with the following formula:

$$h = \frac{2\sigma \cos \Theta}{r \rho g_{\phi,h}}$$

where h denotes the difference in height between the surfaces within and around the pipe. σ is the surface tension of the relevant fluid, Θ the contact angle of the fluid within the pipe with the pipe, r the inner radius of the pipe, ρ the density of the relevant fluid and $g_{\phi,h}$ again the local gravity. (Eichler et al., 2016, p. 89-90)

In the case of barometers in which mercury was used capillarity results in an under estimation of the true pressure. On the one hand because the surface of the mercury within the pipe is lower than around the pipe and on the other because we can't be sure if the contemporary user did read the pressure at point where the mercury touches the glass or at the top of the meniscus, where it would be correct according to the formula above.

However, at the beginning of the 19th century the problem of capillarity was known. For example, in 1776, Henry Cavendish published a table of corrections for capillarity, which his father had obtained through experiments (Cavendish, 1776, p. 382). In the following decades, progress was made with the theory of capillarity, mainly by John Leslie, Thomas Young and Pierre Simon Laplace, who published one of the first of many tables for capillarity correction based on theory in 1812. Nevertheless, Laplace assumed for his table that the shape of the meniscus and therefore the angle of contact, are the same in vacuum as in air (Laplace, 1812, p. 77). This assumption is problematic for thin tubes. While the theory of capillarity experienced only minor modifications after Laplace, the capillarity-correction for mercury barometers in practice remained a problem. Another critical factor was discovered by John Frederic Daniell, who experimented with boiled and unboiled tubes. He found out that the capillarity depression for mercury was smaller if the tube was boiled before it was filled with mercury. Furthermore, in 1842, A. Bravais showed how to measure the angle of contact. However, the problem remained unsolved, in that the surface tension of mercury was unmeasurable within a barometer and could not be supposed invariable even within the same barometer (Middleton, 1964, p. 188-192).

For the work at hand, this means that capillarity could not have been corrected correctly by contemporaries. Neither it is possible to correct the historical series today. As there is no series in use for the work at hand, where the angle of contact is noted separately, nor it is possible to know the surface tension of the mercury in retrospective. Nevertheless, if meta data reveals the width of the tube, the effect of the capillarity on the results may be approximated.

2.1.11. Breakpoint-detection

Since Trechsel's series did not cover the whole timespan of Benoit's series, it was not possible to detect artificial breaks only from the comparison between the series. Neither did

metadata reveal breakpoints in the different series of Trechsel and Benoit. Hence, the absolute and the relative RHtest (Wang 2008a; Wang 2008b; Wang et al. 2007; Wang et al. 2010) were applied to the different measurement series. Because of their relative proximity and the timely coverage the three long-time temperature and pressure series from Geneva, Basel and Gr. St. Bernhard from DigiHom (Füllemann et al., 2011) have been used for the relative RHtest. For testing Benoit's afternoon values, the 3 PM LST values from the reference series have been used. For Benoit's morning measurements, all the morning measurements from the reference series have been used. In a first step, the absolute RHtest was applied to each reference series in order to detect breaks in the reference series. In a second step the relative RHtest on Benoit's series has been applied with each reference series.
An artificial break in Benoit's series was considered to be true if the absolute RHtest applied to the reference series did not identify a significant change-point at the same point in time and either the relative RHtest gave a Type-1 (significant without meta data) change-point of which its $PT_{\max}$ statistic is larger than the corresponding upper bound of the 95% confidence interval of the $PT_{\max}$ percentiles, or the relative RHtest gave a Type-1 change-point of which its $PT_{\max}$ statistic lies within the corresponding 95% uncertainty range. Additionally, this conditions had to be fulfilled for at least two different reference series locations for the morning and afternoon measurements within a range of 30 days.

2.2. The Bernese series

Benoit did not mention what type of instruments he used to measure the air temperature and the atmospheric pressure. Neither did he provide information of how exactly he proceeded to carry out his measurements. Nevertheless, because of the timely and geographic proximity of the series of Benoit and the well-documented series of Trechsel, it will be possible to draw conclusions about the quality and the error of Benoit's series by comparing it to Trechsel's series. Therefore, in a first step, the circumstances of the measurements in general will be discussed in order to identify accordances and differences between the series of Trechsel and Benoit. In a second step, in order to assess the quality and the errors of Benoit's series, they will be compared to Trechsel's series and put into the context of measurements from other neighboring stations, reanalysis data and the literature about historical temperature and pressure measurements.

2.2.1. Connections, accordance and differences

The only information Benoit gave about his measurements, was that he carried them out twice a day at 6 AM and at 2 PM in the second floor of a house at the Kirchplatz in Bern (Benoit, 1853, p.1), which most likely corresponds with the Benoit house at the present-day address Münstergasse 28 in Bern (Weber, 2016).

Therefore, additional means have to be consulted in order to gather more information about the circumstances of Benoit's measurements. One approach to gain more information about Benoit's measurements will be the assessment of Trechsel's series, for which there exists more information concerning the thermometer and barometer used. Trechsel's measurements took place just across the Münsterplatz at house number 317, which corresponds to the present-day address Herrengasse 1. (Source: Stadt Bern, Amtliche Vermessung) From January 1848 onwards, Trechsel's measurements were relocated about 150 meters further to the northeast to the house number 174, which corresponds to the present-day address Kramgasse 12. (Source: Stadt Bern, Amtliche Vermessung) In both cases, the measurements took place in the second floor. Hence, although there must have been differences due to the surrounding building structure, both Trechsel and Benoit were measuring the same weather conditions (Wolf, 1844, p. 169; Wolf, 1848, p. 142).

Trechsel did his measurements at 9 AM, 12 AM, 3 PM and 9 PM, with the exception of January 1844, when he measured at 10 PM instead of 9 PM. For the comparison with Benoit's measurements we only consider the measurements at 9 AM and 3 PM since for these hours the difference to Benoit's measurements was the smallest in terms of timely difference.

In Figure 2 the combined morning and afternoon measurements for pressure and temperature for both Benoit and Trechsel are depicted. For temperature in particular, it can be noted that if there was data available from Trechsel, it was generally as well from Benoit. In the pressure measurements, there were only few gaps in Benoit's data when there was data available from Trechsel. In general, there was less data available for the comparison of the summer values, since three times the data of the whole August was missing in Trechsel's data. Furthermore, since Trechsel's recordings began in January and ended in September, there was also less data for the months of October, November and December.

It can be noted that there were fewer data gaps for temperature than pressure. In Benoit's measurements, there were 66 missing values (NA's) for temperature, which corresponds to 0.58 percent of the data and 137 NA's for pressure recordings, which corresponds to 1.21 percent of the data. Nevertheless, it has to be said that only 77 of the 137 missing pressure values were actual measurement gaps. The other 60 missing pressure values were the result of the process of reduction of the pressure values to mean sea level for which air temperature information was needed. Furthermore, it has to be noted that with 77 NA's, the most NA's in Benoit's pressure series were situated in the first quarter. The same is true for Benoit's temperature series, where 46 NA's were situated in the first quarter.

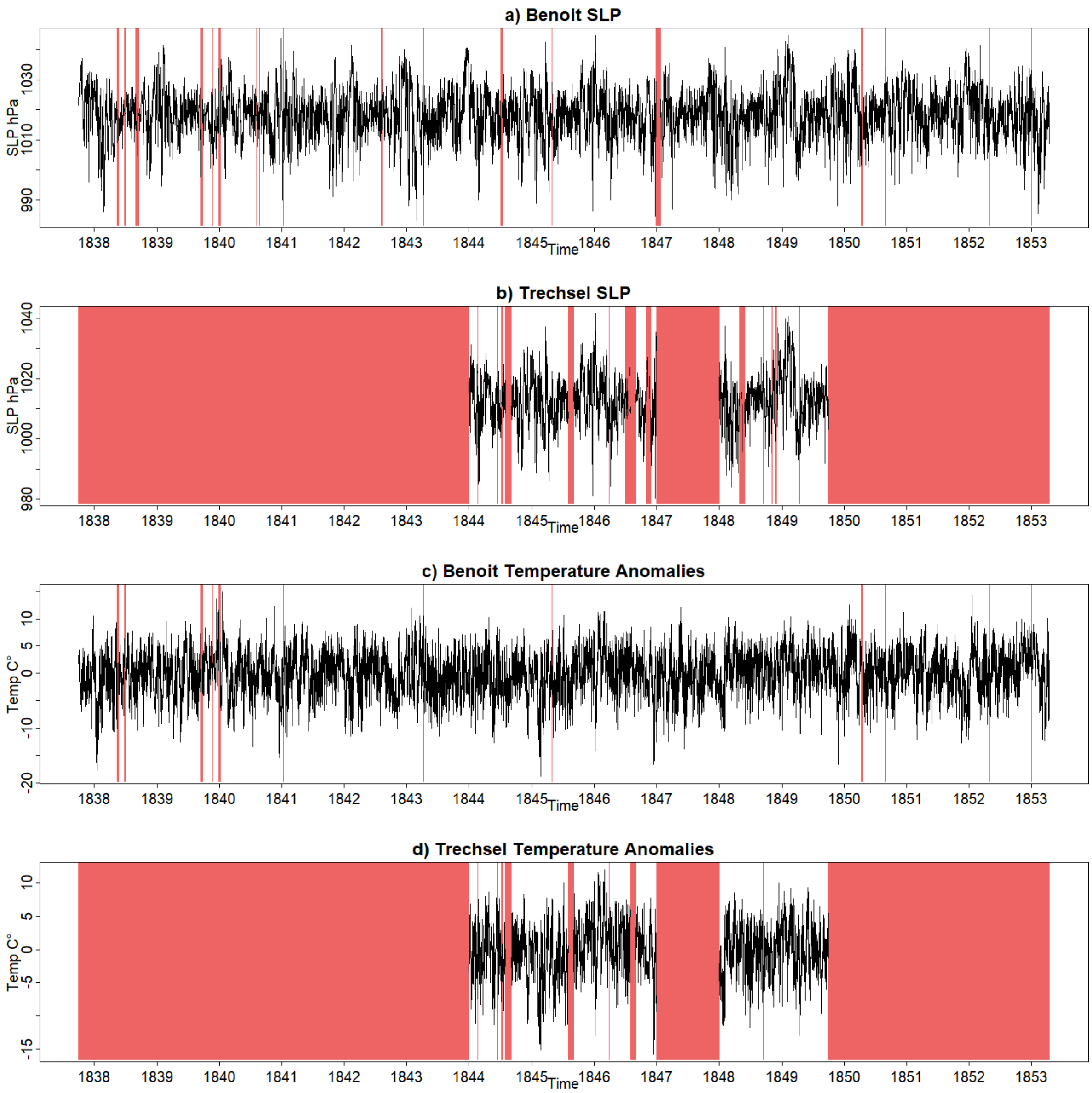

Figure 2: Comparison of Benoit's and Trechsel's measurements with red areas indicating missing data. a) Sea Level Pressure measured by Benoit; b) Sea Level Pressure measured by Trechsel; c) Temperature measured by Benoit with seasonality subtracted; d) Temperature measured by Trechsel with seasonality subtracted.

If the three times data for a whole month and the one time for a whole year was missing was disregarded only 8 temperature values and 90 pressure values were missing. The same problem as in Benoit's case with lost pressure information due to reduction to mean sea level of the pressure data occurred in Trechsel's data. Nevertheless, it was of much less consequence as only eight temperature values were missing in Trechsel's series.

Another important point is the biography of the two authors of the series. Were they trained scientists? Did they carry out their measurements professionally? Did they know each other and possibly could have influenced each other in the ways they did their measurements? In order to answer such questions, Daniel Gottlieb Benoit and Johann Friedrich Trechsel will be shortly introduced to get an understanding of who they were and how this could have affected their results.

Daniel Gottlieb Benoit was born in Bern in 1780. He grew up in Brandis, where his father Abraham Benoit was provincial governor from 1788 to 1794. Before he moved back to Bern, he received his education from a private tutor. In Bern he attended the Progymnasium and afterwards studied Theology. Nevertheless, the political circumstances around the Helvetic Republic made professional prospects of becoming a clergyman bleak and so Benoit decided to become a medic. He studied medicine in Bern, Jena, Bamberg, Würzburg and Paris and was conferred a doctorate in 1805. In 1806, he returned to Bern. In 1815, he became a doctor of medicine at the Inselspital, where he went as far as to become vice medical director. Despite his good reputation, the administration divested Benoit of his office in 1831. Henceforth, he left the medical profession and engaged himself in different councils, commissions and directions related to education, poverty reduction and public life. He lived with his parents, later with his older brother and was never married. From 1815 to 1832, he was a member of the Naturforschende Gesellschaft in Bern, where he served as the secretary in 1816 and 1817 and as the president in 1823. (Hugendubel, 1854, p. 10-21; Wolf, 1854, p. 227-230; Graf, 1886, p. 172).

Johann Friedrich Trechsel was born in 1776 in Burgdorf as the youngest child of a butcher. He grew up under rather poor circumstances and moved to Bern on his own at the age of 15 to study Theology and Mathematics. Before he founded the Wissenschaftliche Lehranstalt in Bern with Emanuel Zeender in 1800, he worked as a teacher at the boys' orphanage and as a pastor in Aubonne and Morges. With the reorganization of the school system in 1805, the Wissenschaftliche Lehranstallt became redundant, but Trechsel became a professor for mathematics and from 1812 onwards for physics at the predecessor of the University of Bern, the Akademie. He was involved in the triangulation of the Canton of Bern and in the planning of the Jura water correction. Furthermore, he was a member of both the Naturforschende

Gesellschaft in Bern, in which he served as president during the years 1821 and 1822 and the Schweizerische Naturforschende Gesellschaft. In the latter, he served in the meteorological commission, where he organized and compiled the coordinated meteorological measurements in different locations across Switzerland. He retired in 1847 and died in November 1849. Trechsel was married from 1803 until his death and only survived one of his six children (Trechsel, 1884, p. 141-149; Graf, 1886, p. 172; Zürcher, 2013).

In summary, it can be said that Benoit most likely did his measurements in an amateur capacity. At the time he started his measurements, he already had left the Naturforschende Gesellschaft Bern and therefore most likely did not have a mandate to collect meteorological data from the Naturforschende Gesellschaft in Bern. Nevertheless, as a highly qualified medic and former member of the Naturforschende Gesellschaft, Benoit was used to scientific work and most likely was aware of the important contemporary standards of meteorological measurements. The sheer size of a project like collecting weather data for more than 15 years twice a day indicates that he didn't do his measurements uninformed. Trechsel, on the other hand, was a trained scientist and served in the meteorological commission of the Schweizerische Naturforschende Gesellschaft, on whose behalf he organized and compiled coordinated meteorological measurements across Switzerland. Therefore, he surely was well informed about contemporary standards of measuring air temperature and atmospheric pressure. Furthermore, his instruments were founded by the Naturforschende Gesellschaft and in order to produce comparable results to other locations in Switzerland. Nevertheless, the barometer Trechsel used was already about 20 years old by the time he started his measurements. Since Trechsel was Benoit's predecessor as president of the Naturforschende Gesellschaft in Bern, they almost certainly knew each other. Nevertheless, it is unclear whether Trechsel had direct influence on Benoit's measurements, or vice versa.

2.2.2. Thermometric measurements

In the following, the respective temperature series of Benoit and Trechsel will be discussed in detail and compared to one other, in order to assess the quality and possible errors of Benoit's series. Furthermore, his series will be put into the bigger picture of the measurements from other stations across Switzerland and of the reanalysis data from HISTALP (Auer et al., 2007).

The breakpoint detection for Benoit's measurements revealed that there was a cluster of change-points between January and the November 1838, which gave no clear breakpoint, but there most likely was a non-climatic disturbance or an adjustment by Benoit which affected his measurements positively afterwards. Furthermore, there was a clear breakpoint between July 24th and August 7th 1843, which was confirmed by a cluster of change points between May and October 1843, which affected Benoit's measurements negatively afterwards. The last breakpoint affected Benoit's measurements positively and occurred around the October 7th 1847.

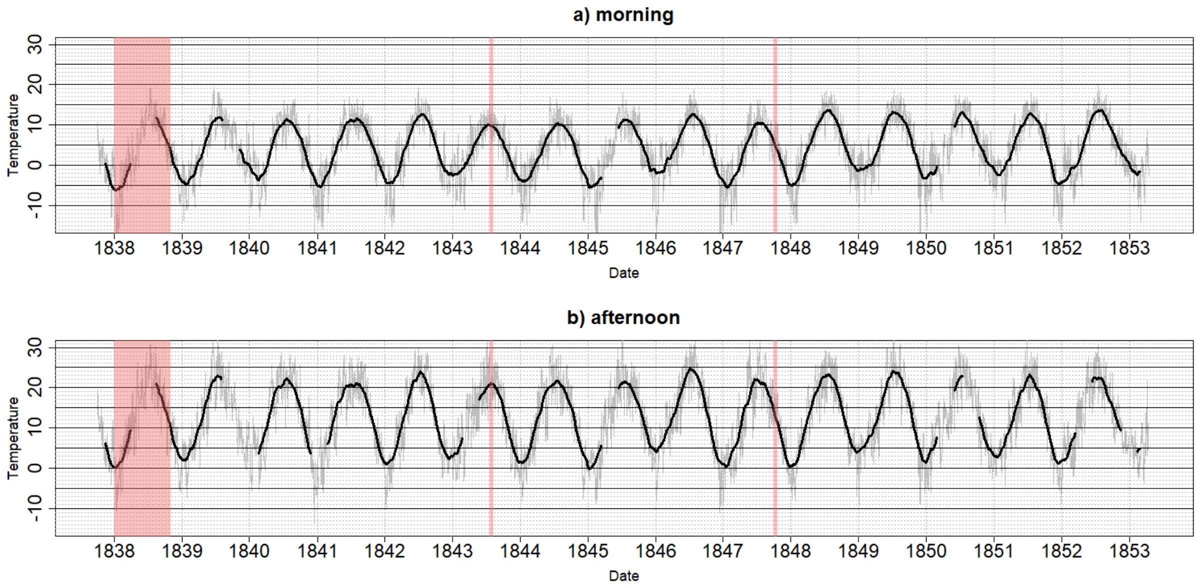

Figure 3: Temperature measurements in ° C by Benoit from October 1837 to April 1853 in grey. The black line represents the 90-days moving average, the vertical red bands indicate breakpoints or probable phases of non-climatic disturbances: a) Morning temperature at 6:00 AM; b) Afternoon temperature at 2:00 PM.

As reasoned above, since there is neither in the case of Benoit's nor in the case of Trechsel's measurements detailed information about the type of thermometer used, it is assumed that they both used mercury thermometers. Hence, extreme high temperatures – typically during summer afternoons – were underestimated and extreme cold temperatures – typically during the winter in the morning – were overestimated. Furthermore, the measurements always took place in the second floor of a building. Therefore, according to the standard of the first half of the 19th century, the thermometers were most likely attached directly to a north-facing wall or to a suspension device several centimeters away from a north-facing wall. Hence, the thermometers were exposed to reflected or scattered radiation in each case, especially since at Herrengasse 1, Münstergasse 28 and Kramgasse 12 alike, there was a south-facing wall less than 10 meters away, higher than the second floor of the respective building reflecting radiation from across the street or the inner yard. Therefore, the effect of reflected radiation should have been enhanced during the months April to September, especially during the hours around noon, when the southern buildings did not shade the respective northern ones and the ground beneath the southern building. These findings are supported by Chenoweth's result (Chenoweth, 1993, p. 1793-1795), which states that the maximum temperature deviation, thus the afternoon temperature of unscreened thermometers with little protection from scattered and reflected radiation compared to free-standing screened thermometers, is the largest during the summer months and reached up to +1.5° C in average. That is, unless the second-floor window was located directly under a large eave, in which case the maximum temperature was underestimated. Minimum or morning temperatures on the other hand, were measured either quite accurately or overestimated the real temperature; in that case, the thermometer was attached directly to the wall as a heat reservoir. Even more in the case that there was an eave directly above the thermometer preventing heat from ascending away. Furthermore, all three buildings are slightly north-northwest aligned. Therefore, there should be a radiation-related disturbance-peak in the hours between 4 PM and 6 PM during the summer months. But since Benoit only measured in the morning and the early afternoon and Trechsel's afternoon and evening measurements took place at 3 PM and 9 PM, there are no recordings during those hours. Nevertheless, afternoon measurements during the summer months might slightly be affected by this effect, though in the case of Kramgasse 12, the north-facing wall is additionally shaded by building structure in the west, reducing the effect of the north-northwest alignment of the building. In the cases of Münstergasse 28 and Herrengasse 1, there is an additional building structure in the west as well, but since it was possible to place the thermometer near to or a few meters away from that building structure, its effect remains unclear.[3]

To summarize the theory, it can be said that during the summer months, the temperature bias due to the thermometric substance is weak for the morning measurements and – dependent on the maximum temperature – stronger for the afternoon measurements. On the other hand, the radiation-related bias remains unclear during the summer months. It may have contradicted and overcompensated the thermometric-substance-bias, leading to an overestimation of the real afternoon temperature. Or – if the thermometer was located directly under a large eave – the radiation related bias reinforced the thermometric-substance-bias, which would lead to an underestimation of summer afternoon temperatures. Morning

[3] The results concerning the alignment of the buildings and the building-structure are a result of on-site observations and comprehensible by using maps and Google-Earth in 3D mode.

temperatures had either been accurately measured or overestimated the real temperature, in cases where the thermometer was attached directly to the wall.

During the winter months, the temperature bias because of the thermometric substance should be weak for the afternoon measurements and – in case of very low temperatures – stronger for the morning measurements. The radiation induced bias should have been generally weaker during the winter months. Afternoon temperatures could have underestimated the actual temperature if the thermometer was located directly under an eave. Just as in the summer, morning temperatures could have been measured quite accurately or overestimated the real temperature when the thermometer was attached directly to the wall and thus reinforcing the thermometric substance bias.

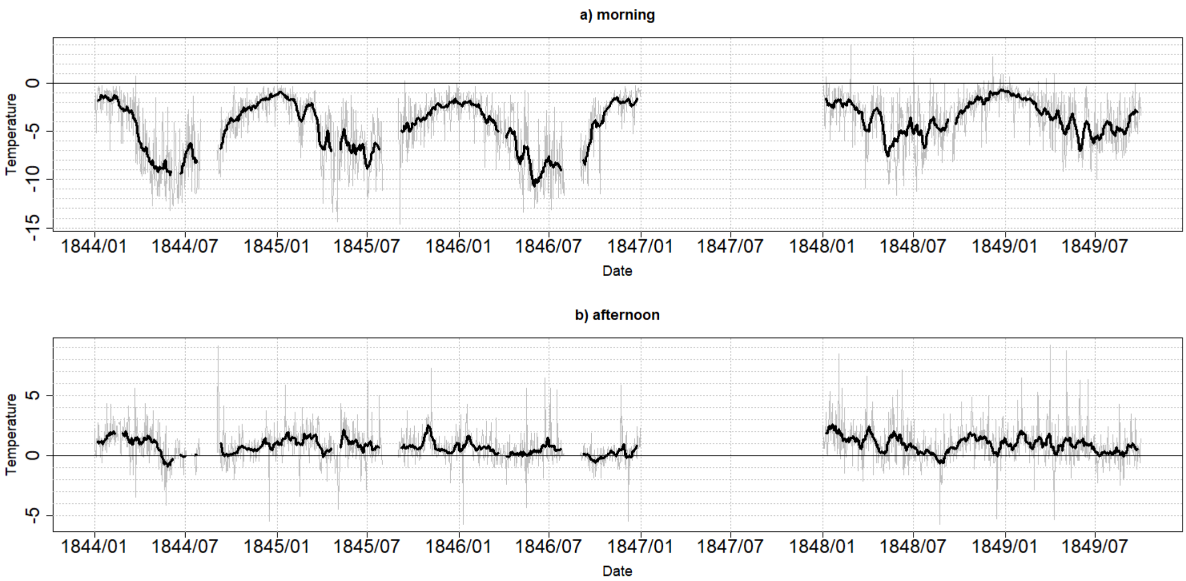

Figure 4: Difference between Benoit's and Trechsel's temperature measurements in degrees Celsius in grey and 15-days moving average thick black line: a) Morning temperature difference (Benoit – Trechsel respectively 6 AM – 9AM LST); b) Afternoon temperature difference (Benoit – Trechsel respectively 14 PM – 15 PM LST)

In the following, the results from the theory will be compared to the outcome of the actual measurements and their comparison. Figure 4 represents the differences between Trechsel's and Benoit's measurements. Figure 4 a) shows the difference between Benoit's measurement at 6:00 AM and Trechsel's measurement at 9:00 AM. Figure 4 b) depicts the differences between Benoit's measurements at 2:00 PM and Trechsel's at 3:00 PM. Logically, the differences are bigger for the comparison of the morning temperatures, as there were always three hours between the measurements. Consequently, the difference was the smallest during the winter months, as the sun rises later during these months and has less power to heat up the air during the hours between 6:00 AM and 9:00 AM. Secondly, it is notable that the differences decreased after Trechsel had relocated his measurements from Herrengasse 1 to Kramgasse 12.

	DJF	MAM	JJ(A)	SON
1844-1846				
6:00 AM	-3.98	2.49	11.51	5.64
9:00 AM	-1.94	8.51	19.65	9.49
DIFFERENCES	**-2.04**	**-6.02**	**-8.14**	**-3.85**
1848				
6:00 AM	-3.71	5.33	13.34	5.23
9:00 AM	-2.11	9.85	18.48	7.97
DIFFERENCES	**-1.6**	**-4.52**	**-5.14**	**-2.74**

Table 2: Seasonal averages of Benoit's and Trechsel's morning measurements for the years 1844 to 1846 and the year 1848 without the values from August in degrees Celsius.

Since there is a difference between the morning measurements at Herrengasse 1 compared to Kramgasse 12, these two parts will be discussed separately in the following. Table 2 shows the seasonally averaged morning temperature measurements for the years 1844 to 1846 and then for the year 1848. For comparability reasons, the August measurements have been left out for the year 1848.

	DJF	MAM	JJ(A)	SON
1844-1846				
2:00 PM	1.77	12.78	23.4	13.14
3:00 PM	0.77	12.14	22.9	12.64
DIFFERENCES	**1.00**	**0.64**	**0.5**	**0.5**
1848				
2:00 PM	2.07	14.29	23.1	12.37
3:00 PM	0.67	13.06	22.46	11.24
DIFFERENCES	**1.4**	**1.23**	**0.55**	**1.13**

Table 3: Seasonal averages of Benoit's and Trechsel's afternoon measurements for the years 1844 to 1846 and the year 1848 without the values from August in degrees Celsius.

In addition to the smaller differences in 1848 compared to 1844 to 1846, it stands out that with the exception of the fall values, all the seasonal averages from Benoit were higher in

1848. As the RHtest revealed, there indeed was a breakpoint during the fall of 1847 that affected Benoit’s measurements positively. On the other hand, Trechsel’s averages were all lower in 1848, with the exception of the spring values. Therefore, either the breakpoint in Benoit’s series is the sole reason for the smaller differences in 1848, or Trechsel reduced his radiation-induced bias for the morning measurements at Kramgasse 12 compared to Herrengasse 1.

The comparison of the afternoon temperature measurements is depicted in Table 3. Benoit’s measurements only show higher average values for the winter and spring measurements of 1848 compared to 1844 to 1846. On the other hand, all the seasonal average differences are positive and all the 1848 average differences are bigger than those of 1844 to 1846. To make more sense from these results, a comparison to the modern measurements at the station Bern Bollwerk may be useful, as modern measurement biases should be minimized compared to the historical ones. Furthermore, the modern measurements were all taken at the same place with the same instruments, which excludes an important source of the differences between Benoit’s and Trechsel’s measurements.

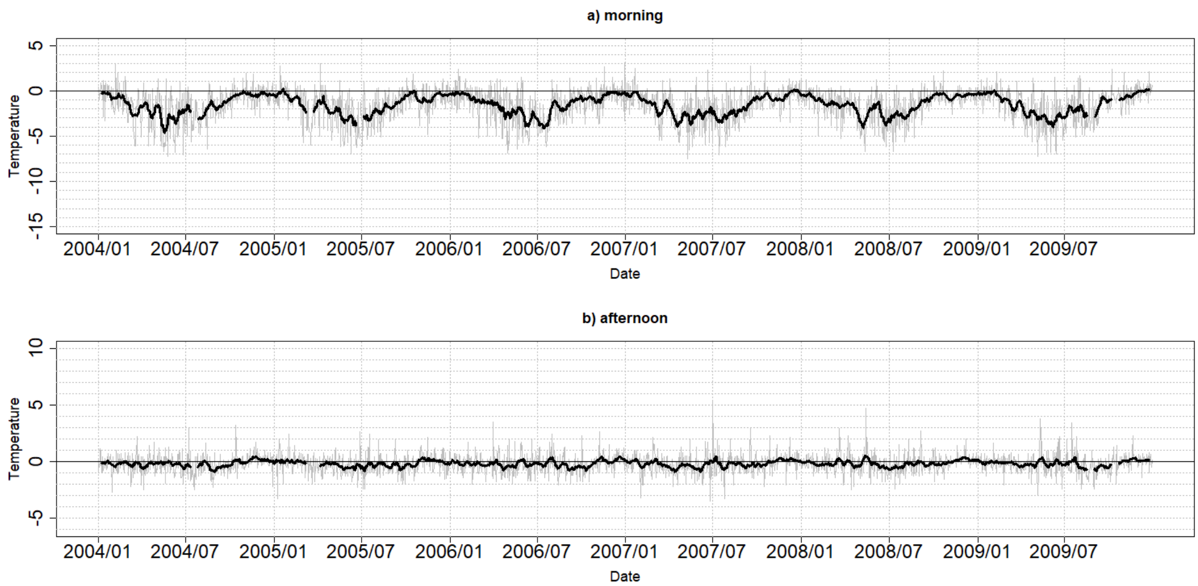

Figure 5: Difference between temperature measurements at Bern Bollwerk in degrees Celsius from 2004 to 2009 in grey and 15-days moving average thick black line: a) Morning temperature difference (5:40 AM – 8:40 AM UTC); b) Afternoon temperature difference (1:40 PM – 2:40 PM UTC) (Source: MeteoSchweiz)

Figure 5 depicts the differences between the hours 5:40 AM and 8:40 AM as well as 13:40 PM and 14:40 PM from the modern station Bern Bollwerk for the years 2004 to 2009 as an example from the same length as the historical segment. Table 4 shows the respective seasonal averages. The station Bern Bollwerk has been chosen because it is the modern measurement station located the closest to historical ones.

2004-2009	DJF	MAM	JJA	SON
5:40 AM	0.18	6.82	15	8.67
8:40 AM	0.67	9.06	17.65	9.59
DIFFERENCES	**-0.49**	**-2.24**	**-2.65**	**-0.92**
1:40 PM	3.47	13.24	22.01	13.51
2:40 PM	3.51	13.49	22.34	13.68
DIFFERENCES	**-0.04**	**-0.25**	**-0.33**	**-0.17**

Table 4: Seasonal averages of the temperature measurements at the station Bern Bollwerk for the years 2004 to 2009. (Source: MeteoSchweiz)

In comparison to the differences between Trechsel's and Benoit's measurements, the curves are generally flatter for both, the morning and the afternoon measurements. On average, the difference of the modern afternoon measurements is negative and smaller compared to the historical differences, which was larger and positive in average. Since we know that Benoit measured higher temperatures after the breakpoint in 1847, which by definition is non-climatically induced, yet only the seasonal averages of the winter and spring afternoon measurements were higher in 1848, it is likely that the true afternoon temperature was lower in 1848 compared to the one of the period 1844 to 1846. Since Trechsel indeed measured lower temperatures during most of the seasons in 1848 compared to the period 1844 to 1846, the effects of the relocation on his temperature measurements is smaller than the one of the reason for Benoit's breakpoint. Furthermore, the effect of the breakpoint in Benoit's series is larger for the morning measurements than for the afternoon measurements.

The seasonal averages of the modern 5:40 AM measurements are strictly higher than those of Benoit in the years 1844 to 1846 and in 1848 at 6:00 AM. This corresponds to the increase of the mean of daily low temperatures over the 170 years between the historical measurements and the Bern Bollwerk measurements (Berkeley Earth, 2015a) and speaks for a generally low temperature bias for Benoit's morning measurements. The seasonal means of the modern 8:40 AM measurements, on the other hand, are higher for the winter, spring and fall measurements compared to the 1844 to 1846 measurements. Compared to the 1848 measurements, the seasonal means of the modern 8:40 AM measurements are higher in winter and fall, pointing in the direction of a warm bias for Trechsel's historical 9:00 AM measurements.

Furthermore, it is unlikely that the historical 2:00 PM temperatures really were lower than the historical 3:00 PM temperatures. Therefore, either Benoit measured too high or Trechsel measured too low values. Additionally, the mean of daily high temperatures during the last 170 years increased in comparable amount to the one of the mean of daily low temperatures (Berkeley Earth, 2015b). The fact that both Benoit and Trechsel measured higher afternoon temperature averages during the summer months compared to the modern measurements points in the direction of a strong positive radiation-induced bias for Benoit's afternoon measurements and a weaker one for Trechsel's in the summer.

In summary, it can be said, that both the literature and the comparison between Benoit and Trechsel's respective measurements and the modern ones from Bern Bollwerk point in the same direction. The most accurate measurements are those that Benoit made in the morning, though there are indicators for errors in Benoit's morning temperatures as well, such as the fact that the effect of the breakpoint in 1847 for Benoit's series is most likely larger for the morning measurements than for the afternoon measurements. Generally, Benoit's afternoon measurements, especially during the summer months, are more strongly affected by non-climatic influences, such as the radiation bias. There are breakpoints in Benoit's temperature measurements in July and August 1843 and in October 1847. Furthermore, the RH test points to irregularities in Benoit's temperature measurements during the year 1838.

In the following, Benoit's temperature measurements will be compared to those of other stations from Switzerland and to the temperature data from HISTALP (Auer et al., 2007) by conducting a correlation analysis.

Table 5 depicts the information about the different reference series. Basel, Geneva and Grand St. Bernard originate from DigiHom (Füllemann et al., 2011) and were chosen due to their importance and continuity as historical Swiss measurement series. Furthermore, the stations Col du Grand St. Bernard and Geneva are located westwards respectively south-westwards from Benoit's station. The station Col du Grand St. Bernard represents the alpine temperatures. Bern (Trechsel) and Utzenstorf were chosen because of their proximity to Benoit's station, while Tegerfelden, Zug and Zurich represent the east in the Swiss Plateau. The data from Tegerfelden, Utzenstorf, Zug and Zurich was digitized at the Institute for Geography at the University of Bern and is not yet published.

NAME	DIST.	ELEV.	YEARS	TIME	TOT. MO.	TOT. AF.
Bern (Trechsel)	0 km	548	1844-1849	9 AM; 3 PM	1635 / 1553	1630 / 1621
Basel	70 km	280	1837-1853	9 AM; 3 PM	5650 / 5624	5605 / 5531
Geneva	130 km	405	1837-1848	9 AM; 3 PM	4058 / 4039	4046 / 3990
Gr. St. Bernard	240 km	2472	1837-1850	9 AM; 3 PM	4786 / 4643	4776 / 4585
Tegerfelden	95 km	370*	1845-1849	Mo.; Af.	2177 /	2176 /
Utzenstorf	22 km	475*	1837-1840	Mo.; 2PM	1019 / 983	896 / 982
Zug	85 km	430*	1843-1853	9 AM; 3 PM	3584 /	3591 /
Zürich	95 km	432	1837-1842	9 AM; 3 PM	1902 / 1888	1888 / 1867

Table 5:Measurement stations used for comparison with Benoit's measurements. Name: Name of the station; Dist.: Approximated distance in km to Benoit's station; Elev.: Elevation in meters above sea level of the station (* no meta data: approximate elevation of city center has been used); Years: The year during which the measurements took place; Time: The hours in LST when the relevant measurements took place; Tot. Mo.: Total amount of used entries for the comparison with Benoit's morning measurements (for temperature / for SLP); Tot. Af.: Total number of used entries for the comparison with Benoit's afternoon measurements (for temperature / for SLP).

Before the correlation analysis was conducted, the seasonality was removed from the measurement series listed in Table 5. Outliers where detected by vision and removed. For the correlation analysis, the Spearman method was used, as the de-seasonalized temperature series are not normally distributed and outliers do not have a strong effect on the correlation coefficient. The correlation analysis was done in terms of the different seasons (DJF, MAM, JJA, SON) and different weather types from the CAP7 classification (Schwander et al., 2017), which is based on the CAP9 described by Weusthoff (2011, p. 46) and consists of the following seven weather types: northeast, indifferent (NE), west-southwest, cyclonic, flat pressure (WSW), westerly flow over northern Europe (W), east, indifferent (E), high pressure over Europe (HP), north, cyclonic (N) and westerly flow over southern Europe, cyclonic. HP is a combination of the weather types *high pressure over Central Europe* and *high pressure over the Alps* from CAP9, while WC is a combination of *west-southwest*, *cyclonic* and *westerly flow over southern Europe*, *cyclonic* from the CAP9 (Schwander et al., 2017, p. 37).

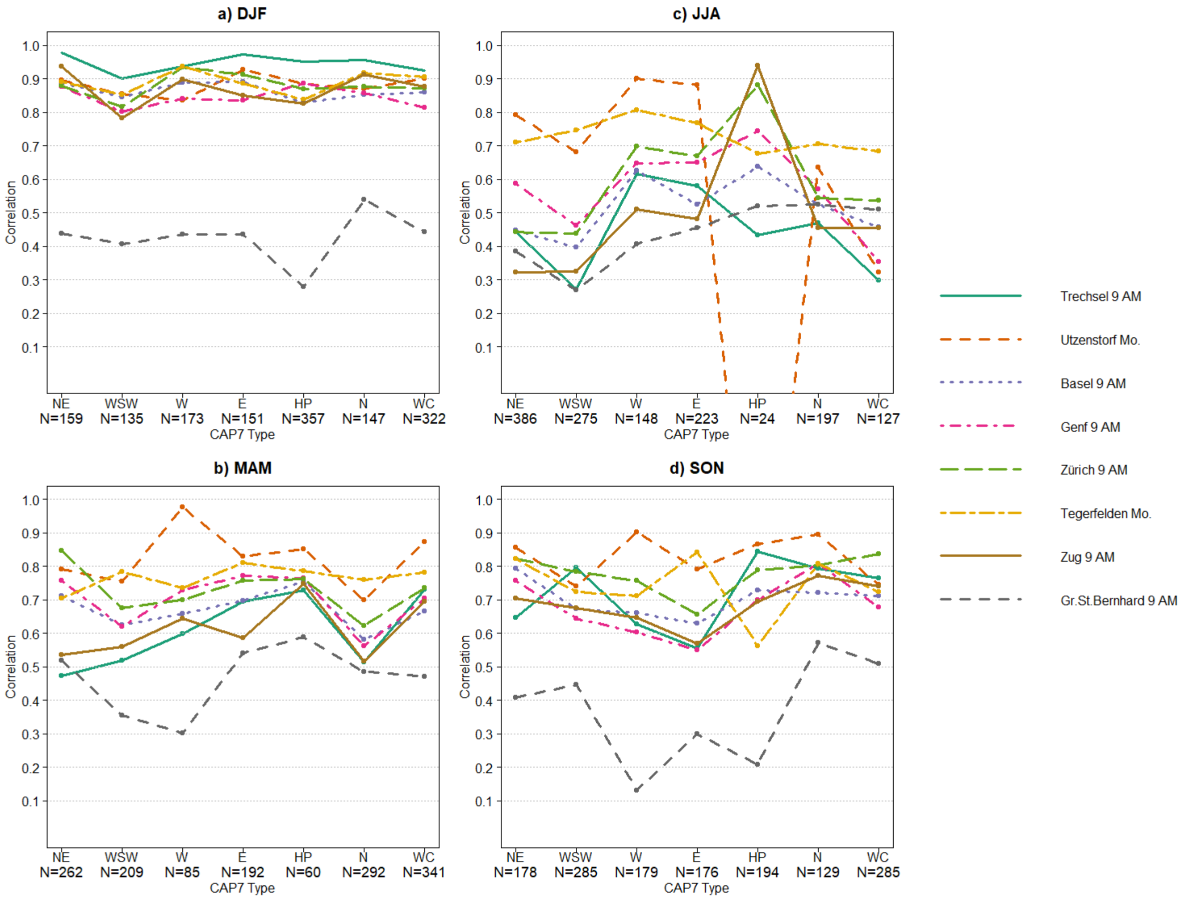

Figure 6: Correlation between Benoit's and the reference series' morning temperature measurements in terms of seasons and CAP7 weather types. Bern (Trechsel) 9 AM in dark green; Utzenstorf morning measurements in orange; Basel 9 AM in blue; Genf 9 AM in pink; Zürich 9 AM in light green; Tegerfelden morning measurements in yellow; Zug 9 AM in brown; Gr. St. Bernhard 9 AM in grey; a) correlation coefficients for the months DJF; b) correlation coefficients for the months MAM; c) correlation coefficients for the months JJA; d) correlation coefficients for the months SON.

Figure 6 depicts the correlation coefficients of the correlation analysis between Benoit's and the reference series morning measurements in terms of the seasons and the weather type classifications from CAP7 (With the number of occurrences for the timespan of Benoit's measurements). During the winter months, the correlation was the highest in average for all the stations over all the weather types, with the exception of the measurements at the station Grand St. Bernhard. The high DJF morning correlation is probably due to the fact that the radiation bias most likely not only affected Benoit's and Trechsel's measurements the least during DJF. Because of the type of bias, it can be expected that, the same is true for the morning measurements at the other reference stations. Therefore, the DJF correlations are higher than those of the other seasons.

For the other seasons, the influence of the diurnal temperature cycle is much stronger, since during the approximately three hours that passed between the different morning measurements, the sun had time to heat up the environment and the air of the different measurement stations. The measurements at Utzenstorf and Tegerfelden show the highest correlation with Benoit's measurements across most of the weather types, especially during MAM and JJA and to a lesser degree, during SON. That indicates temporally closer measurement hours to Benoit's measurements compared to the other reference series.

Another obvious feature of the winter correlations is the much lower correlation between Benoit's measurements and the measurements at Col du Grand St. Bernhard. This is due to the greatest geographical distance and especially to the difference in elevation of the stations Grand St. Bernhard and Bern. A typical phenomenon for HP during the winter months, for example, is the atmospheric inversion, leading to lower temperatures and fog in lower altitudes and to warmer temperatures in higher altitudes. Therefore, the correlation coefficient is the lowest between Benoit's measurements and the ones at Grand St. Bernhard for the CAP7 type HP.

For CAP7 type HP during JJA, there are only 24 counts for the whole series of Benoit. Notably, the negative correlation of the shortest reference series, Utzenstorf, for the morning and the afternoon measurements does not yield much information.

Surprisingly, Trechsel's measurements show a relatively low correlation during MAM and JJA and to a lesser degree during SON as well. This most likely indicates measurement errors for Trechsel's morning measurements. However, the JJA correlation coefficients might be distorted due to the missing values in August for the years 1844 to 1846.

Figure 7 depicts the respective correlation analysis for the afternoon temperatures. Generally, the correlation coefficients are higher across the seasons for all reference series, except for DJF, where the correlation coefficients already were very high for the morning measurements. Furthermore, with the exception of DJF, the correlation coefficients across the stations and the CAP7 types follow more similar patterns in the afternoon compared to the morning measurements. This is due to temporally closer afternoon measurements compared to the morning measurements and the concomitant lower influence of the diurnal temperature cycle. Once more, the exceptional role of DJF values indicates a low temperature bias for the winter morning measurements.

Generally, the agreement between Trechsel and Benoit is better for the afternoon measurements compared to the morning measurements. With the exception of the SON values and single CAP7 types in the other seasons, the correlation coefficient is always the highest between Benoit's and Trechsel's measurements, indicating that both the afternoon measurements from Trechsel and Benoit were affected by the radiation bias in a similar way. The measurements at the second nearest station, Utzenstorf, on the other hand, which happened simultaneously with Benoit's measurements, only show high agreement during SON and to a lesser degree during JJA. In this case, the small data basis and the quality of the measurement could also be an explanation for the relatively low agreement.

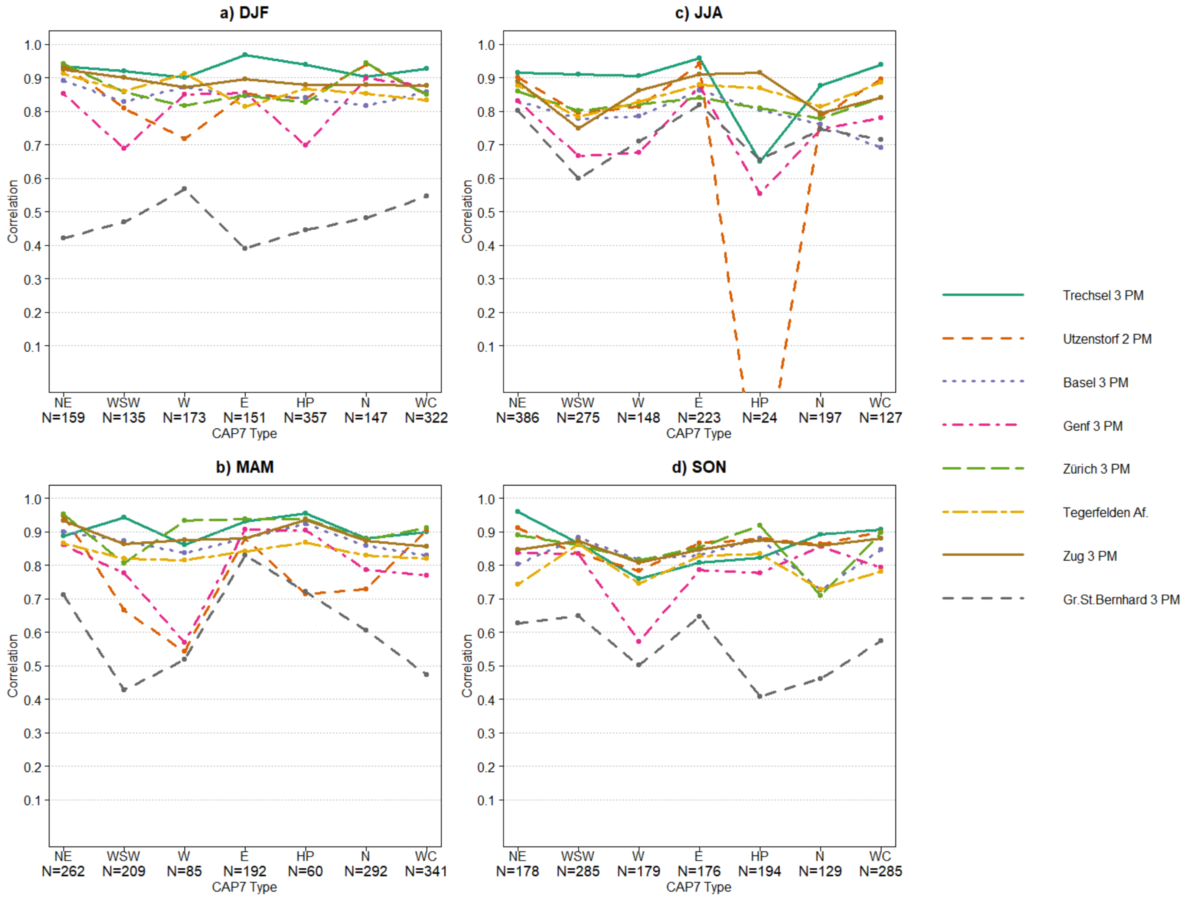

Figure 7: Correlation between Benoit's and the reference series' afternoon temperature measurements in terms of seasons and CAP7 weather types. Bern (Trechsel) 3 PM in dark green; Utzenstorf 2 PM in orange; Basel 3 PM in blue; Genf 3 PM in pink; Zurich 3 PM in light green; Tegerfelden afternoon measurements in yellow; Zug 3 PM in brown; Gr. St. Bernhard 3 PM in grey; a) correlation coefficients for the months DJF; b) correlation coefficients for the months MAM; c) correlation coefficients for the months JJA; d) correlation coefficients for the months SON.

Across all seasons, the correlation between Benoit's afternoon measurements and those of the other stations are relatively high and close together for the CAP 7 type E. The continental air masses from the east seem to have a similar effect on all the temperature measurement stations. Again, during DJF we can see the difference between Grand St. Bernhard and the other stations, what again can be explained with atmospheric inversion, leading to lower temperatures and fog in lower altitudes and to warmer temperatures in higher altitudes.

With the exception of DJF, during westerly flows especially the CAP7 type W Geneva and Grand St. Bernhard – the two geographically most distant stations – often show low correlation values with Benoit's measurements. Since during CAP7, type W weather fronts move over Switzerland, it is more likely that the higher the distance between the two measurement stations, the two measurement stations will be under the influence of a different front, particularly as the front arrived earlier in the west of Bern, while the measurements happened earlier in Bern. This effect explains the higher agreement with stations in the east, where the latter geographical distance partly compensates the timely difference of the measurements during westerly flow.

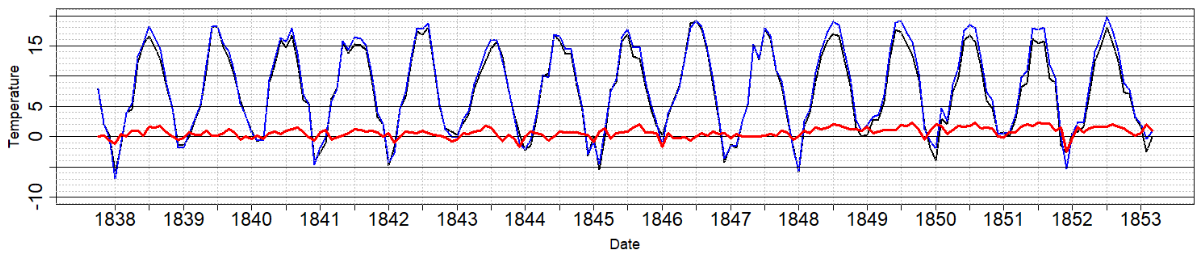

Figure 8: Comparison between monthly average temperature from HISTALP (Auer et al., 2007) and Benoit. In black: HISTALP data; in blue: Benoit's measurements; in red: difference between Benoit and HISTALP. (Benoit minus HISTALP)

Since the HISTALP (Auer et al., 2007) temperature data is only available in monthly averages, Benoit's measurements had to be transformed into monthly averages as well. For that purpose, fist the daily averages then the monthly averages were constructed from Benoit's measurements. Furthermore, the closest grid-point to Bern (lon: 7.416667; lat: 46.91667) was chosen from the HISTALP 5x5 minutes gridded date set.

The Spearman correlation coefficients after subtracting the seasonality are 0.918 for the whole series, 0.938 for DJF, 0.932 for MAM, 0.876 for JJA and 0.906 for SON. The lower agreement between the series during summer once more indicates a positive bias for Benoit's measurements during the warm season and is also visible in Figure 8, where the monthly average temperatures from HISTALP (black line), Benoit's (blue line) and the difference between the two series (red line) are depicted.

Both the clear breakpoints from the summer of 1843 and especially from October 1847 are clearly visible in Figure 8. After the breakpoint of 1843, the difference between HISTALP and Benoit becomes smaller, while after the breakpoint in October 1847 the difference becomes larger again. The overall mean difference is 0.65° C, the one from October 1837 until June 1843 is 0.42° C, from July 1843 until September 1847 it is 0.28° C and from October 1847 until March 1853 it is 1.16° C. The biggest negative and positive differences also occurred during that last period and reached –2.55° C respectively 2.33° C.

Summarizing the results of the comparison between Benoit's temperature measurements, those from the reference series and the reanalysis data from HISTALP, it can be said that although the measurements from Trechsel and did not always show the expected agreement with Benoit's measurements, the overall picture from the comparison between Benoit's and Trechsel's measurements becomes confirmed by the correlation analysis. The winter morning measurements were the ones with the highest agreement, which indicates that they were the least affected by non-climatic disturbances. Furthermore, the breakpoints during the summer of 1843 and in October 1847 were reconfirmed. The fact that in most cases, the correlation analysis in terms of the CAP7 types has produced reasonable results, indicates that both the CAP7 classification and the different reference series, as well as Benoit's measurements, depict the same picture of the historical weather situation, especially in terms of the relative temperature. Since the seasonality had to be subtracted from the different series in order to produce reasonable correlation coefficients, the correlation analysis does not reveal how exact the temperature was measured in terms of absolute values. However, from the literature and the comparison with Trechsel's temperature series, we know that the absolute values of Benoit's morning measurements should be the most accurate, especially during the winter, while Benoit's afternoon measurements were positively biased by non-climatic influences.

2.2.3. Barometric measurements

In this section, the barometric measurements of Benoit and Trechsel along with the known metadata will be discussed in detail, compared to the theory and to each other, in order to draw conclusions about the possible biases of Benoit's pressure measurements.

In order to avoid contortions due to the reduction to mean sea level, for the discussion of Benoit's pressure measurements, the choice of the measurement unit fell on station pressure converted in hPa instead of the reduced values to SLP. The choice for station pressure is also unproblematic for a comparison between Trechsel's and Benoit's measurements, since we assume the altitude of the measurement station in the case of Münstergasse 28 and Herrengasse 1 to be the same. Furthermore, the difference in elevation from the station Kramgasse 12 to the others is known. Hence, we know the difference in atmospheric pressure due to elevation, which accounts for approximately 0.7 hPa according to the barometric formula.

Figure 9 depicts the station pressure measured by Benoit. Compared to the temperature measurements, the two curves for the morning and afternoon pressure measurements are much more similar. Seasonally there is a clear pattern visible regarding to the variance of the measurements, which becomes smaller during the lighter months and larger during the darker months.

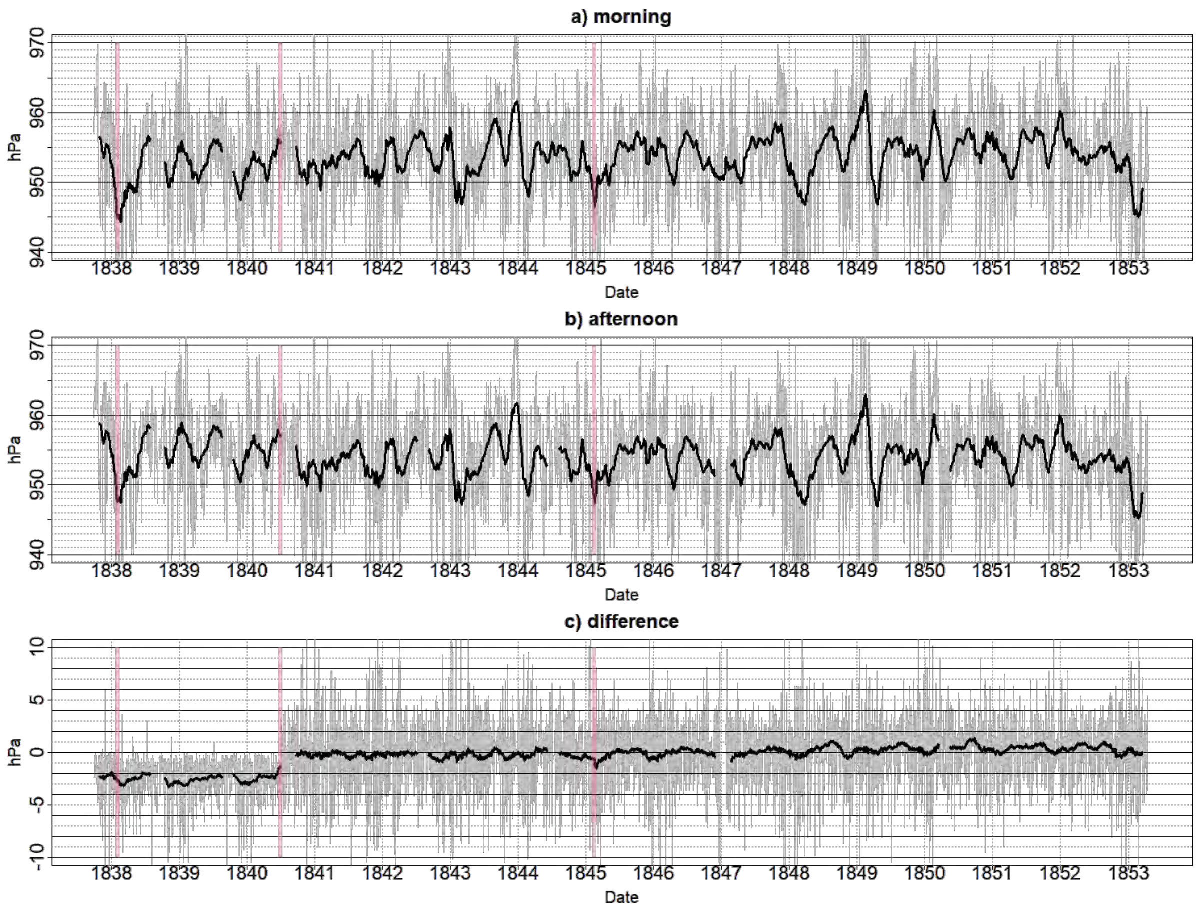

Figure 9: Atmospheric station pressure measurements in hPa measured by Benoit from October 1837 to April 1853 in grey. The black line represents 60-days moving averages and the vertical red bands indicate breakpoints: a) morning pressure measurements at 6:00 AM; b) afternoon pressure measurements at 2:00 PM; c) difference between the morning and afternoon measurements (6:00 AM - 2:00 PM)

In Figure 9 c), the differences between Benoit's morning and afternoon measurements are depicted. Notably, the moving average of the differences is mostly in the negative spectrum until the year 1848 and has a slightly positive trend over the whole timespan of the series. On the one hand, this contradicts what we would expect from the diurnal pressure cycle, which would suggest a constant positive moving average of approximately 0.5 hPa (see Figure 1). On the other hand, a trend in the moving average indicates a possible problem with the barometer or the thermometer used to correct the pressure readings for temperature. Alternatively, there where breakpoints that caused a successive increasing of the differences.

Furthermore, there obviously was a breakpoint during the summer of 1840. The absolute RHtest applied on the difference between Benoit's morning and afternoon measurements gives the 30th of June 1840 as a Breakpoint. This was also the result of the relative RHtest applied on the SLP values, which reveals that the morning measurements were too low and the afternoon measurements were too high until the breakpoint. The other breakpoint of the absolute RHtest on the differences between Benoit's measurements was February 6th 1838, which is confirmed through applying the relative RHtest on the station pressure values. This breakpoint was mainly driven by excessive afternoon measurements prior to the breakpoint. Furthermore, the relative RHtest gave a breakpoint in February 1845. The measured pressure values were higher after the breakpoint.

For Trechsel's measurements, the metadata reveals additional information about the barometer and the circumstances of the measurements. His measurements took place at Herrengasse 1 in the second floor at an elevation of 548 meters above sea level from 1844 to 1846. From 1848 to 1849, Trechsel measured the pressure in the second floor of Kramgasse 12 at an elevation of 542 meters above sea level. Furthermore, we know that Trechsel used a fixed-cistern barometer, which was made in Zurich in the year 1826 by Mechanicus Oeri, who had been a student of Fortin. Oeri had built all the barometers for the atmospheric pressure measurements of the Schweizerische Naturforschende Gesellschaft in 1826. Therefore, a case can be made that Trechsel's barometer was built to comply with contemporary scientific standards. At the time of Trechsel's measurements, however, the barometer was already around 20 years old. Since its first use in 1826, it remained at the same place until Trechsel relocated his measurements to Kramgasse 12 in 1847. The barometer had been constantly observed since the time of its installation in 1826, though only the results of the measurements between 1844 and 1849 were published in the Mitteilungen der Naturforschenden Gesellschaft in Bern. An indirect comparison to the normal barometer stationed in the observatory in Paris showed a positive difference of 0.36 inches, which is accounted for in the published observations. Nevertheless, it is unknown when this comparison took place. Therefore, it is possible that Trechsel's barometer during the relevant time had become less precise due to wear and tear. (Wolf, 1844a, p. 169-170; Wolf, 1848a, p. 142; Wolf, 1848b, p. 214; Hombres-Firmas, 1841, p. 166-169)

The tube of Trechsel's barometer had a width of 7.896mm and one side of the quadratic cistern was 11.5cm long. Therefore, the ratio between the surface in the tube and in the cistern was approximately 1 to 225, which was rather large for fixed-cistern barometers. The noted values were already reduced to 0° C, as is mentioned in the header of the data tables itself, although it was not Trechsel himself did the reduction to 0° C, but Friedrich Henzi, a scholar of Rudolf Wolf responsible for the publication of the meteorological observations in the Mitteilungen der Naturforschenden Gesellschaft in Bern from 1844 to 1854. As Trechsel gave the measurements of the tube and the cistern of his barometer, as well as the derivation from the normal barometer explicitly in Paris inches, we conclude that his observations as well were noted in Paris Inches (Wolf, 1844a, p. 169-170; Graf, 1886, p. 154-155).

According to the literature, several reasons exist for Trechsel's barometer to show wrong values. Capillarity led to an underestimation of the real value independently of the temperature. The correction for temperature led to an underestimation of the real value in the positive spectrum and to an overestimation in the negative spectrum of the ° Celsius scale. (Jelinek, 1867, p. 662) The deviation was the higher the difference was to 0 C. Additionally, the measured temperature itself most likely was not the real temperature of the mercury in the barometer, due to the thermometric substance bias and the dilatation of heat transfer. The same holds for the reduction of the pressure values to SLP, only that the relevant temperatures for the reduction to SLP were outside temperatures. Hence, a general underestimation of the real value can be expected, which becomes stronger for high temperatures respectively an overestimation for temperatures in the negative spectrum of the ° Celsius scale. Nevertheless, the temperature bias which occurs when pressure values were corrected for temperature is due to indoor temperatures which are unknown in Trechsel's and in Benoit's case.

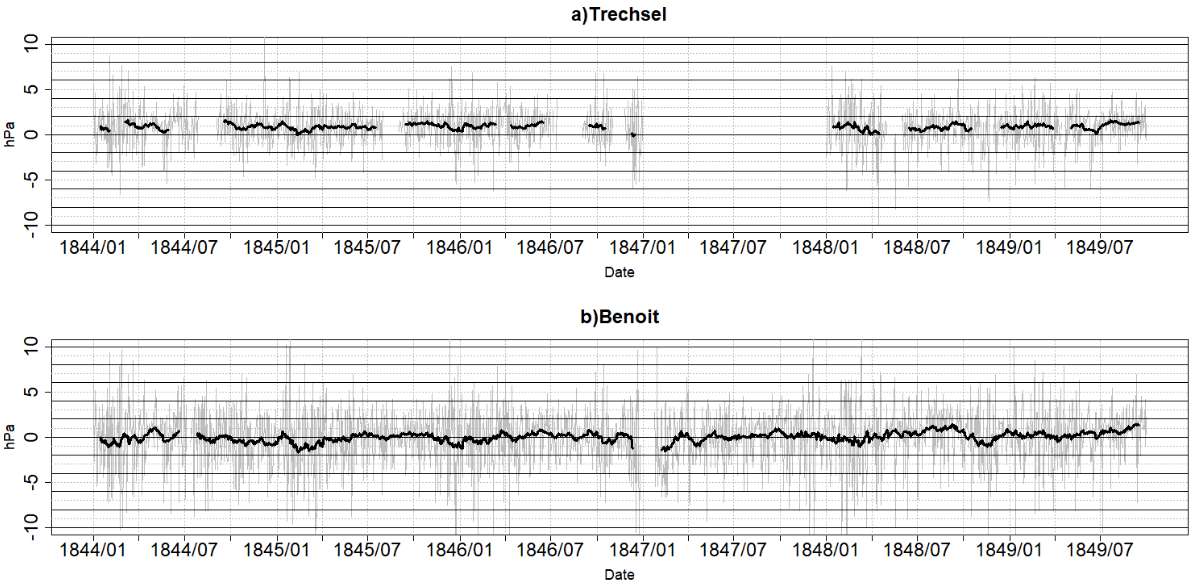

Figure 10: Difference between Trechsel's and Benoit's morning and afternoon measurements for the years from 1844 to 1849. In grey the differences of the station pressure measurements are represented in hPa. The black line represents a 30-days moving average: a) Difference between Trechsel's morning and afternoon pressure measurements (9 AM – 15 PM); b) Difference between Benoit's morning and afternoon pressure measurements (6 AM – 14 PM LST).

Figure 10 compares the differences of Trechsel's morning and Afternoon pressure measurements with those of Benoit. Obviously, there was more variance in the differences between Benoit's measurements than in the differences between Trechsel's measurements. This can partly be explained by the greater timely difference between Benoit's measurements (8 hours) compared to Trechsel's (6 hours). Furthermore, the variance increased during the winter-months and became smaller during the summer-months. As discussed above, the differences between Benoit's morning and afternoon measurements contradict the diurnal pressure cycle, while they comply with the diurnal pressure cycle in Trechsel's case. Hence, Benoit either measured too low morning values or too high afternoon.

In Benoit's case, the differences during the winter months contradict the diurnal pressure cycle even more than the differences during the summer months, as the seasonality of the differences between Benoit's measurements confirms. The seasonality has its minimum during January and December at approximately -0.3 hPa and its maximum in August at approximately 0.3 hPa. Since there exists a seasonal cycle in the differences, it is most likely due to heat radiation that the differences between Benoit's morning and afternoon pressure measurements were not constant in average over a year.

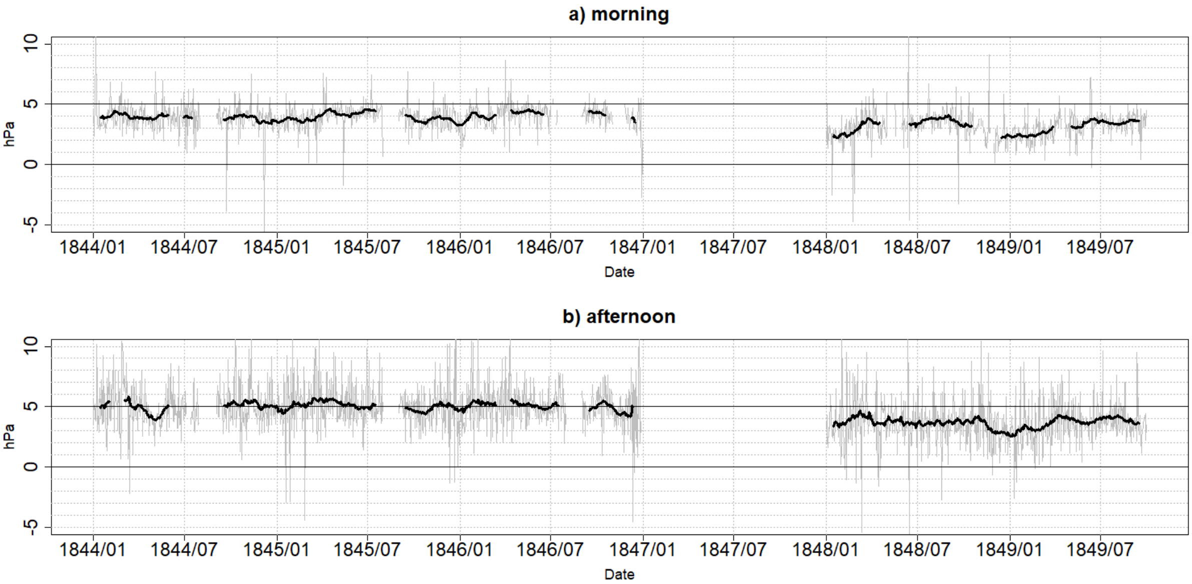

Figure 11: Difference between Benoit's and Trechsel's pressure measurements in hPa in grey and the respective 30-days moving average in black: a) Morning pressure difference (6 AM – 9AM); b) Afternoon pressure difference (14 PM – 15 PM)

Figure 11 depicts the differences between Benoit's and Trechsel's morning and afternoon pressure measurements. In general, it can be noted that Trechsel constantly measured lower pressure values than Benoit, that the differences became smaller when Trechsel moved his measurements to Kramgasse 12 – possibly due to the lower elevation of the measurement station at Kramgasse 12 – and that the variance of the differences between the afternoon measurements is bigger than the variance for the differences between morning measurements. However, between the morning measurements were three hours and between the afternoon measurements only was one hour. The higher variance for the difference between Benoit's measurements and the diurnal pressure cycle contradiction (Figure 10) combined with the higher variance and the larger difference between the afternoon measurements points in the direction of an overestimation of the pressure readings by Benoit in the afternoon.

Nevertheless, far bigger than the differences between Benoit's morning and afternoon measurements were the differences between Trechsel's and Benoit's measurements. As discussed above, due to capillarity and correction for temperature, Trechsel's measurements most likely underestimated the real pressure value in average. However, it is impossible to detect by how much exactly, making it impossible to calculate something like a mean error of Benoit's measurements from Trechsel's measurements.

By using the barometric formula, the theoretical value for Benoit's afternoon measurements should have been approximately 948.7 hPa in average, while Benoit's actual afternoon measurements are 955.9 hPa in average for the period 1844 until 1849. The same problem occurs, though, in the case of the modern measurements at station Bern Bollwerk, where the theoretical value should have been 950.0 hPa, while the average of the 1:40 PM UTC measurements from 2004 to 2009 was 954.1 hPa, the average difference of 4.1 hPa compared to 7.2 hPa in Benoit's case is still much smaller. A possible explanation for Benoit's high measurement values, would be that he reduced his pressure values to 10° or 20° R instead of 0°. If we assume he did so, it is possible to reduce his measurements from 10° respectively 20° R to 0°. In this case, we would get average values of 953.7 hPa respectively 951.5 hPa. The reduction to 10° R by Benoit would be a plausible explanation, because that value was very common among contemporaries in the early 19th century. (Brugnara et al., 2015, p. 1034) The differences between the theoretical value of the barometric formula and the actual measurements would yield 5 hPa, which comes much closer to the modern average difference.

In summary it can be said therefore, that from both a relative and absolute perspective Benoit's morning measurements were more precise than his afternoon measurements. Benoit's afternoon measurements were most likely on average too high. In terms of the seasons, the variance increased always during winter, what is consistent with the analysis of the storminess in chapter 3. Furthermore, there were breakpoints in February 1838, June 1840 and in February 1845.

In the following, Benoit's pressure measurements will be compared to those of other stations from Switzerland and to the pressure data from unpublished parts of the 20th Century Reanalysis (20CR) by conducting a correlation analysis. The unpublished parts of the 20CR are stored on the server of geographical institute of the University of Bern.

In order to compare the pressure values from Benoit to those of other stations, the pressure values were reduced to SLP. Therefore, there is a trend for the diurnal pressure cycle to be reinforced due to higher afternoon temperatures (see Figure 1). Since we know that the thermometric measurements are biased, especially the afternoon temperature measurements of Benoit and probably those of the other stations too, we have to be careful interpreting the results of the correlation analysis. The reference series stations are the same as for the temperature analysis (see Table 5), only without the stations Tegerfelden and Zug because there was no pressure data available for these stations. Therefore, the eastern part of Switzerland is only represented by the station Zurich. Again, the seasonality was subtracted from the different SLP series in order to get reasonable results from the correlation analysis. Since the series with subtracted seasonality do not indicate a normal distribution, the Spearman method was used to compute correlation coefficients.

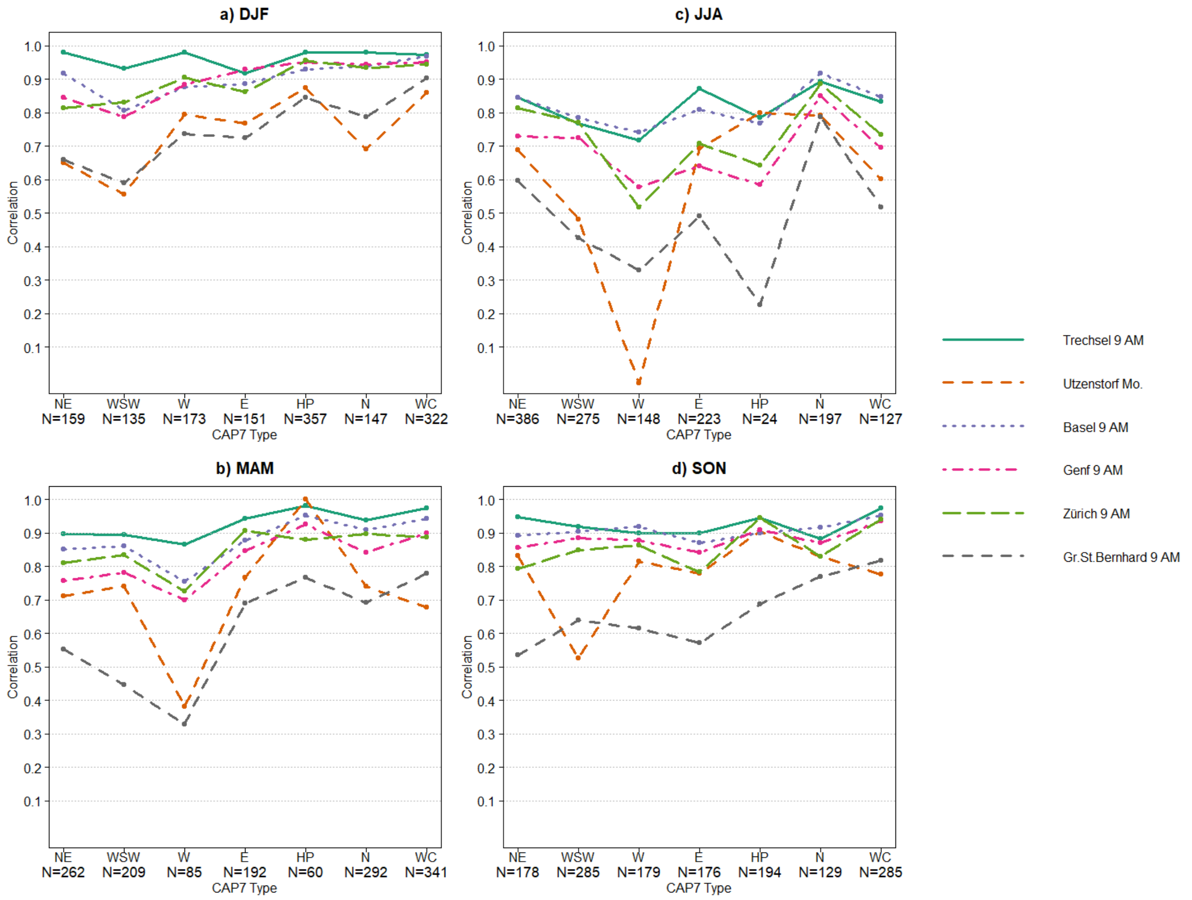

Figure 12: Correlation between Benoit's and the reference series' morning pressure measurements in SLP in terms of seasons and CAP7 weather types; a) correlation coefficients for the winter months; b) correlation coefficients for the spring months; c) correlation coefficients for the summer months; d) correlation coefficients for the fall months.

Figure 12 depicts the results of the correlation analysis of the morning measurements in terms of the seasons and the different CAP7 weather types. With the notable exception of Utzenstorf, the DJF correlation coefficients across the CAP7 types are the highest for all the reference stations. Furthermore, all the stations follow a similar pattern in terms CAP7 type during winter. During summertime, there are rather low correlation coefficients compared to the other seasons.

Unlike for temperature, the correlation between Trechsel's and Benoit's data is relatively high for the morning measurements. Only during summer is the correlation between the two measurements rather low, particularly since the measurements at Basel show a higher correlation for 4 CAP7 types. Again, as the second nearest station, Utzenstorf shows a rather low correlation throughout the seasons and the different CAP7 types compared to the other reference series, which indicates a rather low quality of the pressure measurements at Utzenstorf.

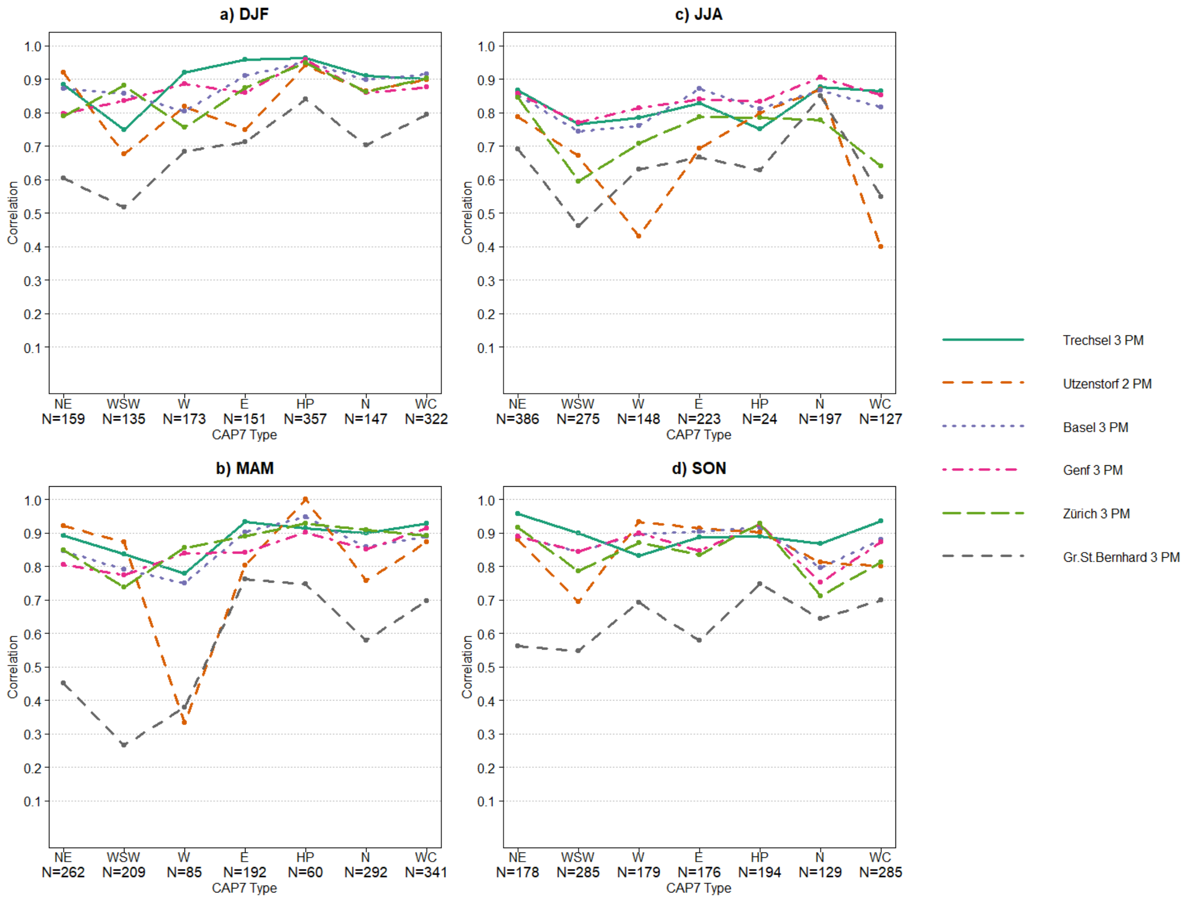

Figure 13: Correlation between Benoit's and the reference series' afternoon pressure measurements in SLP in terms of seasons and CAP7 weather types; a) correlation coefficients for the winter months; b) correlation coefficients for the spring months; c) correlation coefficients for the summer months; d) correlation coefficients for the fall months.

When comparing the morning correlations with the afternoon correlations from Figure 13, most of the patterns in terms of seasons and CAP7 weather types are strikingly visible for both day times. The correlation coefficients for CAP7 type WC for example is relatively high for all stations during all the seasons, with the exception of the summer seasons when the CAP7 type WC occurs the least.

Another example of consistent patterns across stations and seasons would be the high correlation during the weather type HP. During the spring and especially during summer seasons, the occurrence of HP is rather low, so little information can be gleaned from the correlation coefficients. For the winter and fall seasons, on the other hand, the correlation coefficients are relatively high across all stations, including Col du Grand St. Bernard, which is reasonable as the area where the stations are located is at the center of a high-pressure system, where the vertical differences in pressure should not be too high.

Furthermore, it can be noticed that Trechsel's morning measurements correlate better with those of Benoit compared to the afternoon measurements. This is in accordance with what the comparison in terms of differences between Benoit and Trechsel above have revealed but points in the direction of a lower quality of the afternoon measurements of Trechsel's measurements. However, the generally lower agreement of the afternoon values with Benoit's measurements also points in the direction of lower a lower quality of his afternoon measurements. Although, the generally lower agreement of the afternoon values can also partly be explained with the bias resulting from the reduction to SLP values, with tendentially more biased afternoon temperature values. In terms of the seasons, the lower agreement between summer pressure measurements can also be explained with the same mechanism, especially since the agreement between the morning values was worse than between the afternoon values. The average three hours between Benoit's and the reference series' measurements preponderate especially during the summer season, when the temperature difference between those morning hours was the largest.

Figure 14 depicts the difference between Benoit's SLP values and the ones from 20CR. The difference was built after removing the seasonality from both series. The U-shape of the differences is most likely due to an error in the 20CR data. Therefore, the same pattern results by building the differences between the 20CR data and the series from Basel for example. Furthermore, the breakpoints from the relative RHtest with the other measurement series do not coincide with the U-shape of the differences between Benoit and 20CR. However, the 1838-breakpoint is visible in the morning differences and the 1840-breakpoint is visible in the afternoon differences.

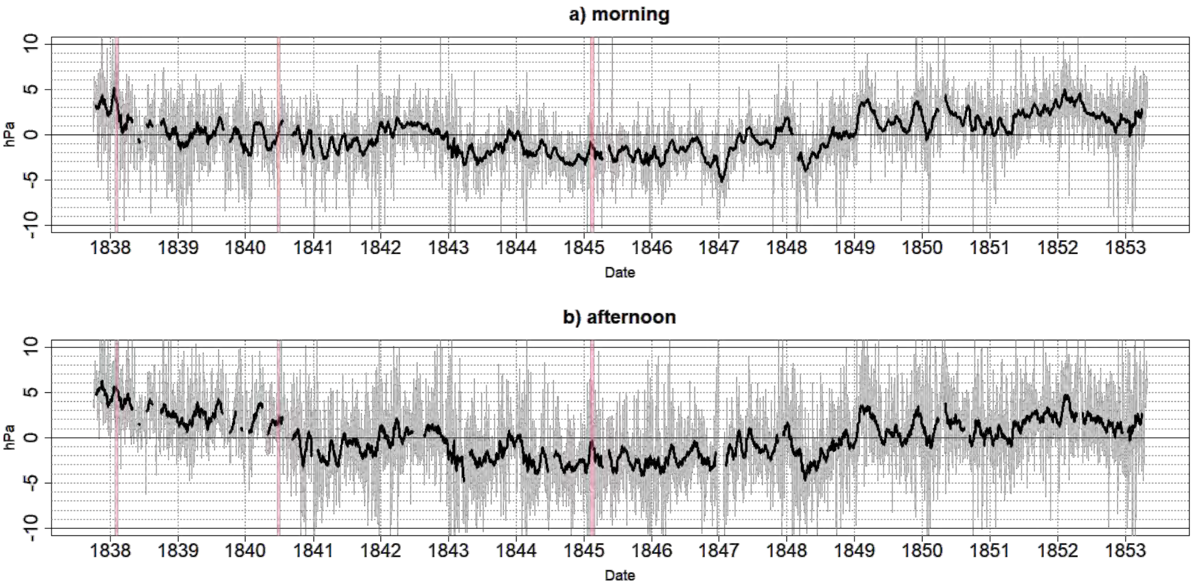

Figure 14: Difference between Benoit's and 20CR SLP values in hPa in grey and 30-days moving average thick black line. The vertical red bands indicate the breakpoints from the relative RHtest: a) Morning pressure difference (Benoit 5:30 AM UTC – 20CR 6 AM UTC); b) Afternoon pressure difference (Benoit 1:30 PM UTC – 20CR 12 PM UTC)

Again, the variance of the differences is much higher for the afternoon values, what partly can be explained with the bigger timely difference between the afternoon values. On the other hand, it indicates again a problem with Benoit's afternoon measurements. As in the analysis conducted above, the variance has a seasonal component and increases during the cold season.

Generally, the agreement between Benoit's SLP values and those of 20CR is worse than the agreement between Benoit's temperature values and those of HISTALP. One reason for the worse agreement would be the much larger grid cells of 20CR compared to HISTALP (2x2 degrees vs 5x5 minutes). On the other hand, the part used from 20CR doesn't belong to the published part of 20CR and most likely is less precise than the published part for the relevant grid cell as well. Last but not least, it indicates that the pressure measurements during the mid-19th century were less precise than the respective temperature measurements, as the multiple source of possible pressure measurement errors discussed in the chapter 2.1 suggest.

The relatively low agreement in absolute terms depicted in Figure 14 was not reflected by the Spearman correlation coefficients, which yield 0.93 for the winter seasons, 0.9 for the spring seasons, 0.84 for the summer seasons and 0.93 for the fall seasons with respect to the morning measurements. With respect to the afternoon measurements, the correlation coefficients gave lower values with 0.87 for the winter seasons, 0.8 for the spring seasons, 0.67 for the summer seasons and 0.86 for the fall seasons. Therefore, the higher variance for the afternoon differences translates into lower average correlation across the seasons.

In summary, it can therefore be said that from both a relative and absolute perspective, Benoit's morning measurements were more precise than his afternoon measurements. On the other hand, Benoit's afternoon measurements were too high in average. Although it is possible that Benoit reduced his pressure values to 10° R instead of 0°, we cannot be sure about the correctness of his pressure values in terms of absolute values. Other attempts to validate historical instrumental pressure records have struggled with the same problem (e.g. Cornes et al., 2012b, p. 1143). In terms of the seasons, the variance increased always during winter, what is in accordance with generally higher variability of the pressure during the winter semester compared to the summer semester (see Chapter 3). On the other hand, the agreement between Benoit's measurements, the different stations and the 20CR data was the worst during the summer seasons, which can be partly explained with the reduction to SLP by using more biased temperature values compared to the winter seasons. Furthermore, there were breakpoints during February 1838, June 1840 and in February 1845. Until the breakpoint during June 1840, the morning measurements were negatively biased and the afternoon measurements were positively biased additionally.

2.3. Length fluctuations of the Lower Grindelwald Glacier

In the second part of the work at hand, the output from the first part — especially the barometric measurements and other measurement series — will be used to get a better understanding of the climate including the weather conditions from the mid-19th century and how it was connected to the fluctuations of Lower Grindelwald Glacier. Because of its location and accessibility, the Lower Grindelwald Glacier is one of the best-documented glaciers. By analyzing historical paintings, photographs and written sources, Heinz J. Zumbühl reconstructed the length-fluctuations of the Lower Grindelwald Glacier for the last 500 years (Zumbühl, 2016, p. 45-114).

To get an understanding of how climate including weather conditions and glacier lengths are connected, the basic concepts of modeling the length of a glacier will be briefly introduced and the results of previous studies about the climate sensitivity of the Lower Grindelwald Glacier will be summarized. Furthermore, the data and the method used to connect the pressure data to length fluctuations of the Lower Grindelwald Glacier will be introduced.

2.3.1. Basic Concepts of Glacier Dynamics

Unlike the mass balance of a glacier (net growth in volume of ice over a year) the glacier length is a more filtered and indirect signal of climatic forcing. In addition to the climate forcing, the glacier length depends on factors such as glacier size, topography and debris cover (for a detailed description of glacier physics and a description of their flow, see: Nye, 1965; Paterson 1994). The response time of a glacier is the time the glacier needs to get from one steady state to another after a change in the mass balance, while the reaction time is the time-lag between a climatic perturbation the reaction of the glacier front. Typically, the response time is two to three times longer than the reaction time of a glacier (Steiner et al., 2008, p. 423-424). However, there may be climatic conditions that allow for a more immediate reaction of the glacier snout. After runs of cool summers, for example, glaciers of different sizes in southern Norway advanced simultaneously (Matthews and Briffa, 2005, p. 25).

2.3.2. The Lower Grindelwald Glacier and its history of research

The reconstructed lengths of the Lower Grindelwald Glacier by Zumbühl (2016, p. 45-114) serve as the basis for the second part of the work at hand. The Lower Grindelwald Glacier reached its latest maximum length for the last 300 years in the year 1856. During the years between 1810 and 1820, the glacier went through a strong growing phase, from then on experiencing only minor fluctuations. A final growing phase from 1840 to 1850 then culminated in the maximum size of 1856, before a long and almost steady retreat until 1890 began (Zumbühl, 2016, p. 91-105).

Therefore, the question concerning the factors accounting for the length of variations of the Lower Grindelwald Glacier in the middle of the 19th century arises. Several studies dealt with the reconstruction of the length of the Lower Grindelwald Glacier and its climate sensitivity. Brönnimann for example, reconstructed the length of the Lower Grindelwald Glacier using precipitation and temperature data from HISTALP and the formula and weights determined by Karl von Sonklar. Sonklar had suggested that precipitation from October to April and temperature from May to September were the main factors that influence glacier growth. The reconstructions by Brönnimann reproduced the reconstructed glacier length from Zumbühl very well, even if the maximum from 1856 was slightly underestimated. (von Sonklar, 1858, p. 171; Brönniman,2015, p. 216-220)

Steiner et al. performed a sensitivity analysis based on a neural network model, which was trained with precipitation and temperature data derived from proxy data to investigate the relative importance of the different climatic influencing factors for selected growing and retreating phases of the Lower Grindelwald Glacier. According to Steiner et al., the 1810-1820 advance was mainly driven by low summer temperatures and to a lesser degree, by high precipitation in the fall. Furthermore, they came to the conclusion that for most of the advances of the Lower Grindelwald Glacier, low spring and summer temperatures were the main driving factors for glacier advances. Nevertheless, in most cases high precipitation during the accumulation season also contributed to the glacier advances. Generally, the Lower Grindelwald Glacier seems to be more sensitive to temperature than to precipitation compared to glaciers located in higher latitudes. (Steiner et al., 2008, p. 426-433)

Schmeits and Oerlemans reconstructed the glacier length by coupling a mass-balance with an ice-flow model, hence focusing more on the topographical properties of the glacier compared to the studies mentioned above. By taking the topography into account, the response time of the glacier to climatic forcing could be estimated. In the case of the Lower Grindelwald Glacier, it ranges from 34 to 45 years, though the first differences in the length of the glacier already manifest after fewer than 10 years. The main weakness of the study by Schmeits and Oerlemans is the precipitation input data they used for the period before 1865, for which they only could use the average precipitation from Grindelwald of the years 1865-1978. Thus, there was no variation in precipitation input before 1865. Concerning the climate sensitivity of the glacier, Schmeits and Oerlemans came to similar conclusions as Steiner et al. Generally, temperature anomalies have the larger effect on the mass-balance of the glacier. Summer temperature is the main driver of glacier length fluctuations, followed by spring and fall temperatures. Winter temperatures do have an effect on the parts of the glacier located beneath an altitude of 2000 meters above sea level. Anomalies in precipitation have the biggest effect during the winter season followed by spring and fall precipitation. Precipitation during spring is important due to the snow cover in the following summer season, which increases the albedo. (Schmeits and Oerlemans, 1997)

During the first half of the 19th century, volcanic (Unknown Eruption 1808, Tambora 1815, Babuyan Claro 1831, Cosigüina 1835) and solar activity were the only factors which could influence the temperature and precipitation on a hemispheric to global scale. Several studies dealt with those factors during the first half of the 19th century. Anet et al. (2014, p.

933-934) disentangled the impact of solar and volcanic activity on tropospheric temperature and precipitation during the Dalton Minimum by using an interactive atmospheric ocean chemistry model. They came to the conclusion that the negative temperature anomaly from 1809 on was triggered by volcanic eruptions and maintained after 1816 by lower solar irradiance. The eruptions of Babuyan Claro in 1831 and of Cosigüina in 1835 led again to a drop in temperatures until the late 1830s, especially in the northern Hemisphere. Furthermore, their model showed that after volcanic eruptions, the North Atlantic Oscillation (NAO) is pushed into a NOAplus-like phase in the winters following a volcanic eruption, which leads to an increase in precipitation in northern Europe and to a decrease in southern Europe.

In summary, it can therefore be noted that the long-term fluctuations of the Lower Grindelwald Glacier are well understood and reproducible. In particular, the special climatic conditions during the first three decades of the 19th century and the respective climate-glacier relation are well explored. According to Nussbaumer et al. (2016, p. 219-221), the simultaneous advance of different glaciers in the western and central Alps during the 1820s is mainly a result of the cold decade from 1811 to 1820. According to the arguments from Anet et al. (2014, p. 933 – 934), Steiner et al. (2008, p. 426-433) and Matthews and Briffa (2005, p. 25), the cold decade was induced by the eruptions of the Unknown Volcano and Tambora and maintained by the Dalton Minimum (1790-1840) during the 1820s and led to cold summers and a positive precipitation anomaly during the seasons fall and winter. Brugnara et al. (2015, p. 1038-1039) went even further into detail and were able to prove an eastward shift of the storm track during the winters 1815/1816 and 1816/1817. Furthermore, they reproduced a positive anomaly of storminess in the summers of 1816 and 1817 and linked their outcome to the wet summer conditions of 1816 and 1817 over the alps.

The period from the late 1830s to the retreat of the glacier from the 1860s onwards, on the other hand, is not investigated into detail as it is in the three decades before. However, Karl von Sonklar (1858, p. 192-193) pointed out the relevance of the years 1836 to 1845 as a decade of very glacier-friendly conditions with wet winters and cold summers. These glacier-friendly conditions became confirmed by Brönnimann (2015, p. 219), who relied on temperature reconstructions and precipitation data from HISTALP. On the other hand, Sonklar’s glacier growth index is based only on measurement data from Hohenpeissenberg. Furthermore, the precipitation and temperature data from HISTALP consists of monthly averages. Nussbaumer et al. (2016, p. 219-221), on the other hand, pointed out the below-average temperatures from 1847 to 1851, the high solid precipitation rate from 1851 to 1853 and their subsequent positive influence on glacier growth in the Alps.

Therefore, a closer look at the temperature and precipitation conditions from 1836 to 1853 could clarify aspects of the glacier growth in the Bernese Alps, which led to its peak in the 1850s.

2.3.3. Analysis of the weather

The sub-daily instrumental data from the city of Bern recovered in the first part of the work at hand covers almost the whole range of years – mentioned by Sonklar, Brönnimann and Nussbaumer et al. – relevant for the glacial advance during the 1840s and 1850s. Together with other instrumental data series from Switzerland and Europe, Benoit's recovered pressure data now allows us to zoom into the timescale. By using the atmospheric pressure data, the frequency of low pressure systems passing the region, or storminess according to Brugnara et al. (2015, p. 1037), can be reconstructed. This allows for conclusions about winter precipitation. The storminess also allows for conclusions about the summer temperature. To increase the robustness of temperature-related interpretations of the storminess analysis, the reconstructed daily weather types by Schwander et al. (2017) will be used again.

Questions such as the following shall be answered: Were the summers colder or shorter, or were there a lot of cold surges during regular summers? Was there a southward shift of the storm track, leading to more precipitation during the different winter seasons?

Therefore, in a first step seasonal precipitation and temperature anomalies from HISTALP for the years 1836 to 1853 above the Lower Grindelwald Glacier will be reconstructed. In order to explain the weather conditions, the daily and sub-daily pressure series on a transect from northern Europe to the southern slopes of the Alps will then be used to conduct an analysis of the storminess. In order to increase the robustness of the storminess analysis and its relation to temperature and precipitation anomalies above the glacier and to increase the robustness of the analysis, the CAP7 daily weather types will be used. In a final step, the outcome of the weather analysis will be used to draw conclusions about fluctuations of the Lower Grindelwald Glacier.

Table 6 depicts the measurement series used to conduct the storminess analysis. Besides the digitized and validated data in the first part of the work at hand, there is also data from Amsterdam, which stems from Wallbrink H. and Brandsma, T. (2008). The Armagh data stems from Hanna et al. (2008), the London data from Cornes et al. (2012a), the Milan data from Maugeri et al. (2002), the Paris data from Cornes et al. (2012b), the Stockholm data from Moberg et al. (2002), the Turin data from Di Napoli & Mercalli (2008) and the Uppsala data from Bergström & Moberg (2002). For the stations Basel, Geneva and Col du Grand St. Bernard, the data originates from DigiHom (Füllemann et al., 2011). The data from Zurich was digitized at the Institute for Geography at the University of Bern by Denise Rimer and has not yet been published.

NAME	LON.	LAT.	START	END	TIME
Amsterdam	4.9	52.37	Jan. 1836	Dec. 1853	noon
Armagh	353.35	54.35	Jan. 1836	Dec. 1853	DA
Basel	7.59	47.56	Jan. 1837	Dec. 1853	noon
Bern (Benoit)	7.45	46.95	Oct. 1837	Apr. 1853	14:00
Geneva	6.14	46.2	Jan. 1836	Nov. 1853	12:00
Gr. St. Bernard	7.19	45.89	Jan. 1836	Dec. 1853	12:00
London	359.88	51.51	Jan. 1836	Dec. 1853	DA
Milan	9.19	45.46	Jan. 1836	Dec. 1853	DA
Paris	2.35	48.86	Jan. 1836	Dec. 1853	DA
Stockholm	18.06	59.33	Jan. 1836	Dec. 1853	DA
Turin	7.74	45.12	Jan. 1836	Dec. 1853	12:00
Uppsala	17.63	59.86	Jan. 1836	Dec. 1853	DA
Zurich	8.54	47.38	Jan. 1837*	Dec. 1852*	12:00

Table 6: Measurement stations used for storminess analysis. Name: Name of the station; lon.: longitude of the station; lat.: latitude of the; Start: Beginning of the measurement series; End: End of the measurement series (*measurement gap for the years 1849-1851); Time: The hours in LST when the relevant measurements took place (noon: around noon but no specific measurement hour, DA.: Daily average).

Before applying the storminess analysis, outliers had to be removed from the data depicted in Table 6. This was done by applying a median absolute deviation filter (Howell, 2014) for each station and measurement hour separately, using the formula:

$$(x_i - median(\boldsymbol{x}))/\ mad(\boldsymbol{x})$$

where $\boldsymbol{x}$ denotes a vector of measurements from a single station for a certain measurement hour. Values for which the outcome was higher or even six where replaced by NA. The cot-off value 6 is rather conservatively chosen in order to remove only unrealistically values.

Since, the storminess analysis in the work at hand is very similar to the analysis Brugnara et al. (2015, p. 1037-1039) did for the years 1815-1817, a similar setup has been chosen for the work at hand, to produce comparable results. Just as in Brugnara's case, a 2–6-day bandpass Lanczos filter (Duchon, 1979) with a 31-day convolution vector has been applied to the pressure data. Furthermore, the noon measurements were also chosen, partly because of the comparability to Brugnara's results and partly due to highest amount of data for the noon measurements. Furthermore, we used the same climatology as Brugnara et al. did. The results are thus shown as the anomalies from the 1961–1990 climatology of the closest grid point in the 20th Century Reanalysis. The 20th Century Reanalysis V2c data was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at https://www.esrl.noaa.gov/psd/ (Compo et al., 2006; Compo et al., 2011; Giese et al. 2016; Hirahara et al., 2014; Reynolds et al., 2007; Whitaker et al., 2004).

In contrast to Brugnara's setup, on the one hand, the measurement values were not interpolated to 12:00 UTC, as for several European stations, only daily averages were available. Hence, it was not possible to simulate simultaneous measurements. Furthermore, the interpolation of the measurements to 12:00 UTC is not expected to have a major effect on the results. This is because the stations where there was actual measurement data available are located between 4 and 9 degrees longitude and so the effect of the location is not more than 30 minutes difference to UTC. On the other hand, with the exception of Benoit's measurements, which took place around 14:00, LST the measurement times were close to 12:00 LST. Additionally, it is reasonable to assume that the stated measurement hours on the historical notes are no more than an approximation. In the case of Basel, for example, we know the noon measurements took place within a range of three hours between 11:00 and 14:00 LST. Even tough, in 60% of the cases the measurements took place at 13:00 LST for the other 40% the result of the interpolation would be wrong.

On the other hand, Brugnara et al. expressed their results in terms of the storminess during winter (120-day period from November 15th to March 14th) and summer (120-day period from May 18th to September 14th). In the work at hand, the whole year was analysed and divided into the seasons DJF, MAM, JJA and SON due to comparability to the results of Steiner et al. (2008).

Additionally, to the storminess of the different stations the seasonal average of the NAO index (Luterbacher et al., 2001) will be plotted, in order to see whether there are relations between the storminess and the NAO.

The anomalies of the CAP7 weather types were calculated by building the monthly sums of the days representing a specific weather type and subtracting the climatology of the same structure for the years from 1961 to 1990. The timespan of the climatology was chosen in order to comply with the climatology for the storminess. For the analysis of the weather conditions from 1836 to 1853 the anomalies then were summarized into the group of cyclonic weather types N, WC and WSW and into the weather types NE, E, N, WC which entail negative temperature anomalies. (Schwander et al., 2017, p. 36-37) Furthermore, the Spearman correlation between temperature and precipitation anomalies above the glacier and the cyclonic respectively the weather types which should entail negative temperature anomalies was calculated.

Since, the analysis of the storminess was calculated only for the seasons, the sample size was not large enough for a meaningful correlation analysis between the storminess and the temperature and precipitation anomalies above the glacier.

3. Results and Discussion

The analysis will start with an overview of the monthly temperature and precipitation anomalies for the years from 1836 to 1853.

3.1. Temperature and precipitation over the Lower Grindelwald Glacier

Figure 15 depicts the monthly temperature anomalies for the closest grid point (lon./lat.: 8.08 / 46.58) to the Lower Grindelwald Glacier from the 5x5-minute temperature dataset from HISTALP (Auer et al., 2007), with respect to the 1831 to 1860 climatology in light red respectively and to the 1961 to 1960 climatology in dark red. The anomalies are divided into yearly seasons. The difference between the 1831 to 1860 climatology and the 1961 to 1990 climatology ranges from -0.69° C (June) to +1° C (September). June was the only month for which the 1831 to 1860 climatology revealed a higher temperature than the modern climatology. The climatology of all the other months reflect a warming between the two climatologies. Additionally, Sonklar's qualitative weather assessment (SQWA) is depicted as cold(cc), cold(c), warm(w) or very warm(ww). Unlike his glacier growth index, the SQWA is based on temperature and precipitation data from all around the Alps. (von Sonklar, 1858, p. 176-186)

The below-average temperatures from 1847 until 1851 mentioned by Nussbaumer et al. (2016, p. 221) are most evident for the MAM months and SON months, though, there are several months with a strong positive anomaly during the MAM months. The comparison between the temperature anomalies from HISTALP and the SQWA for temperature reveals a high agreement concerning the sign of the anomaly, while the strength of the trend is not represented very well. This might be due to the fact that Alpine characteristics of the relevant grid point from HISTALP are not well-represented in Sonklar's data, which stems from lower altitude measurement stations.

The most striking feature is the under-average temperature during the SON months. Since warm anomalies during November only play a minor role concerning the glacier-growth, the SON seasons of the years from 1836 to 1842 and the years from 1847 to 1852 may be seen as rather cold, with the exception of the years 1839, 1841 and 1849. The SON seasons from 1843 to 1846, on the other hand, show tendentially above average temperature, but with a rather low amplitude. Furthermore, the SON seasons 1841 and 1843 to 1845, coincide with below-average JJA-seasons and therefore are compensated. In general, the JJA seasons show negative temperature anomalies during the years from 1840 to 1845, with the exception of the year 1842. With the exception of a negative anomaly in 1847 and a positive one in 1849, the amplitude of the anomalies during the JJA season becomes much weaker from the year 1847 onwards.

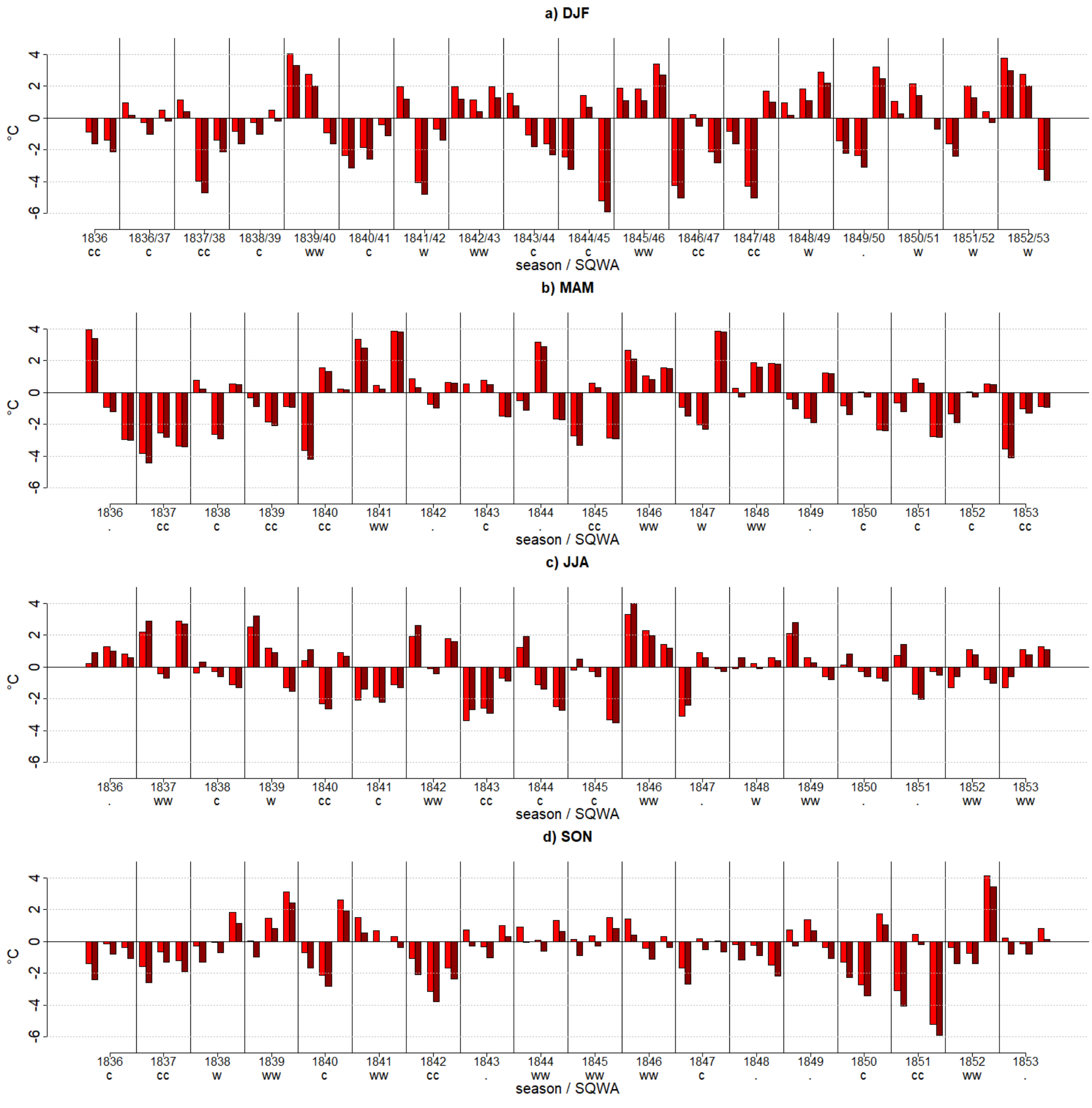

Figure 15: Monthly temperature anomalies from HISTALP in degrees Celsius by seasons. a) DJF; b) MAM; c) JJA; d) SON with Sonklars qualitative weather assessment (SQWA). Light red: with respect to the 1831 to 1860 climatology; Dark red: with respect to the 1961 to 1990 climatology.

Analogously to the November temperature, since the March temperature only plays a minor role for glacier growth, the MAM-seasons from 1836 to 1839 and from 1850 to 1853 were subnormally cold. The latter period exhibits lower amplitudes. For the years between, on the other hand, the picture is less clear, with above-average and below-average temperate years with varying amplitudes. In terms of glacier growth the DJF temperature anomalies are only important if they are high enough to lead to glacier melting. Therefore, only single Months during the DJF-seasons of the years 1839/40, 1845/46 and from 1848/49 to 1852/53 come into question. 1846 is the only year that shows above-average temperatures throughout the year.

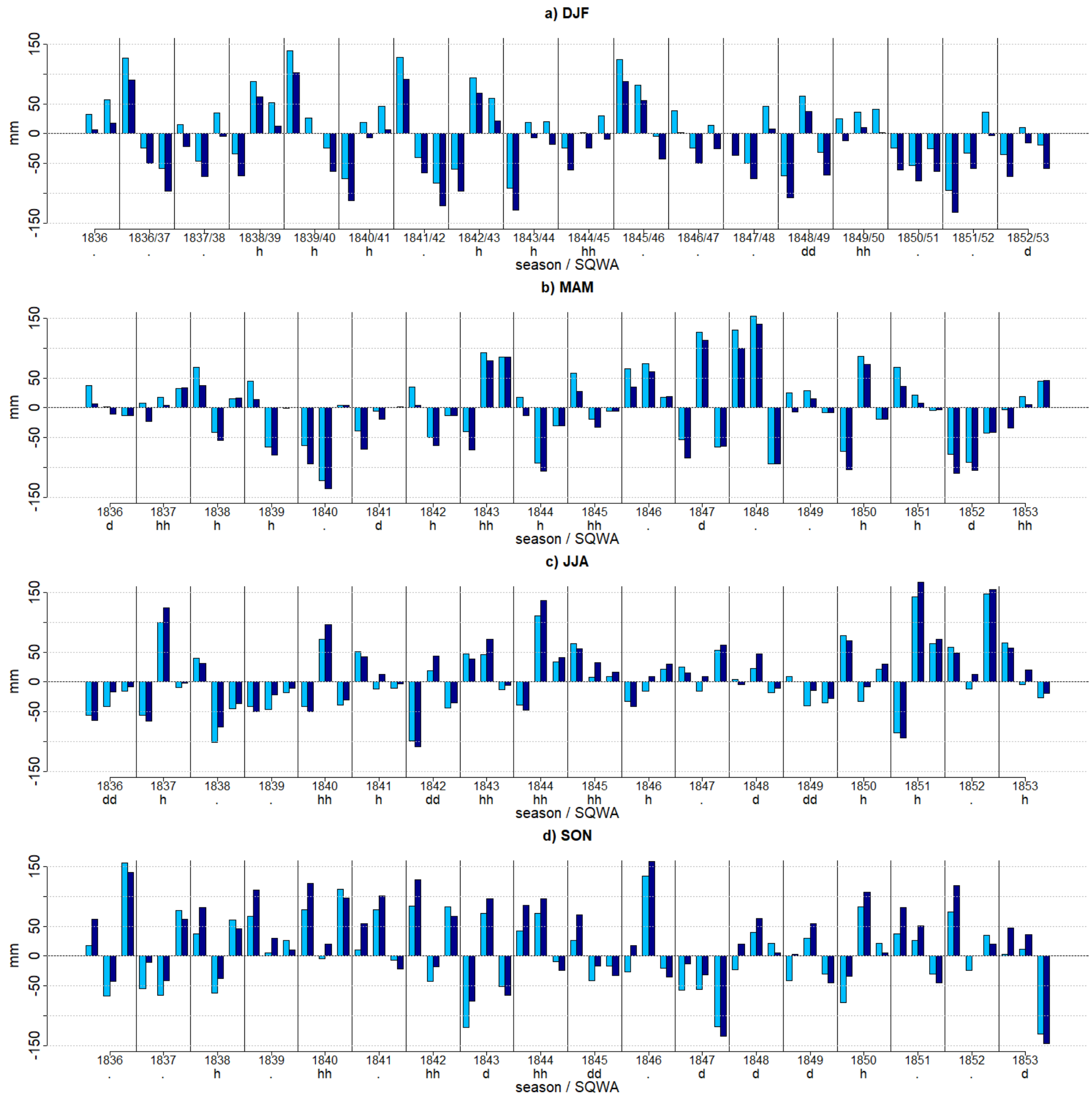

Figure 16: Monthly precipitation anomalies from HISTALP in mm by seasons (a) DJF; b) MAM; c) JJA; d) SON). Light blue: with respect to the 1831 to 1860 climatology; Dark blue: with respect to the 1961 to 1990 climatology

Figure 16 depicts the same diagnostics as Figure 15, only for precipitation instead of temperature. The values of the precipitation climatologies are less consistent than those for the temperature climatologies. The differences range from -43.83mm (September) to +38.3mm (January). Generally, the 1831 to 1860 SON and JJA climatologies are wetter and the 1831 to 1860 DJF and MAM climatologies are drier than their respective 1961 to 1990 climatologies.

For humidity, Sonklar distinguished between very dry(dd), dry(d), humid(h) and very humid(hh) seasons. For precipitation, the agreement between the SQWA and the data from HISTALP is a lot less pronounced than for temperature. The same reasoning with the Alpine character of the selected grid point may be adduced, as for the differences in the strength of the temperature trend. Additionally, precipitation shows a much larger spatial variability than temperature. Hence, differences between measurement stations spread around the Alps and one specific 5x5-minute Alpine grid point are a matter of course. The high solid precipitation rates for the years 1851 to 1853, as pointed out by Nussbaumer et al. (2016), are not visible in the HISTALP data set for that specific grid point, with the exception of single months during the SON seasons.

Again, the most prominent precipitation patterns are shown during the SON seasons. With the exceptions of the years 1837, 1843, 1845, 1847, 1849 and 1853 all the SON seasons from 1836 to 1853 show a positive precipitation anomaly, even compared to the wetter 1831 to 1860 climatology. Therefore, particularly at the beginning and the end of the period, there are several years in a row with above-average precipitation rate during the SON season. During the different DJF seasons, on the other hand, wet months compensate dryer ones and vice versa. With respect to the drier 1831 to 1860 climatology, only the DJF seasons during the years 1838/39, 1839/40, 1842/43, 1845/46 and 1849/50 exhibit a clear positive precipitation anomaly, while they only show negative anomalies during the years 1843/44, 1848/49 and 1850/51 to 1852/53. The important role of the MAM precipitation due to the albedo comes into effect for the years 1838, 1843, 1846, 1848 and 1851. The MAM seasons during the years 1840, 1844 and 1852 were the only ones with clearly subnormally dry conditions.

In summary, it can thus be noted that there was a run of subnormal summer temperatures during the years 1840 until 1847, interrupted by two above-average warm summers in 1842 and 1846.

Tendentially, the spring seasons were cold below average during years at the beginning and the end of the investigated period. Precipitation-wise, the spring seasons were rather undistinguished. Furthermore, 10 out of 18 fall seasons were subnormally cold, from which 8 were additionally wet. 12 out of 18 SON-seasons were wet above average and therefore partly compensated the often undistinguished or subnormally dry winter seasons. There was never more than one year in a row during which either the summer season or the fall season was not subnormally cold, with the latter being wetter. 1846 and 1849 were the only years during which no season was subnormally cold, whereby 1846 was a very wet year throughout the seasons relevant for glacier-growth.

3.2. Summer storminess and CAP7 anomalies from 1840 to 1847

One salient feature for the period between 1836 and 1853 was the run of cool summers from 1840 to 1847 interrupted by the warm summers in 1842 and 1846. The temperature anomalies during these years are reflected quite well in the storminess above the region, as Figure 17 demonstrates. With the exception of Milano in 1841, during the years 1841 and 1843 the summer anomaly of the storminess above the region around the Alps (Basel, Bern, Geneva, Col du Grand St. Bernard, Milano, Turin and Zurich) was higher than 1 hPa standard deviation and therefore higher than any of Brugnara's (2015, p. 1039) values for the same region for the summer seasons (120-day period starting on May 18^{th}) 1815 to 1817.[4] This coincided very well with the temperature anomalies, as 1841 and 1843 were the only two summer seasons with only negative temperature anomalies for all three months with respect to both, the modern and the contemporary climatology. (Figure 15 c))

The most important feature depicted in Figure 17 though, is that there was clearly a higher storminess above the region around the Lower Grindelwald glacier during the summer seasons from 1840 to 1845. The pattern of the anomalies above the other stations follows the one of the stations around the glacier, while for Uppsala and Stockholm, the storminess was also above average, though it remained below the amplitude of the more southerly stations. Therefore, the analysis of the storminess does not suggest a general southward-shift of the storm track during the summer months from 1840 to 1847 as the main reason for a cold anomaly over the glacier. Instead, the pattern suggests generally stormier conditions from central Europe to Scandinavia. Nevertheless, there were single summer seasons for which the pattern suggests a southward- or westward-shift of the storm track, such as the summer seasons during 1847 and 1839 respectively.

[4] The diagnostic with the 120-day period starting on May 18^{th} from Brugnara et al. applied to our data revealed generally lower positive as well as negative anomalies, though some of the anomalies of the 120-day summer season during the years 1841 and 148 above the region around the glacier are still above 1 hPa standard deviation. Hence, they are still higher than any of Brugnara's values above the same region for the summer-seasons 1815 to 1817.

Since the analysis of the storminess depicts seasonal results, it is possible that negative anomalies were partially compensated by positive anomalies over the course of a single summer season. Therefore, it is possible that during the summer seasons from 1840 to 1845, the storm track was temporarily shifted to the south of the Scandinavian stations.

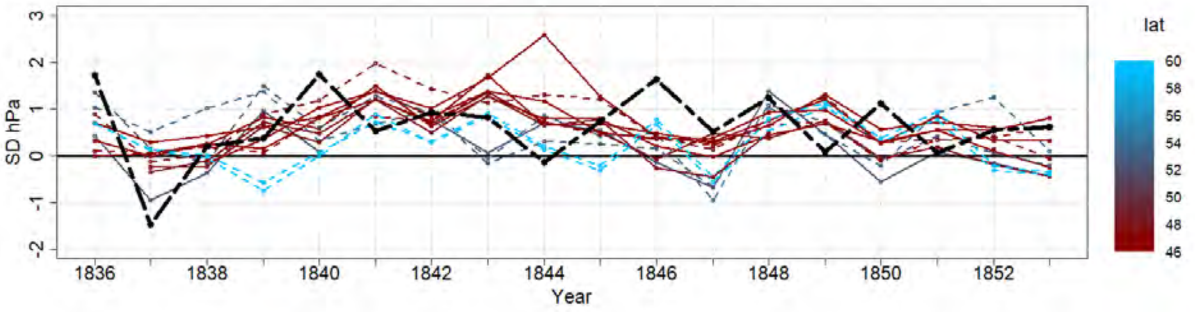

Figure 17: JJA-anomalies of the storminess in hPa standard deviation for different stations on a north-south transect of European stations (Table 6) with respect to the 1961 to 1990 climatology from the respective nearest grid point of twentieth century reanalysis. Solid lines represent measurement data and dashed lines represent daily average data. The latitude is expressed in the red-blue color-spectrum. The thick black two-dashed line represents the seasonal average of the NAO index. (Luterbacher et al., 2001)

Another way to explain the negative temperature anomaly during the summers of 1840 to 1847 is to compare them to the anomalies of the weather types from the CAP7 classification (Schwander et al., 2017). Figure 18, which depicts the monthly summer anomalies of the daily weather types with respect to the 1961 to 1990 climatology, was divided into the cyclonic/non-cyclonic scheme by colour. Blueish colours represent cyclonic conditions, while reddish colours represent non-cyclonic conditions. A comparison between the CAP7 anomalies and the temperature anomalies from HISTALP (Figure 15 c)) reveals that during months with positive anomalies for cyclonic conditions, the temperature above the glacier was tendentially below average and vice versa. Only two out of 24 months during the summer seasons between 1840 and 1847 did not fit into that pattern (August 1843 and August 1846). 14 out of 24 months from 1840 to 1847 revealed a cumulated anomaly of the cyclonic weather types above zero, while during the whole period from 1836 to 1853, only 26 out 54 months showed a positive anomaly. This underlies the importance of the summer seasons from 1840 to 1847 in relation to glacier growth.

Furthermore, the pattern of cyclonic conditions did not coincide with neither the anomalies of the storminess nor with the anomalies of the cyclonic weather types. Yet, it strikes the eye that only 2 out of 18 summer seasons showed a negative value of the NAO index.

The accordance between the CAP7 anomalies and the temperature anomalies is reflected in the Spearman correlation coefficient between the cumulated anomalies of the cyclonic weather types and the temperature anomalies above the glacier, which gave a significant relation of -0.59.

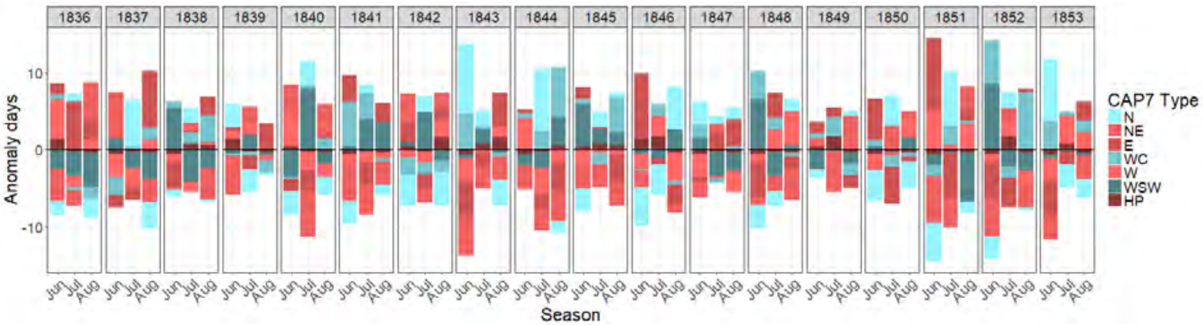

Figure 18: JJA-anomalies of the daily weather types from the CAP7 classification (Schwander et al., 2017) in days with respect to the 1961 to 1990 climatology. The cyclonic anomalies are represented by blueish and the non-cyclonic by reddish colors.

The accordance between the temperature anomalies and the storminess over the whole period is worse than the accordance between the anomalies of the HISTALP temperature and the weather type anomalies. This might be due to the lower spatial and temporal variability of SLP during summer. The baroclinic instability during summer seasons is reduced and the results of the storminess analysis is not as meaningful as for the other seasons (Brugnara et al., 2015, p. 1038). At the same time, the reconstruction of the daily weather types was most inexact for the summer months and most exact for the winter months (Schwander et al., 2017, p. 36). Although both the analysis – the storminess and the weather type analysis – behave less precisely for the summer months, the colder temperatures during the summers from 1840 to 1847 are reflected in both the analysis.

Hence, it can be noted that with the exception of the summers of 1842 and 1846, the summer months from 1840 to 1847 were dominated by rather cyclonic conditions. Therefore, six out of eight summers during that period were either entirely or partly cold below average.

3.3. Storminess and CAP7 anomalies during fall

Figure 19 depicts the storminess of the fall seasons analog to Figure 17 for the summer seasons. For the stations around the Alps, the pattern of the storminess during summers resembles the pattern of the storminess during the fall seasons. Both patterns show a constant positive anomaly during the years 1840 to 1844 (1845 for the summer seasons). For the fall seasons, there was another period from 1847 to 1850 during which there was a constant positive anomaly of the storminess above the Alps. The same anomaly of the storminess is visible for the summer months, only less distinct during the years 1848 and 1849. The NAO index on the other hand often shows negative anomalies during summer seasons with high storminess above the Alps and vice versa.

While the increase in storminess between 1840 and 1844 tendentially coincided with positive precipitation anomalies above the glacier, the increase in storminess from 1847 to 1850 coincided with negative temperature anomalies above the glacier. However, the falls of 1840 and 1842 were also subnormally cold thus shortening a warm summer (1842) or reinforcing the effect of a negative temperature anomaly during summer (1840).

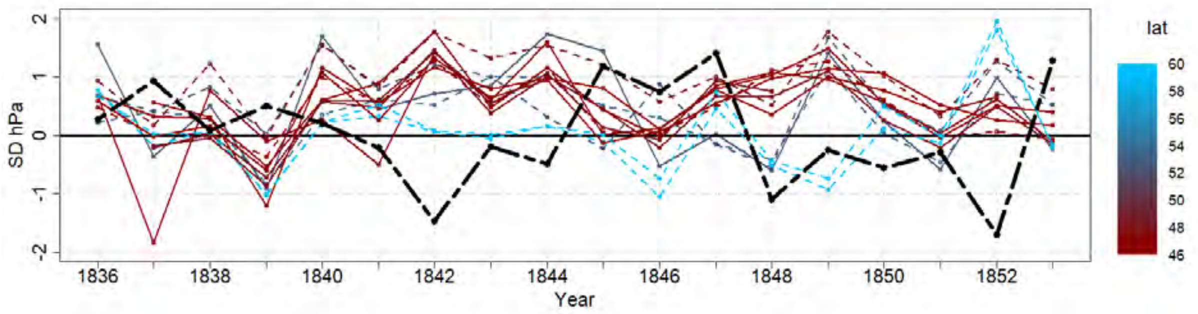

Figure 19: SON-anomalies of the storminess in hPa standard deviation for different stations on a north-south transect of European stations (Table 6) with respect to the 1961 to 1990 climatology from the respective nearest grid point of twentieth century reanalysis. Solid lines represent measurement data and dashed lines represent daily average data. The latitude is expressed in the red-blue color-spectrum. The thick black two-dashed line represents the seasonal average of the NAO index. (Luterbacher et al., 2001)

Generally, the storminess above the stations around the Alps was above average during the fall seasons. Only in 1839 was the average storminess at the stations around the Alps below the value of the climatology. Compared to the summer seasons, though, the anomaly of the storminess above the Scandinavian stations was often lower during fall. Particularly during the fall seasons of the years from 1842 to 1844 and from 1848 to 1849, the pattern suggests a southward shift of the storm track. A closer look at those seasons could therefore disclose relationships between the SLP anomalies and the storminess.

Figure 20 compares the anomalies of the SLP from the EKF400 data set (Franke et al. 2007) with the anomalies of the storminess for the fall seasons from 1842 to 1844 and from 1848 to 1849. The SLP anomalies during the years with a shift of the storm track resemble each other, with a positive SLP anomaly around the region of Iceland. This pattern resembles a negative NAO and therefore corresponds with a shift of the storm track and concomitant stormy conditions in central Europe. Only during the fall of 1843, which was the season among the five with the weakest storminess above central Europe and the lowest gradient in storminess between the stations outside of Scandinavia, there is no positive anomaly above Iceland. The course of the NAO index (Luterbacher et al., 2001) in Figure 19 confirms the assumption of negative NAO phases, with clear negative values for the fall seasons of 1842, 1844 and 1848 and a slightly negative for 1843 and 1849.

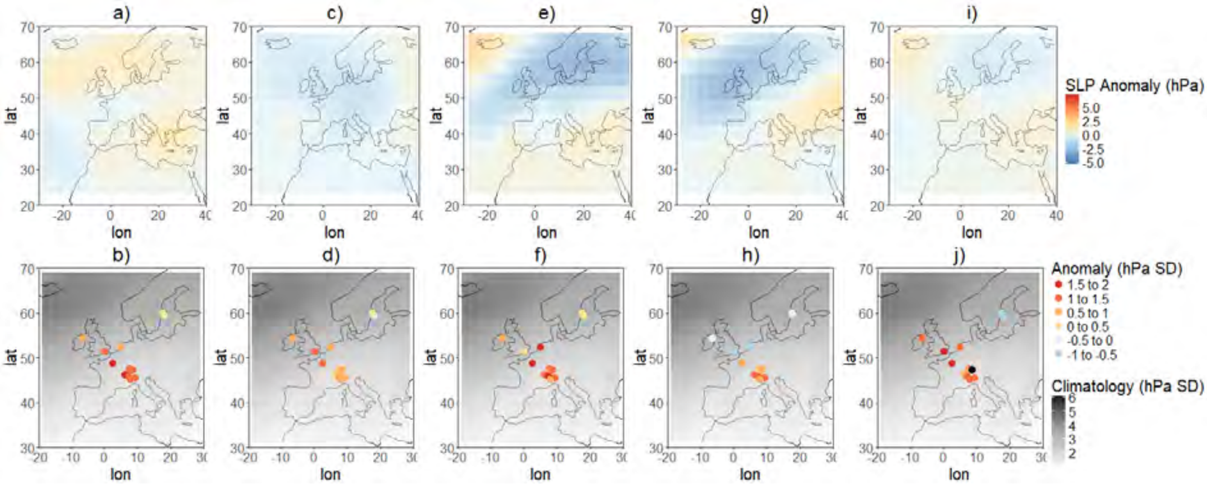

Figure 20: Fall SLP anomalies in hPa from EKF400 (Franke et al. 2007) in the upper row and SD of daily bandpass-filtered SLP in hPa in the lower row for the years 1842 (a) and b)), 1843 (c) and d)), 1844 (e) and f)), 1848 (g) and h)) and 1849 (i) and j)) compared to the respective 1961 to 1990 climatology from the EKF400 for SLP and from 20CR for storminess. The black dot in j) marks an NA for the station Zurich.

Nevertheless, the storminess alone is not able to explain the wet and cold fall conditions during the entire period spanning 1836 to 1853, yet the pattern of the precipitation anomalies above the glacier is well reflected in the anomalies of the CAP7 weather types. The Spearman correlation coefficient between the cumulated anomalies of the weather types N, WC and WSW and the precipitation anomalies above the glacier, gave a significant relation of 0.60.

In contrast to the summer seasons, the anomalies of the cyclonic weather types N, WC and WSW did not coincide well with the temperature anomalies, as a comparison between Figure 21 a), Figure 15 d) and Figure 16 c) reveals. According to Schwander et al. (2017, p. 36), the weather types NE, E and N should entail negative temperature anomalies due to continental flow with cold air coming from the east or the north and due to a low-pressure system located south of the North Sea in the case of weather type WC. But this schema of weather type anomalies neither reflects the temperature anomalies above the glacier during the fall seasons, as the Spearman correlation analysis gave a relation of insignificant -0.31.

Nevertheless, many of the fall seasons are dominated by positive anomalies of the cyclonic weather types. 46 out of 54 months show a positive anomaly of cyclonic weather types.

For the weather type HP, on the other hand, there are a lot of negative anomalies throughout the fall seasons from 1836 to 1853.

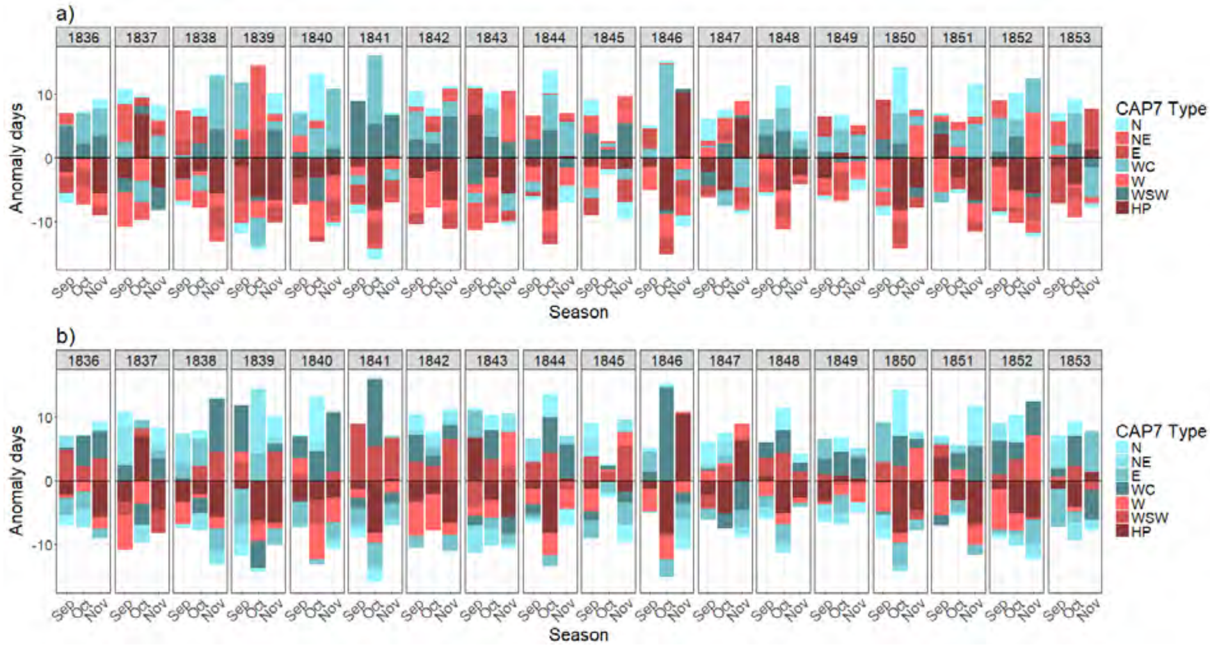

Figure 21: SON-anomalies of the daily weather types from the CAP7 classification (Schwander et al., 2017) in days with respect to the 1961 to 1990 climatology. a) The cyclonic anomalies are represented by blueish and the non-cyclonic by reddish colors. b) The weather types with cold anomalies are represented by blueish and the ones with warm anomalies by reddish colors.

In summary, it can be noted that the storminess above the region of the Alps did not reflect the pattern of the precipitation and temperature anomalies over the whole period, even though, the pattern of the storminess suggests a southward shift of the storm track during single fall seasons and tendentially a high storminess throughout the whole period during the fall months. However, the anomalies of the CAP7 weather types N, WC and WSW were able to reproduce the precipitation anomalies. The temperature anomalies, on the other hand, were not well-reflected in the CAP7 weather type anomalies. Generally, the fall seasons during the investigated period were dominated by cyclonic weather types.

3.4. Storminess and CAP7 anomalies during spring and winter

Figure 22 depicts the storminess of the spring seasons. In contrast to the summer and fall seasons, the spring season’s storminess was less frequently above and more frequently around and below the climatology. Generally, the identified negative temperature anomalies at the beginning and the end of the period and the positive precipitation anomalies during the years 1838, 1843, from 1846 to 1848 and 1851 are not well reflected by higher storminess. The negative precipitation anomalies during the years 1840, 1844 and 1852, on the other hand, coincide with low storminess values above the stations around the Alps. Nevertheless, the relation between storminess and precipitation anomalies is not clear.

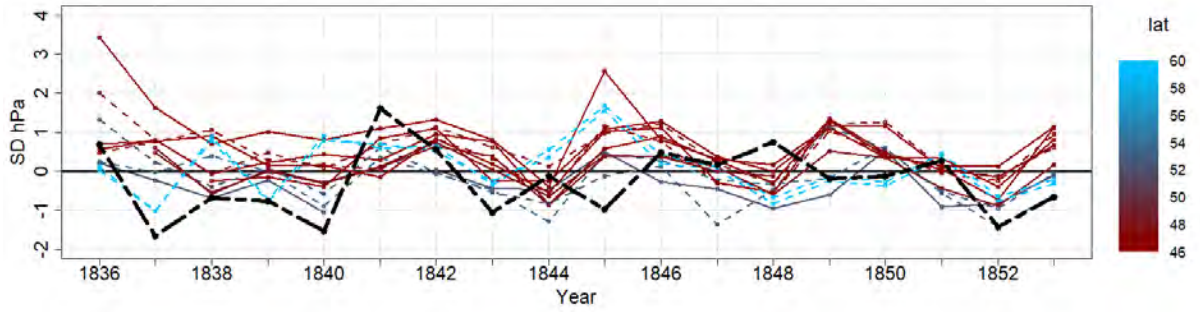

Figure 22: MAM-anomalies of the storminess in hPa standard deviation for different stations on a north-south transect of European stations (Table 6) with respect to the 1961 to 1990 climatology from the respective nearest grid point of twentieth century reanalysis. Solid lines represent measurement data and dashed lines represent daily average data. The latitude is expressed in the red-blue color spectrum. The thick black two-dashed line represents the seasonal average of the NAO index. (Luterbacher et al., 2001)

Figure 23 represents the same diagnostic as Figure 21, only for spring instead of fall. CAP7 anomalies during spring represent both the precipitation and the temperature anomalies quite well. The cyclonic/non-cyclonic weather type schema from Figure 23 a) represents the precipitation anomaly pattern, while the cold/warm anomaly weather type schema from Figure 23 b) represents the temperature anomalies.

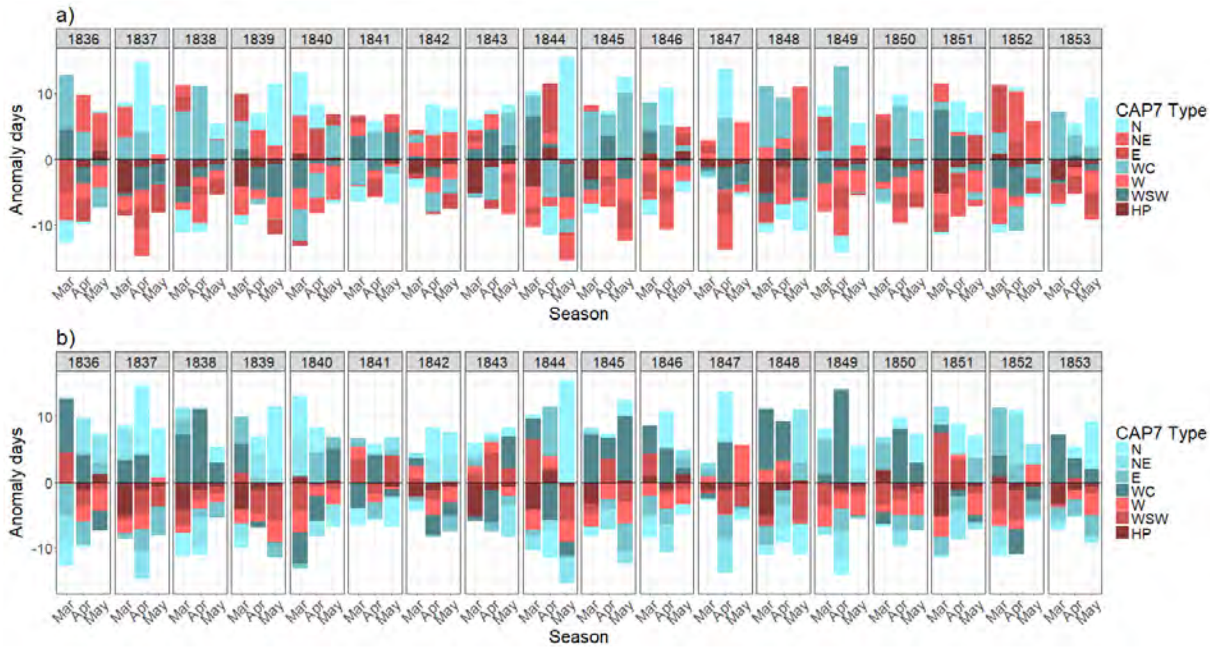

Figure 23: MAM-anomalies of the daily weather types from the CAP7 classification (Schwander et al., 2017) in days with respect to the 1961 to 1990 climatology. a) The cyclonic anomalies are represented by blueish and the non-cyclonic by reddish colors. b) The weather types with cold anomalies are represented by blueish and the ones with warm anomalies by reddish colors.

In terms of the Spearman correlation coefficient, the precipitation anomalies gave a significant relation of 0.61, while the temperature is reflected by a significant relation of -0.59. Consequently, the cold anomalies at the beginning and end of the period from 1836 to 1853 are well represented in Figure 23 b). 42 out of 54 months show a positive cumulative anomaly of the cold weather types N, NE, E and WC. The pattern of the NAO index coincides rather well with the pattern of the anomalies of the cold weather types N, NE, E and WC. The NAO index was tendentially negative when the cold weather types were prevailing.

As depicted in Figure 24, the storminess of the winter seasons shows the highest variability from season to season compared to the other seasons. Furthermore, the storminess of the winter seasons above the stations around the Alps was most often below that of the climatology. Additionally, the storminess at the stations around the Alps during the winter months resembles the winter precipitation anomaly pattern more than the respective storminess patterns during the other seasons for both the temperature and precipitation anomalies. Temperature anomalies, on the other hand, are not well-reflected. There is no single winter season for which the storminess pattern suggests a southward shift of the storm track. With the exception of the storminess above Basel, only during the winter 1844/45 was the storminess above all the northern stations below the storminess above those around the Alps. Hence, if there was a substantial southward shift of the storm track during the winter months, it was during the winter season of the year 1844/45. For all the other winter seasons, the pattern seems to suggest uniformly stormier or less stormy conditions for all the stations.

As the erratic pattern of the storminess, also the NAO index followed a rather erratic pattern. However, there was no clear relation neither between the storminess above the Alps nor the storminess above northern Europe and the NAO index.

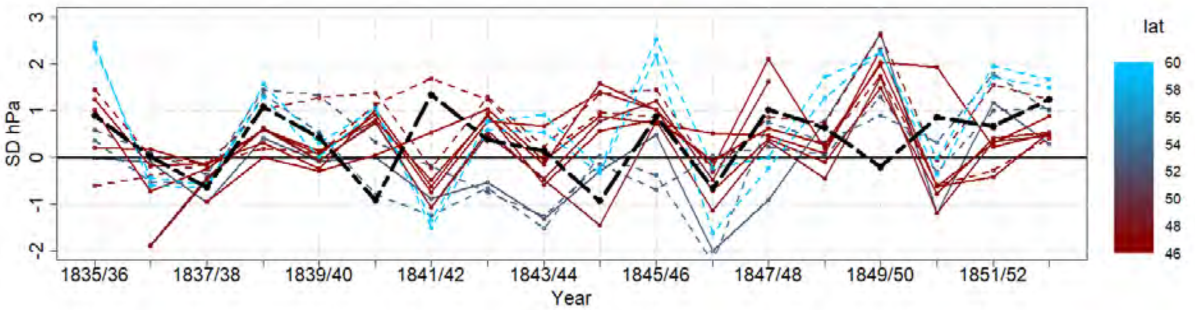

Figure 24: DJF-anomalies of the storminess in hPa standard deviation for different stations on a north-south transect of European stations (Table 6) with respect to the 1961 to 1990 climatology from the respective nearest grid point of twentieth century reanalysis. Solid lines represent measurement data and dashed lines represent daily average data. The latitude is expressed in the red-blue color spectrum. The thick black two-dashed line represents the seasonal average of the NAO index. (Luterbacher et al., 2001)

The winter storminess pattern is very erratic and this applies to the winter CAP7 anomalies as well. The cumulative anomalies of the cyclonic weather types correlate well with the precipitation anomalies above the glacier and are reflected in a significant Spearman correlation coefficient of 0.62, as well as the cumulative cold weather types reflecting the temperature anomalies well with a significant Spearman correlation coefficient of -0.6. The erratic pattern of the weather types is reflected in the cumulated anomalies of the cyclonic and the cold weather types as well, for which there are 30 respectively 29 out of 54 months in the positive spectrum.

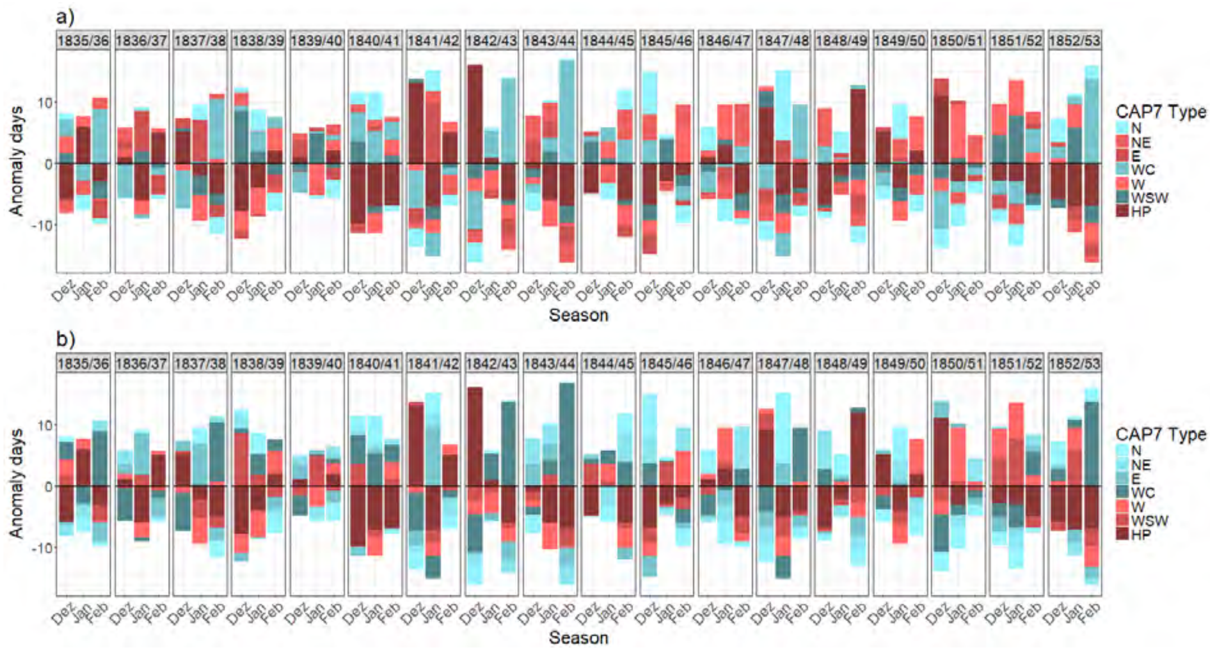

Figure 25: DJF-anomalies of the daily weather types from the CAP7 classification (Schwander et al., 2017) in days with respect to the 1961 to 1990 climatology. a) The cyclonic anomalies are represented by blueish and the non-cyclonic by reddish colors. b) The weather types with cold anomalies are represented by blueish and the ones with warm anomalies by reddish colors.

Overall, it can be noted that the average storminess above the stations Basel, Bern, Geneva, Col du Grand St. Bernard, Milano, Turin and Zurich during the winter season has the highest explanatory power with respect to precipitation anomalies, followed by the storminess of the summer seasons with respect to temperature. Nevertheless, the anomalies of the weather types show a higher accordance with the temperature anomalies and the precipitation above the glacier. While the anomalies of the cyclonic weather types N, WC and WSW gave significant Spearman correlation coefficients around 0.6, they also best explained the temperature anomalies during the summer seasons with a significant Spearman correlation coefficient of -0.59. The temperature anomalies during the winter and the spring seasons, on the other hand, were best explained by the anomalies of the weather types N, NE, E and WC, which are responsible for continental flow with cold air coming from the east or the north or for cold air masses. This is due to a low-pressure system located south of the North Sea.

Both the cold summers from 1840 to 1847 and the cold and wet fall seasons during the whole period investigated were due to a dominance of cyclonic weather types during that periods. The subnormally cold springs, on the other hand, were due to predominant weather types responsible for cold air masses from the east or the north.

3.5. Relation between the weather and the glacier length

A reconstruction of the glacier length by calculating a glacier growth index with von Sonklars (1858, p. 189-191) method did not produce reasonable results, neither by using the storminess data nor the CAP7 weather types. Both input factors contained too few information about the weather conditions above the glacier.

The storminess data only resembled the pattern of the winter precipitation and the summer temperature. During the seasons spring and fall the storminess data was only very weakly connected to precipitation and temperature, as discussed above. During the period from 1836 to 1853 the fall seasons for example coincided with positive precipitation anomalies from 1840 to 1844 while the temperature was close to the average during the fall seasons of 1841, 1843 and 1844. On the other hand, the stormy falls from 1847 to 1850 rather coincided with negative temperature anomalies above the glacier, while the precipitation pattern was rather erratic. Furthermore, the subnormally cold spring seasons at the beginning and the end of the investigated period were completely hidden in the storminess data.

The anomalies of the CAP7 weather types on the other hand showed a Spearman correlation between 0.6 and 0.62 for the glacier relevant precipitation patterns and between -0.59 and -6 for the temperature patterns. Only for the fall precipitation the correlated coefficient of -0.31 was worse. Nevertheless, a lot of information, such as air moisture, CO_2 concentration or cloudiness is missing or only indirectly contained in the anomalies of the weather types.

Therefore, only a qualitative analysis between the weather conditions from 1836 to 1853 is reasonable. This will be done by relating the outcomes of the Chapters 4.1. to 4.4. to the theory of the climate respectively weather sensibility of the Lower Grindelwald Glacier.

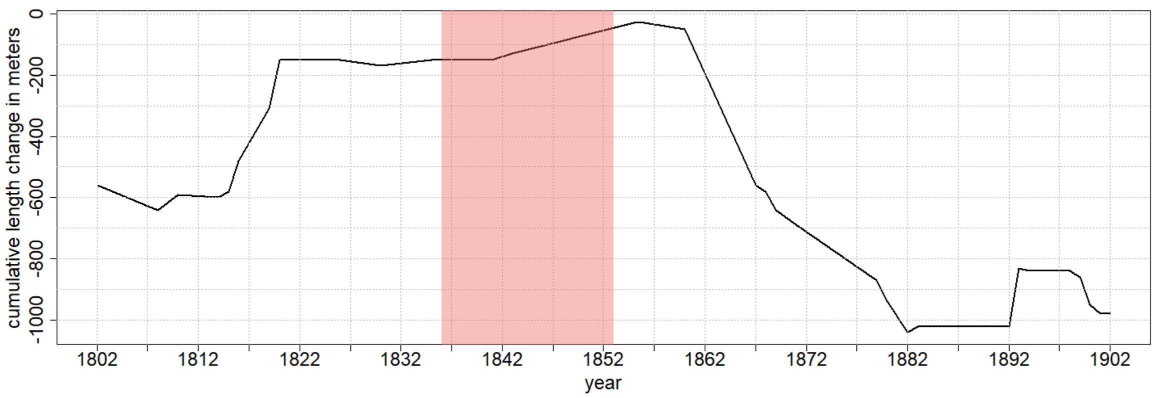

Figure 26: Reconstructed length of the Lower Grindelwald Glacier from Zumbühl (2016, p. 113-114) with a red band indicating the timespan of the analysis.

Figure 26 depicts the cumulative length change of the Lower Grindelwald Glacier during the 19th century after Zumbühl et al. Zumbühl. (2016, p. 113-114) As discussed above, the glacier went through a strong growing phase in the course of the eruptions of the Unknown Volcano and the Tambora. Furthermore, the Dalton minimum led to cold temperatures and prevented an overcompensation of temperature drop in the course of the 1820s. The eruptions of Babuyan Claro in 1831 and of Cosigüina in 1835 caused a temperature drop until the late 1830s. Hence, from the 1840s onwards there was no additional forcing, which could have led to cooling on a hemispheric to global scale. On the contrary, after a few years of recovery from the influence of the volcanic eruptions and a normalization of the solar activity, a rapid retreat of the alpine glaciers to pre-1820s levels could reasonably be expected.

Yet, the Upper Grindelwald Glacier started to grow during the 1840s. Since the response time of the Lower Grindelwald Glacier lies between 34 to 45 years, consequently the reaction time between 20 and 30 years, the glacial advance simply could be a signal of the cold decades from 1815 to 1835. Nevertheless, most of the glaciers in the Bernese Alps advanced from 1840 onwards simultaneously (Zumbühl, 2016, p. 136). This matches the pattern of glaciers of different sizes and characteristics advancing simultaneously after runs of cool summers, described by Matthews and Briffa. (2005, p. 25)

As discussed above there was a run of cool summers between 1840 and 1847 which coincided with the glacial advance in the Bernese Alps, induced by cyclonic conditions and rather stormy conditions in central Europe. There were summer months during which there was snowfall as far down as to the pre-Alps, as Benoit (1853, p. 35; p. 46; p. 70; p. 71; p. 96) noted for the months July 1840, June 1841, June 1843, July 1843 and August 1845. Due to the albedo and the positive mass balance, summers during which snow falls on parts of the glacier — which under normal circumstances would be subject to melting — are extremely favorable for the growth of a glacier, especially if such conditions occur over several years in a row.

In addition to this, the summer seasons during the years before and after the run of cold summers were shortened by rather cold spring and fall seasons, both induced by anomalies of the weather types N, E, NE and WC.

In terms of the precipitation, the fall was the most important season, since wet winters alternated with drier ones. The wet fall seasons during almost the entire investigated period were dominated by cyclonic conditions. Furthermore, the fall seasons compared to other seasons were the stormiest in the Alps. The storminess during the fall seasons of 1840 and 1844 coincided with positive precipitation anomalies above the glacier, while the storminess from 1847 to 1850 rather coincided with negative temperature anomalies. Additionally, there was a southward shift of the storm track during the fall seasons of 1842, 1844 and 1848, which coincided well with negative phases of the NAO.

Casty et al. (2005, p. 1871) only found significant correlation values between the NAO index and temperature and precipitation values in the alpine region for the extended winter seasons (DJFM), with a positive correlation for temperature and a negative correlation for precipitation. Nevertheless, there were visible patterns of such a relation between the NAO index, the storminess and the CAP7 weather type anomalies for the seasons fall and spring during the period from 1836 to 1853. In spring the negative anomalies of the NAO index resembled the anomalies of the cold weather types N, E, NE and WC. During the fall seasons the storminess coincided with negative anomalies of the NAO index.

In summary it can be said that especially the signal of the cold anomalies during the summer seasons from 1840 to 1847 is visible in the advance of the Lower Grindelwald Glacier. Nevertheless, the positive precipitation anomalies during the fall seasons are evident as well and certainly had a positive effect on the growth of the glacier, as well as the negative temperature anomalies during the fall and spring seasons. Hence, predominantly the summer temperatures as well as the fall precipitation played an important role, as already for the period 1810 to 1820 (Steiner et al., 2008, p. 426-433). Both factors were important for the advance of the glacier from 1840 to the mid 1850s.

4. Conclusion

The temperature and pressure series recorded at the city of Bern from 1837 to 1853 by Daniel Gottlieb Benoit has been digitized and validated. The goal of the validation process was to reconstruct the sources of measurement errors as precisely as possible. However, since the knowledge about the exact circumstances of the measurements and the structure of the instruments would have to be more comprehensive, the circumstances merely allowed for qualitative statements about the error.

The comparison of Benoit's digitized temperature series to the reference series of Johann Friedrich Trechsel, to other historical measurements from different locations across Switzerland, to the HISTALP data and to the outcome of the literature research revealed that the winter morning measurements were the ones least affected by biases. The afternoon measurements were generally more affected by a positive bias. Furthermore, the bias varied with the seasons and was the largest during the summer season. Consequently, the bias due to insufficient protection of the thermometer to scattered and reflected radiation was the dominant one. Breakpoints during the summer of 1843 as well as during October 1847 have been identified in Benoit's temperature measurements. Generally, the temperature measurements were more reliable in relative than in absolute terms.

The outcome of the validation of the pressure series, on the other hand, revealed that from both a relative and absolute perspective, Benoit's morning measurements were more precise than his afternoon measurements. Despite a possible temperature correction for 10° R instead of 0°, we cannot be sure about the correctness of the pressure values in terms of absolute values. The accordance between Benoit's measurements, the different stations and the 20CR data was generally high. The worst results turned out to be during the summer seasons, which can be partly explained by the reduction to SLP values through using more biased temperature values in comparison to the winter seasons. Furthermore, there were breakpoints during February 1838, June 1840 and February 1845. Up to the breakpoint of June 1840, the morning measurements had been negatively biased and additionally the afternoon measurements were positively biased.

It can generally be stated that the validation of pressure measurements from the first half of the 19th century is more problematic than the validation of the temperature measurements. Due to disturbances of the historical pressure measurements which cannot be replicated, the results of the validation of the pressure measurements are tainted with more uncertainty. Nevertheless, some of the results can be used for the validation of earlier series from the city of Bern and other locations. The larger bias for the noon temperature measurements for example should generally be existent, since there was no protection of the thermometer from scattered radiation before the timespan of the series validated in the work at hand.

The results of the first part of the work at hand may be adapted and assigned to older daily or sub-daily temperature and pressure measurements from the city of Bern, which are already digitized. Especially, the evaluation of Trechsel's series may be of use because it goes further back in time than the published parts used in the work at hand. It was measured with the same instruments presumably at the same location (Herrengasse 1). Finally, a continuous and homogenized series from the city of Bern back into the mid-18th century could now be assembled.

The analysis of the relation between the weather from 1836 to 1853 revealed clear results. A run of subnormal cold summers during the years between 1840 and 1847, interrupted by two above-average warm summers in 1842 and 1846, coincided with a growing phase of the Lower Grindelwald Glacier and other glaciers from the Bernese Alps. The negative temperature anomalies during the summer months from 1840 to 1847 were reflected in the anomalies of the storminess as well as in the anomalies of cyclonic CAP7 weather types.

The subnormally cold spring seasons during years at the beginning and the end of the period from 1836 to 1853 further shortened the warm periods during years, without a negative temperature anomaly for the JJA months. The anomalies of the weather types N, NE, E and WC, which are accompanied by cold temperatures throughout central Europe, did match the pattern of the negative temperature anomalies during the spring seasons.

During the period from 1836 to 1853, there were many fall seasons with strong positive precipitation anomalies and negative temperature anomalies. Although neither the anomalies of the cyclonic nor the cold CAP7 weather types reflected the cold anomalies, the precipitation anomalies were well-described by anomalies of the cyclonic weather types. The analysis of the storminess showed a similar pattern as the storminess during the summer months and was quite well-reflected by negative phases of NAO index. The cold and wet fall seasons also shortened the summer season in terms of temperature and prolonged the winter seasons in terms precipitation.

Wet winter months and seasons, on the other hand, were often compensated by rather dry months within the same season or were followed by a dry winter season in the following year and vice versa.

In the light of all this, the advance of the Lower Grindelwald Glacier was the result of a run of cold and short summers, accompanied by wet fall seasons, which overcompensated the rather indifferent winter seasons. As this pattern resembles the one Steiner et al. identified for the advance of the Lower Grindelwald Glacier from 1810 to 1820, it would be interesting to ask for resemblances between the years from 1810 to 1820 and from 1840 to 1855. Especially, a closer look at the repercussions of the Atlantic Multidecadal Oscillation (AMO) and the NAO on central European weather during the first half of the 19^{th} century would be desirable, as there was a constant negative phase of the AMO from the 1780s to the late 1840s. (Gray et al., 2004)

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Declaration

under Art. 28 Para. 2 RSL 05

Last, first name: Flückiger, Julian

Matriculation number: 08-117-525

Programme: M.Sc. in Climate Science

Bachelor ☐ Master ☒ Dissertation ☐

Thesis title: Glacier-friendly weather? Sub-daily pressure and temperature data from the city of Bern around the mid-19th century

Thesis supervisor: Prof. Dr. Stefan Brönnimann and Prof. Dr. Christian Rohr

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due acknowledgement has been made in the text. In accordance with academic rules and ethical conduct, I have fully cited and referenced all material and results that are not original to this work. I am well aware of the fact that, on the basis of Article 36 Paragraph 1 Letter o of the University Law of 5 September 1996, the Senate is entitled to deny the title awarded on the basis of this work if proven otherwise. I grant inspection of my thesis.

Bern 30.7.18
Place, date

Signature