An Evaluation of Meteorological Observations by Samuel Studer (1807-1818)

Master's Thesis

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Abstract

Early instrumental measurement series contain a vast amount of climatological data. Within this study, the meteorological observations by Samuel Studer from 1807 to 1818 are evaluated. By summarizing information on the life of Studer and his social environment, this study works out the motivation behind the lengthy endeavor of noting sub-daily measurements and observations for 48 years. The aim of this study was to report on the limitations and potential of the series and to make the series more accessible for future research. The temperature and air pressure measurements from Studer underwent a homogeneity assessment. In addition, the precipitation observations were transformed into quantitative data. A case study further investigated the climatic consequences of the Unknown Eruption and the eruption of Mount Tambora. The research question, whether the climatic consequences of these eruptions can be found in the Studer series, is answered by applying hypothesis testing to the monthly data. This study has presented the Studer series and has made it more accessible to future research. The main limitations concern the availability of the metadata for the entire Studer series and the vast amount of missing values during Studer's travels (especially in the summer months). The length and high resolution of this series, however, provide a great opportunity for it to be embedded in studies that also include other early instrumental measurements series of Switzerland; thus, it is a valuable source of information for climate research.

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Table of Contents

1. Introduction

One person's commitment to 48 years of meteorological observations and measurements represents the basis of this thesis. The man behind this lengthy endeavor was Samuel Emanuel Studer. Toward the end of the 18th century and the beginning of the 19th century, this intellectually curious professor committed to observe and to measure the weather three times a day. He noted meticulously the values of temperature and air pressure and made further observations on wind and the general weather conditions. Studer, who was born in Bern, Switzerland, set up his measuring station in his hometown at the Burgerspital, an establishment that is still well known in Bern. Studer generated a large amount of data, which can be of great use for climate research.[1] "Knowledge of the past is one of the keys to interpreting the present and forecasting the future,"[2] reads one of the first lines of a key study conducted by Camuffo and Jones (2002). However, in Switzerland, a national meteorological network was only initiated in December 1863.[3] Even globally, data coverage does not allow for a mean temperature series extending to the pre-industrialized era. Paradoxically, this time also marks the onset of an increase associated with fossil fuel emissions.[4] To understand and to estimate the anthropogenic effects on climate, historical climate analysis can help to provide a "more accurate understanding of the natural background climate variability."[5] Records that go back to the era prior to the 1850s are very valuable to climate sciences. They can provide crucial information on decadal climatic anomalies and changes.[6] For this reason, the project named *Swiss Early Instrumental Measurements for Studying Decadal Climate Variability* (CHIMES) aimed at making several records of the early instrumental period (i.e., the period up to 1850)[7] more accessible by taking images of the original records and digitizing the data.[8] This work also included the Studer series, which enabled a preliminary study in 2019 to evaluate the Studer data. The sections of the period analyzed (1808-1810 and 1815-1816) were chosen to answer the following question: To what extent can the effects of two volcanic eruptions be seen in the Studer data and how can they be compared with each other?[9] This thesis directly connects to

[1] Cf. Studer, Meteorologische Betrachtungen, BB BE, Mss. Hist. Helv. XX 5.1–5.5 [from here on: Studer: Meteorologische Betrachtungen 1779-1827].
[2] Cf. Camuffo, Jones 2002.
[3] Cf. Pfister et al. 2019: 1346.
[4] Cf. Böhm et al. 2010: 42.
[5] Cf. Brázdil et al. 2005: 363.
[6] Cf. Pfister et al. 2019: 1356.
[7] Cf. Böhm et al. 2010: 42.
[8] Cf. Pfister et al. 2019; Brönnimann et al. 2020; Brugnara et al. 2020.
[9] Cf. Hari 2019.

this preliminary study by further evaluating the data and choosing more sophisticated methods and applying them to a larger choice of variables over a longer time period.

1.1. Research Questions/Aim and Limitations of the Thesis

This thesis aimed to finish what has been started with the preliminary study.[10] The focus of this preliminary study was on two extreme events, namely two volcanic eruptions in the early 19th century. It aimed to fill a research gap because the Studer series has not yet been thoroughly evaluated. This master's thesis continued to pursue this evaluation. The overarching goal of this thesis, however, was to make the Studer time series more accessible and to refurbish the important metadata. By working through the source, homogenizing the temperature and air pressure measurements, and converting descriptive notes about precipitation to quantitative data, the Studer series should be of use for future studies. In addition, through the homogeneity assessment of the temperature and air pressure data, the potential as well as the limitations of this time series have been presented. The evaluation of the precipitation observations should embed this study in other research that has included the Studer series and will contribute to the overarching goal of this thesis.

The second aim of this study was to connect it directly to the preliminary study by expanding the period of investigation. In the preliminary study, the years 1808-1810 and 1815-1816 were evaluated. The gap between 1810 and 1815 has been filled and the period has been expanded by another two years. Hence, the period from 1807 to 1818 is the focal point of this study. Further, a case study has been conducted to answer the following research question: Can the climatological consequences of the Unknown Eruption and the eruption of Mount Tambora be detected in Studer's data in the two years after the eruptions? This research question has several sub-questions: Are the temperature and air pressure anomalies significantly lower in the two summers following the eruptions? Are the precipitation anomalies in the Studer data significantly higher in the two summers after the eruptions? Are these hypotheses also true when investigating the periods March-August and September-February in the two years following the eruptions?

In general, the evaluated period still has to be limited; otherwise, the study would go beyond the scope of a master's thesis, especially due to the high resolution and vast amount of data this series offers. Thus, the period most relevant to investigate the climatic impacts of the Unknown

[10] Cf. Hari 2019.

Eruption and the Mount Tambora eruption has been chosen. Nevertheless, there are also conclusions that indicate the potential and limitations of the unevaluated period. It was further considered important to finish what has been started by the preliminary study, which is mainly done by the case study. In comparison to this preliminary study, the time period as well as the investigated variables have been expanded from temperature measurements to also include air pressure and precipitation to investigate the hypotheses regarding the climatic impacts of the volcanic eruptions. The variables have been purposely limited to fulfill the aim of this study and information on, for example, wind and cloud coverage have been excluded. The thesis intentionally excluded the explicit comparison to or embedment in other time series, as the aim was to focus on the Studer data itself. The homogeneity assessment has been conducted to gain additional insight about the Studer series. This tool has been applied to fulfill the aim of this study and might be neither perfect nor complete in every way. However, the aim was also to use more sophisticated quantitative methods compared with the preliminary study, an endeavor that entails the use of new methods.

1.2. State of Source Materials

The ultimate starting point of this study can be traced to the CHIMES project. The aim of that project was to collect and to digitize early instrumental meteorological measurement series to produce a systematic inventory. The project saw a need to extend these records back to pre-industrial times to better understand decadal variability in weather and the climatic variations that occurred in the 18th and 19th centuries in central Europe.[11] In the 1950s, only three series reaching further back than 1864 had been re-evaluated for Switzerland (Geneva, Basel, and Great St. Bernard Pass). The series collected for the CHIMES project present individual difficulties. The history of meteorological measurements is one of many discontinued projects. Because the measurements usually did not follow systematic standards, it is necessary to refurbish not only the data itself but also other background information on the origin and circumstances of the observations, and even the observers themselves. Many series have been found and the measurements, as well as the available metadata, have been photographed and digitized to enable future users to make use of the data.[12] This preparatory work has made this study possible, as this thesis is based on the materials provided by the CHIMES project.

[11] Cf. Pfister et al. 2019: 1345.
[12] Cf. ibid.: 1350.

The underlying source of this study is the meteorological observations by Samuel Studer.[13] The digitization has been very valuable to ensure processing the data was as unproblematic as possible. The photographs have also been of immense value, as the archive was not accessible for a long period of time during this study, due to a global pandemic. The quality control on temperature and air pressure conducted in Chapter 4 of this study, however, has revealed many limitations of the initial digitization conducted by the CHIMES project. Thus, many values still had to be digitized[14] as part of this study. In addition, the descriptive notes had not been transcribed and digitized, an endeavor that has been partially done in this study. The CHIMES project does not stand alone with the work it has done on early instrumental measurement series. The *Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region* (HISTALP) database, for example, has collected and homogenized monthly records of temperature, pressure, precipitation, sunshine, and cloudiness for the "Greater Alpine Region." Approximately ten years of work went into that endeavor, which goes to show the lengthy work behind such a compilation.[15]

1.3. State of Research

1.3.1. Historical Climatology

The first definition of the term "historical climatology" was delivered by Ingram, Underhill, and Wigley in 1978. They defined it as a sub-discipline concerned with the study and the climatic interpretation of documentary evidence,[16] excluding non-descriptive evidence and thus including only periods when written records were available.[17] However, more modern definitions exist, which take the term further than Ingram, Underhill, and Wigley did. A very extensive literature review of historical climatology was given in 2015 by Chantal Camenisch in her book *Endlose Kälte*.[18] The elaboration of the state of research of historical climatology here can only be seen as an overview. It should not be seen as a complete review because it is focused on Europe—and especially Switzerland—to fit the purpose of this study. Following Camenisch, historical climatology as an independent scientific discipline was established by

[13] Cf. Studer: Meteorologische Betrachtungen 1779-1827.
[14] In this study, the terms "transcription" and "digitization" will be used as follows: The term transcription will only be used for the word-for-word rendering of actual words. For the rendering of data, the term digitization will be used, because the data are immediately processed further and integrated into the relevant data table. The word "digitization" does not necessarily include the act of taking photos or scanning the source. If photographs were taken of the source, this will be mentioned specifically.
[15] Cf. Auer et al. 2007.
[16] Cf. Ingram, Underhill, Wigley 1978: 329.
[17] Cf. Brázdil et al. 2005: 365; Mauelshagen 2010: 16.
[18] Cf. for a more detailed review Camenisch 2015: 15-30.

Emmanuel Le Roy Ladurie.[19] In 1959, he proposed a new research path, where climatic factors must be isolated and recognized before historians could attempt to determine the possible influence of this factor in the history of mankind.[20] In his later work, he further advocated that climate history should be freed from any anthropogenic preoccupation or presupposition.[21] An opponent of Ladurie's view was Hubert Horace Lamb, as he followed the approach of the connection between climate and human history.[22]

The Bernese social, economic, and environmental historian Christian Pfister is a pioneer for climate research in the field of historical climatology, especially in Switzerland.[23] With *Klimageschichte der Schweiz 1525-1860*[24] and *Wetternachhersage*,[25] he has shaped historical climate reconstruction of past climatic conditions and the term "Wetternachhersage."[26] Pfister positioned historical climatology at the interface between climatology and (environmental) history.[27] He defined three objectives for modern historical climatology: reconstruction of weather and climate, investigation of vulnerability of past societies to climatic extremes and natural disasters, and exploration of past discourses on climate.[28] Pfister was also one of the contributors to *The Palgrave Handbook of Climate History*,[29] which gives a great overview of the current state of research, the methods of climate reconstruction, and the periods and regions of historical climatology, as well as climate and society, and further includes case studies in climate reconstruction and impacts. Another reconstruction was provided by Rüdiger Glaser in *Klimageschichte Mitteleuropas*,[30] which includes a reconstruction of weather, climate over 1,200 years.

[19] Cf. ibid.: 15-30.
[20] Cf. Le Roy Ladurie 1959: 6-7.
[21] Cf. Le Roy Ladurie 1967: 25; see also Mauelshagen 2010: 23. This rejection of determinism was a prerequisite for Le Roy Ladurie as the only form of climate history: a history without people. See also Mauelshagen 2010: 20-26.
[22] Cf. Camenisch 2015: 17; Mauelshagen 2010: 27.
[23] Cf. Brázdil et al. 2005: 365; Camenisch 2015: 18; Mauelshagen 2010: 27.
[24] Cf. Pfister 1988.
[25] Cf. Pfister 1999.
[26] With his *Wetternachhersage*, Pfister presented a 500-year-long reconstruction, which is considered a milestone in historical climatology. He succeeded in converting temperature and precipitation indices that he introduced in 1988, in a monthly resolution. For more details, see Pfister 1999.
[27] Cf. Pfister 2010: 25; Brázdil et al. 2005: 365.
[28] Cf. Brázdil et al. 2005: 365-366; Mauelshagen 2010: 20; Pfister 2010: 25.
[29] Cf. White, Pfister, Mauelshagen 2018.
[30] Cf. Glaser 2013.

1.3.2. Early Instrumental Measurement Series and Volcanic Eruptions

An essential method that has been applied to this study is a homogeneity assessment. Such studies have been conducted at length on other time series. A major project already mentioned in Chapter 1.2 is the compilation and homogenization of the "Greater Alpine Region" early instrumental measurement series into the HISTALP database.[31] A further project along these lines is the project with the name *Improved understanding of past climatic variability from early daily European instrumental sources* (IMPROVE) coordinated by Dario Camuffo and Phil Jones. They saw the potential of early instrumental measurement data to develop and to validate climate models on different time and spatial scales. The project has provided highly reliable temperature and air pressure series.[32] This research gives much information on the application of homogenization and generally deals with early instrumental sources. Besides providing the temperature and air pressure series, they have also summarized information on the instruments themselves and have pinpointed technical difficulties or aspects of which one needs to be aware.[33]

For Swiss time series, spanning to the pre-industrial era, the Basel, Geneva, and Great St. Bernhard Pass series have been made more accessible and have undergone a homogenization.[34] These three series were also included in the DigiHom project, which entailed the digitization and homogenization of historical climate data from MeteoSwiss.[35] For a thorough description of digitized datasets from Switzerland, the study conducted by Brugnara et al. (2020) should be taken into account, especially since this study is also concerned with difficulties digitization can pose.[36] Even though large projects such as IMPROVE have been launched to improve past climatic variability from early instrumental measurement sources, little has been done on the study of precipitation. For example, the IMPROVE project does not include early instrumental measurement series of precipitation. Indeed, little is known about precipitation patterns of pre-industrial times from instrumental data. However, numerous studies have been performed on precipitation using natural proxy information or documentary proxy records.[37] Fortunately, Gimmi et al. (2007) conducted an extensive reconstruction study of precipitation series, and

[31] Cf. Auer et al. 2007.
[32] Cf. Camuffo, Jones 2002.
[33] Cf. Camuffo 2002a; Camuffo 2002b.
[34] Cf. e.g., Bider, Schüepp, Rudloff 1959; Bider, Schüepp 1961; Schüepp 1961.
[35] Cf. Füllemann et al. 2011.
[36] Cf. Brugnara et al. 2020.
[37] Cf. Gimmi et al. 2007: 186.

used precipitation series of Bern as an example. The authors also included the Studer series in their study and thus the evaluation of precipitation in this thesis will often refer to that study.[38]

The state of research of the two volcanic eruptions discussed here has been extensively elaborated in the preliminary study[39]; therefore, it will not be repeated here. However, a study conducted by Krämer should be added. For research on the socioeconomic impacts of the Mount Tambora eruption on Switzerland, his study *"Menschen grasten nun mit dem Vieh". Die letzte grosse Hungerkrise der Schweiz 1816/17*[40] should be consulted. He aimed to present an overall account of the last famine in Switzerland and thus show the situation in Switzerland in the years 1816/1817.

Many more research projects could be mentioned at this point on both early instrumental measurement series as well as on the two volcanic eruptions. This summary of the state of research is thus far from complete but should provide reference points to certain studies that have been referenced to complete this study.

1.4. Structure of the Thesis

The structure of this thesis has been chosen to evaluate the Studer series and to answer the posed research questions concerning the volcanic eruptions. Following this introductory chapter, Chapter 2 will present the applied methods, which represent a major distinction compared with the preliminary study. The main body of the thesis has been divided into three chapters. Chapter 3 will elaborate on Studer and the source of his series. Then, Chapter 4 will extensively present the air temperature and pressure measurements as well as the precipitation observations that are part of the Studer series. The temperature and air pressure data will undergo a homogeneity assessment following the World Meteorological Organization (WMO) guidelines.[41] Hence, the sub-chapters will follow these procedural steps as well. After the homogeneity assessment, the monthly averages of air temperature as well as pressure will be presented. While the precipitation observations will be dealt with differently, they will also be presented quantitatively. The final part of the main body, Chapter 5, will contain a case study that connects directly to the preliminary study. In this chapter, the two volcanic eruptions that

[38] Cf. ibid.: 186.
[39] Cf. Hari 2019: 6-7.
[40] Cf. Krämer 2015.
[41] Cf. Aguilar et al. 2003.

are the focus of this case study will be presented and, finally, the results from the previous chapters will be used to answer the research questions posed concerning the volcanic eruptions (also in the preliminary study). Chapter 6 will conclude this thesis and give an outlook on further possible research.

2. Methods

The reconstruction of an early instrumental measurement series requires qualitative and quantitative methods. The structure of this study explained in Chapter 1 includes three sub-sections in the main bodies of this study, for which different methods will be applied.

The first part of the study considered that the basis of this thesis is a historical source. Thus, a thorough source criticism examining the author's circumstances, environment, and mainly the intentions to conduct meteorological measurements and observations will be applied. This source criticism will be used to explain the vast differences in the content of the source as well as its structure, and it will point toward difficulties or specialties that have to be considered when dealing with this source. This endeavor will tie in neatly to the homogeneity assessment explained next, as this part will introduce the metadata[42] of the series. The station and in some cases also the network history explain the conditions within which the data have been produced and give information about the quality and homogeneity of the data.[43]

The second part of the main body of this study (Chapter 4) will deal with the measurements and observations themselves. The temperature and air pressure measurements will undergo a thorough homogenization process, mostly following the guidelines for homogeneity assessment provided by the WMO.[44] The homogenization process aims to detect and to remove non-climatic breaks (i.e., inhomogeneities) that can lead to serious misinterpretations of the climate.[45] These artificial breaks and biases in a time series can stem from, for example, station or instrument relocations, instrument replacement, or improvement in measurements over time.[46] These changes can either cause sharp discontinuities or gradual biases. A homogeneous series should only reflect variations that are caused by variations in climate itself.[47]

The first step of the homogeneity assessment includes the metadata analysis as well as the quality control.[48] Some metadata analysis will be completed as part of the source criticism. For temperature and air pressure, metadata analysis will be performed when introducing the

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[42] This word is from the Greek "meta" (beyond) and the Latin "datum" (a given fact). It can be understood as the data behind the data; see Aguilar et al. 2003: 1.
[43] Cf. Auer 2018: 99.
[44] Cf. Aguilar et al. 2003.
[45] Cf. ibid.: 28.
[46] Cf. Auer 2018: 99.
[47] Cf. Aguilar et al. 2003: 28.
[48] Cf. ibid.: 31.

measurements and used instruments in Chapter 4. The quality control will check the data for various errors that could have been made as part of the recording by the observer himself, by the transcription or digitization, or by data formatting or manipulation.[49] The sub-steps of the quality control will be elaborated in the specific sections and will include the unit conversions.[50] The pressure measurements will undergo a data pre-processing following the steps applied in the study by Brugnara et al.[51] In addition, a first impression of the data will be gathered by creating monthly boxplots. This widely used graphical tool illustrates five sample quantiles: the minimum, the lower quartile, the median, the upper quartile, and the maximum. The graph consists of a box, bounded by the upper and the lower quartile, with a line in the middle, representing the mean. The whiskers are extensions of the box and extend 1.5 times the distance of the interquartile range[52] away from the quartiles. Data points beyond that are outliers and need further attention. Thus, a boxplot represents an easy-to-understand sketch of the distribution of the data and, therefore, will be used throughout the study.[53]

The second step recommended by the WMO is the creation of a reference time series.[54] A common approach to build a reference time series is to select and to weigh an adequate neighbor station according to their statistical resemblance to the candidate series (i.e., the test series, here the Studer series).[55] This study, however, will not build a reference series but rather use different, highly correlated series and conduct the break point detection on all of them to distinguish the valid breakpoints.[56] The correlations will be calculated using Pearson correlation coefficient, which is the ratio of the sample covariance of the two datasets (x and y) divided by the product of the two standard deviations (s). This measure tests for the sign and strength of a linear relationship between two variables.[57]

$$r_{xy} = \frac{Cov(x,y)}{s_x s_y} \quad (Equation\ 2.1)$$

[49] Cf. ibid.: 15-16.
[50] See ibid.: 14 for units.
[51] Cf. Brugnara et al. 2015.
[52] i.e., the difference between the upper and lower quartile; see Wilks 2011: 26.
[53] Cf. Wilks 2011: 29-30.
[54] Cf. Aguilar et al. 2003: 31.
[55] Cf. ibid.: 34.
[56] See also i.e., Kuglitsch et al. 2012: 5.
[57] Cf. Aguilar et al. 2003: 50.

In R, either *Equation 2.1* can be applied or one can use the R function *cor* and define the method as "Pearson." The correlation is not based on ranks and is neither robust nor resistant.[58] As the method will be applied, these terms as well as the problem with this will be explained.

The reference series should be homogeneous and not be from a single network to overcome the problem of detecting breaks in the reference rather than the so-called candidate series (i.e., here the Studer series).[59] Multiple series are used to overcome this problem. For the breakpoint detection, which is the third step of the homogeneity assessment,[60] the Craddock test will be applied.[61]

$$s_i = s_{i-1} + a_j - b_j - (a_m - b_m) \qquad (\textit{Equation 2.2})$$

The method accumulates normalized differences between the reference series and the candidate series according to *Equation 2.2*, where *a* refers to the reference series, *b* to the candidate series, and a_m and b_m to their long-term means, where $s_0 = 0$. If both the reference and the candidate series are homogeneous, the accumulated differences will randomly oscillate around zero. Inhomogeneities (or breakpoints) can be detected by sharp changes in the slope of the accumulated differences.[62] The test will be applied on the monthly mean temperature and air pressure data.

In the last step of the homogeneity assessment, the detected breakpoints will be adjusted.[63] To detect which breakpoints are real inhomogeneities, the metadata will be searched to identify a physical cause. Otherwise, the breaks will have to be judged individually to decide on their adjustment. Further, a linear regression analysis will be applied to look for artificial trends.[64] This parametric approach assumes the data is a linear function including a trend and normal white noise ($\varepsilon(t)$).[65]

$$x(t) = \beta \cdot t + \alpha + \varepsilon(t) \qquad (\textit{Equation 2.3})$$

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[58] Cf. Wilks 2011: 52.
[59] Cf. Kuglitsch et al. 2012: 5.
[60] Cf. Aguilar et al. 2003: 31.
[61] Cf. Craddock 1979.
[62] Cf. Fessehaye et al. 2019: 5218.
[63] Cf. Aguilar et al. 2003: 31.
[64] Cf. ibid.: 36.
[65] Cf. Wilks 2011: 215-218.

The underlying assumptions of linear regression as trend analysis are based on their residuals, which are assumed to be normally distributed, independent (i.e., no serial correlation), and identically distributed (i.e., constant variance).[66] To test these assumptions, the following plots will be graphed and explained through their application: histogram, Q-Q plot, Tukey-Anscombe plot, and autocorrelation function. To conduct the trend-test, the R function *trend.linreg* will be used. The function is included in the R package *trend.acwd* created by Christoph Frei; he made it available to his students in the course "Analysis of Climate and Weather Data" he taught at ETH Zurich.

If the underlying assumptions cannot be verified, the test result may be compromised and thus a non-parametric test should be considered as an alternative. For this, the Mann-Kendall trend test can be applied. This non-parametric approach is a special case of Kendall's tau test[67]: It tests whether two variables have a tendency for a monotonic association.[68] The function *trend.MannKendall* will be applied. The null and alternative hypotheses will be explained as part of its application to the Studer series. For precipitation, these methods will not be applied, as the underlying data will be binomial counts of days with precipitation.

Lastly, hypothesis testing will be used to detect the impacts of the Unknown and the Mount Tambora eruption in the case study. Hypothesis testing yields a binary decision that a specific hypothesis about the data may or may not be true.[69] The hypothesis test follows a strict procedure. In short, a test statistic is first identified based on the data and question at hand. Then a null hypothesis (H_0) is defined with the hope that it will be rejected. Then, an alternative hypothesis (H_A) is defined, which is often the opposite of H_0. Next, the null distribution needs to be obtained by sampling the distribution for the test statistic, in the case of a true H_0. Finally, the observed test statistic needs to be compared to the null distribution.[70] A significance level α—the area of the null distribution in the rejection region—of 5% is usually chosen. If the p-value (the probability that the observed value of the test statistic will occur according to the null distribution) is less than or equal to the significance level, H_0 is rejected.[71] This method could be elaborated at length, however, the provided background should suffice to understand the

[66] Cf. ibid.: 218-220.
[67] Cf. ibid.: 56. Compared with Pearson correlation coefficient, it is more robust and resistant because it calculates the relationships among matching data pairs.
[68] Cf. ibid.: 166-168.
[69] Cf. ibid.: 133.
[70] Cf. ibid.: 134-135.
[71] Cf. ibid.: 135.

procedure followed in Chapter 5 of this study. To be a bit more precise, a one-sided Student's t-test will be applied, thus assuming that the test statistic follows a Student's t distribution, which is characterized as having heavier tails than the Gaussian distribution but otherwise being very similar to it.[72] The test will be one sided because violations of H_0 are expected to be on one side of the null distribution.[73] The test will be implemented in R by using the function *t.test* and defining the alternative to be "less" or "greater," depending on the underlying H_0.

[72] Cf. Wilks 2011: 141.
[73] Cf. ibid.: 136-137.

3. Source Review

Numerous instrumental measurement journals are available for the period after 1750.[74] Before embarking on further data analysis, it is important to assess the quality of the underlying source. Thus, it is necessary to question the value of a series for assessing climatic conditions and fluctuations. This depends on their length, their regularity, and the completeness of the observations.[75] Ideally, the measurement journals should span over periods as long and as regular as possible with few gaps. These features are also based on the claim of Le Roy Ladurie, who demanded among other things for continuous, quantitative, and, above all, homogenous data series.[76] Unfortunately, it is rare for early instrumental measurement series to fulfill these criteria. One reason is that those records have never been produced to assess the climate. Furthermore, the observations were done at a time when the standards of measurement and observation were markedly different than today's standards. Thus, they are subject to problems such as measurement errors or statistical uncertainty.[77] The purpose of this chapter will be to assess the quality of the Studer time series, and also to identify further potential sources of errors. However, we would not be evaluating the Studer time series if it were not thought to be a suitable time series. Already from a general observation, one can see the length, the regularity, and the few gaps in this extraordinary time series.

Before dealing with a source such as the meteorological observations by Studer, one must critically review the source. First, its authenticity must be assessed. Whenever possible, it is best to work with the original source, which luckily is not a problem with Studer's observations.[78] Further, especially when dealing with meteorological observations, the reliability of the observer needs to be addressed.[79] The observers usually wrote down what they thought of or knew of as relevant.[80] Thus, it is important to figure out who the observer was, why they chose to observe the weather, and, what their social and academic environment was like. We need to pose the questions: Why did the observer stick to observations for a long time period? What kind of knowledge did they have about instrumental measurements? What was their claim regarding the observations and measurements? To what network(s) were they

[74] Cf. Pfister 1988: 28.
[75] Cf. ibid.: 26.
[76] Cf. Le Roy Ladurie 1967: 25.
[77] Cf. Brönnimann 2015: 23.
[78] Cf. Pfister 1988: 40.
[79] Cf. ibid.; Glaser 2001: 29.
[80] Cf. Brönnimann 2015: 12.

connected? The following sub-chapters will, therefore, introduce Samuel Studer and the source, and critically analyze the latter.

3.1. Samuel Studer

The observer of the evaluated early instrumental measurement series, Samuel Emanuel[81] Studer, was born on 18th November 1757, in Bern.[82] He was the son of a wealthy butcher, also named Samuel, and his wife, Magdalena Hartmann.[83] The Studer family was naturalized from Grafenried as early as 1593. They never had an active part in the government but were often representatives of the Bernese church. They were mainly dedicated to handicrafts and industry.[84] Studer's youth represented very formative years. He lost his father when he was only eight years old. From then on, his upbringing was directed by one of his uncles, Daniel Ludwig Studer, who was interested in mathematical sciences and later a professor of theology in Bern.[85] Additionally, the zeitgeist led him to a scientific education. The years of his upbringing coincided with a time in cultural history, namely the Enlightenment, in which scientific education and activities became increasingly important for the upper and middle classes of citizens.[86] Samuel Studer also showed an early tendency toward scientific studies. At first, his aim was to pursue a medical career, but from a young age, he suffered from poor health, and his relatives advised him not to pursue a medical career. In addition, as a young man from the middle class, the higher civil service was closed to him due to economic circumstances.[87] During his training at the Latin school on Herrengasse in Bern, Studer had the reputation of an excellent student. Instead of a scientific education, Studer opted for a spiritual career, which still offered him the opportunity to pursue his scientific interests privately.[88] It was through this interest that he met Jakob Samuel Wyttenbach, who was ten years his senior.[89] At the time he was a preacher at the Burgerspital but was promoted to another position in 1781, whereupon Studer was able to take over his former position at the Burgerspital. Studer interrupted his stay in the city of Bern in 1789 because he had accepted a position as pastor in Büren an der Aare, which he occupied for seven years.[90] His son Bernhard Studer, a well-known

[81] Cf. Häberli 1959: 42.
[82] Cf. Braun 2016; Dübi 1910: 42; Häberli 1959: 42; Lebensgeschichtliche Umrisse des Herrn Altdecans Studer von Bern 1834: 3; Wolf 1855: 114.
[83] Cf. Häberli 1959: 42; Braun 2016.
[84] Cf. Häberli 1959: 42.
[85] Cf. Lebensgeschichtliche Umrisse des Herrn Altdecans Studer von Bern 1834: 3.
[86] Cf. ibid.
[87] Cf. ibid.: 3-4.
[88] Cf. Häberli 1959: 43.
[89] Cf. Lebensgeschichtliche Umrisse des Herrn Altdecans Studer von Bern 1834: 5.
[90] Cf. Braun 2016; Dübi 1910: 42-43.

theologian in Bern, was born there.[91] In 1796, Studer returned to Bern, and from that time, he occupied the chair for practical theology.[92] From 1827 to 1831, he was the highest dean of the Bernese church.[93]

Wyttenbach introduced Studer to the family of Mr. Walther on a trip to the Alps in 1781; Studer later married Mr. Walther's daughter, Maria Margarethe Walther, who became the mother of his four children.[94] Studer, who grew up during the Enlightenment, became an enthusiastic nature lover with a great interest in exploring and describing nature.[95] Early on, he was able to write down the geological, mineralogical, and topographical conditions in his work *Beschreibung der Gegend von Thierachern und des Eggguths daselbst* on the family estate on the *Egg zu Thierachern*.[96] When the Alps became an object of scientific research in the 18th century,[97] Studer was also a frequent visitor to the Bernese Oberland and the Valais. He also traveled to these areas with his brother and tried to explain the topography and contributed to the standardization of the naming of the areas, whereby his brother played an essential role, as Studer had suffered from severe myopia since an early age.[98] With the knowledge of geography at the time, little more was possible than observing and working with the existing hypotheses. Nonetheless, in his travel notes from 1788, a fairly detailed drawing with strange wedge proportions of granite and lime was found in the Urbach valley. This drawing was used later by geologists to investigate this point more precisely.[99] Despite his joy in traveling to the Alps, Studer's main passion was Swiss entomology (the scientific study of snails) and conchyliology (the scientific study of shellfish).[100] This preference was based on a box of snails and mussels that he had received from his sister at the age of 19.[101] With great interest and care, he collected as many species as possible on his travels in the Swiss countryside to be able to add them to his collection.[102] He was working on a study on the Swiss mollusk[103]; the title page of this script

[91] Cf. Dübi 1910: 43.
[92] Cf. Häberli 1959: 42.
[93] Cf. Braun 2016.
[94] Cf. Lebensgeschichtliche Umrisse des Herrn Altdecans Studer von Bern 1834: 7.
[95] Cf. Häberli 1959: 42.
[96] Cf. ibid. 47.
[97] Cf. Walter 2013.
[98] Cf. Häberli 1959: 48.
[99] Cf. Lebensgeschichtliche Umrisse des Herrn Altdecans Studer von Bern 1834: 6.
[100] Cf. Braun 2016; Dübi 1910: 43; Lebensgeschichtliche Umrisse des Herrn Altdecans Studer von Bern 1834: 5-6.
[101] Cf. Häberli 1959: 52.
[102] Cf. Lebensgeschichtliche Umrisse des Herrn Altdecans Studer von Bern 1834: 6-7.
[103] Cf. Braun 2016.

was dated 1787. However, it was not until 1820 that he decided, at the urging of his friends of nature, to share the work only in part for printing.[104]

Studer was also interested in making meteorological observations and recording them meticulously, which is essentially what is observed in this thesis. On 20 December 1779, at 9:00 in the morning, he wrote down the temperature, air pressure, and direction of wind for the first time, which he observed with his measuring devices at the Burgerspital in Bern.[105] From then on, he performed this activity three times a day. Even when he moved to Büren an der Aare in 1789, he moved his instruments and continued to take daily measurements there. He stopped this work in 1827 because his weak eyes no longer allowed him to read and write down the measured values correctly.[106] These observations meant a lot to Studer. It was reported that even on 16 November 1789, the day of his wedding to Maria, he stopped at the Burgerspital on the way from Köniz to read and to write down instrumental measurements, which truly shows the significance of this activity to him.[107]

Studer's work to promote scientific research in Switzerland was important and partially determined by the zeitgeist. Studer's environment and social network must also be explained in more detail, as they played an essential role in his interest in nature and ultimately for his meteorological observations. Hence, a brief excursion about the most relevant scientific communities in Switzerland and Studer's involvement in them is necessary.

Already in 17 century, instrumental measurements had started with the advent of the Enlightenment. Humans became curious to explore physically and, eventually, to explain their environment.[108] In Switzerland, the period of instrumental measurements and observations was started by Johann Jakob Scheuchzer in 1708. In addition to gathering his own data, he also tried to spark curiosity of the educated public on this topic. The interest in meteorological observations and measurement awoke in the mid-1700s.[109] In the late 18th century, many meteorological networks were established by private initiatives of scientists, physicians,

[104] Cf. Häberli 1959: 54.
[105] Cf. Studer: Meteorologische Betrachtungen 1779-1827.
[106] Cf. Wolf 1855: 114.
[107] Cf. Häberli 1959: 51.
[108] Cf. Brönnimann 2015: 12.
[109] Cf. Pfister 1975: 20.

colonial administrators, or clerics.[110] As part of this *Sozietätenbewegung*,[111] these societies were founded by the Enlightenment utopia for improvement, which was mostly oriented in two directions: self-education organizations—allowing members to acquire "useful" knowledge and skills—and, especially from the second half of the century onward, these societies also organized very concrete and practical activities to realize their ideas.[112] One of these societies was the Physikalische Gesellschaft Zürich (Physics Society Zurich), founded in 1746 by a group of men interested in natural sciences; it was formed around the scholar Johannes Gessner, who was appointed to take meteorological measurements.[113] According to Christian Pfister,[114] the Physikalische Gesellschaft Basel (Physics Society Basel) sent correspondence to Johann Heinrich Respinger on 25 June 1755, and asked him to take meteorological measurements.[115] However, the main correspondent of the Physikalische Gesellschaft Basel was most likely Johann Jakob D'Annone, who himself started his own meteorological measurements in 1755.[116] The Bernese measurement and observation network Oekonomische Gesellschaft Bern (Economic Society of Bern) was founded by Johann Rudolf Tschiffeli in 1759.[117] As Samuel Studer later joined this society, it is worth going into more detail regarding the emergence of this society.

A year before the emergence of the Oekonomische Gesellschaft, in December 1758, Tschiffeli addressed the public in the context of the supply crisis of 1757/1758 with an appeal to support financially a contest for grain cultivation. The appeal reached an unexpected echo, which prompted Tschiffeli and his partner Samuel Engel, who stayed in the background during this action, to involve other people they trusted in organizing the contest. The circle merged to form the Oekonomische Gesellschaft in 1759.[118] To create publicity for the founding program, the society published journals, with the aim to encourage cooperation. They wanted to collect details about the nature of the soil, temperature, local products, and cultivation methods. Such information was delivered by well-experienced people, well informed about their own region. The Society also communicated that precise meteorological observations would be no less

[110] Cf. Brönnimann 2015: 13-14.
[111] Also *Gelehrte Gesellschaften*, which can be translated to *societies movement*. Societies are understood as exclusive associations in the Ancien Régime with predominantly male members, developed mainly in the context of the Enlightenment, with the aim to distribute learned knowledge and morality. See Erne, Weibel 2012.
[112] Cf. Baumgartner 2015: 45.
[113] Cf. ibid.; Erne 2017; Pfister 1975: 20.
[114] Cf. Pfister 1975: 20.
[115] Cf. ibid.
[116] Cf. Euro-Climhist.
[117] Cf. ibid.: 21; Erne 2017.
[118] Cf. Pfister 1975: 21.

desirable. These meteorological observations were even mentioned in the first place among the objects to be included in the journal. This conception was not new but probably based on the French journal *Journal Oeconomique*, which had been published since 1753 by French agronomists.[119] The appeal was nothing short of groundbreaking, as it led to the establishment of a meteorological measurement and observation network. The Oekonomische Gesellschaft is seen as a forerunner of the Swiss Natural Research Society, which established the first nationwide network in the 19th century, as the efforts to standardize the measuring instruments suggest that the economists' long-term goal was a nationwide network with standardized instruments. Of note, Scheuchzer had already addressed the public with a letter in 1697, including a questionnaire with 186 questions about researching the Swiss meteorological conditions. Scheuchzer himself named the Royal Society as a role model. It was eventually Samuel Engel who was in contact with Johann Gessner, the president of the Physikalische Gesellschaft Zürich, to win him over as a correspondent for meteorological observations.[120]

The Oekonomische Gesellschaft Bern performed additional pioneering work in Switzerland by constructing a meteorological observation network, which was equipped with standardized instruments and units and was observed following the same instructions concerning, for example, the positioning and general handling of the instruments. On 9 March 1759, a committee worked out how and where meteorological observations should be conducted in order to be most comparable. They selected the instruments with the aim to achieve comparable results in various locations. For this endeavor, they chose mercury thermometers instead of the widespread spirit of wine thermometer and adapted the Réaumur scale (°Ré) because it had been more widely adapted than the Fahrenheit scale. They largely applied the French system of measurement and measured air pressure, temperature, and in some cases even precipitation. Furthermore, wind directions were also monitored, using an easily rotatable wind vane.[121]

It is important to highlight again the motivation and goal setting behind the first attempt at a network with standardized instruments.[122] The founders wanted to tackle the problem of economic development from the aspect of agricultural reform-education and combined with a scientific-experimental view to create a foundation for scientific knowledge. The goal was to contribute to the fields of pedology,[123], botany, plant physiology, veterinary medicine, and

[119] Cf. ibid.: 22.
[120] Cf. ibid.
[121] Cf. ibid.: 24.
[122] Cf. ibid.: 26.
[123] The scientific study of soil science.

meteorology to promote and to improve agriculture, ultimately to avoid food supply shortages and to increase the population.[124] Besides the curiosity that drove this movement, people also had an interest in meteorological observations to understand the causes of illness.[125] The forecast of weather and knowing the nature of the season in advance has always preoccupied those involved with agriculture because the connection between meteorological events and the food and income situation was directed by the weather and had fateful significance for most people of the pre-industrial era. Hence, the goals were to forecast the weather and study the relationship between meteorological elements and the crop yield, enhancing knowledge among the rural society to combat superstitious cultivation traditions and to study the relationship between meteorological elements and the outbreak and course of diseases.[126] To combat uncertainties and to improve the economic situation, a large amount of meteorological observations was necessary.[127] Thus, numerous people began observing the weather and, eventually, branch societies in the German and French part of Bern were founded.[128] Some came sooner or later into contact with the Oekonomische Gesellschaft. While the history of the Oekonomische Gesellschaft Bern could be elaborated further, it is only the goal of this thesis to show the context of this Society to try to explain the motivation that drove Samuel Studer to his extraordinary observations. [129]

Studer joined the Oekonomische Gesellschaft Bern in 1786 on Wyttenbach's recommendation. Because he reported to them on his daily meteorological observations, the society even provided him with better observation instruments. Studer was also instrumental in founding the general Naturforschende Gesellschaft (Natural Research Society) in Herzogenbuchsee in 1797 and was appointed the first president of this society. However, due to the ongoing political upheavals at that time, the society did not last. At the beginning of the 19th century, the Berner and Schweizer Naturforschende Gesellschaft (Bernese and Swiss Natural Research Societies) were definitively constituted for this purpose. When the Schweizer Naturforschende Gesellschaft was officially founded in Geneva in 1815, Studer was an important initiator and organizer, factors that led to his position as Vice President in 1816.[130] In addition to the regular memberships of the Berner and Schweizer Naturforschende Gesellschaft, he was also involved

[124] Cf. Pfister 1975: 27-29.
[125] Cf. Brönnimann 2015: 13.
[126] Cf. Pfister 1975: 29.
[127] Cf. ibid.: 33.
[128] Cf. Erne 2017.
[129] Cf. in detail Pfister 1975: 39.
[130] Cf. Häberli 1959: 55-57.

in the same associations in Geneva and Zurich, which was a sign of his great interest in current research problems and a general interest in scientific issues.[131] After a life shaped by his vocation as a theologian, but also by his interests in various elements of nature, Samuel Studer died in Bern on 21 August, 1834, at the age of 76.[132]

3.2. Source Criticism

3.2.1. Classification of the Source

Due to its interdisciplinarity, historical climatology deals with different methods and sources.[133] The data of historical climatology can be categorized into direct and indirect data.[134] Direct data are either observations or measurements and can only be archives of societies. Indirect data are also called proxy data; they are traces in nature of climate processes and can be both archives of nature and societies.[135] Early instrumental measurements can be categorized as direct data. However, a further distinction between observations or measurements is needed. Observations include descriptions of, for example, catastrophes or general weather patterns and conditions from the viewpoint of the observer himself. On the contrary, measurements are data within the source of, for example, temperature, air pressure, and precipitation, among other measurable variables.[136] Archives of societies can be divided further into either personal or institutional. Measurements within meteorological networks are categorized as institutional sources, whereas measurements by individual observers are personal sources.[137] The aim of this sub-chapter is to categorize the source dealt with in this study, namely the meteorological observations by Samuel Studer.

The name of the source already makes it clear that it is an archive of society. However, as it contains the term "observations," it is also labeled as an early instrumental measurement series, the category within the direct data needs to be distinguished further. The source written by Samuel Studer contains measurements of temperature and air pressure. These quantitative measurements will be treated as data within the source and the term "measurements" will be used to describe them. Moreover, the Studer series contains qualitative data about the general weather conditions and the direction of wind.[138] The term "observations" will be used when

[131] Cf. ibid.: 59.
[132] Cf. Braun 2016; Lebensgeschichtliche Umrisse des Herrn Altdecans Studer von Bern 1834: 3.
[133] Cf. Camenisch 2015: 39.
[134] Cf. Brázdil et al. 2005: 370.
[135] Cf. ibid.: 371; Camenisch 2015: 40-41; Mauelshagen 2010: 40.
[136] Cf. Pfister 2018: 37.
[137] Cf. ibid.: 38.
[138] Wind could be both, but here it is treated as observations.

dealing with this descriptive data. Following Pfister (2018), the observations should be considered historical climate sources as the distinction of the data as the information referring to weather and climate is coded by an individual and thus also contains his viewpoint.[139] The term “data” will therefore only be used for the measurements themselves. Nevertheless, Studer himself gave the source the title *Meteorological Observations*. Thus, the term “observations” or alternatively “records” will also be used when dealing with the source as an entity.

Chapter 3.1 gave an overview of Samuel Studer as a person and his life. His involvement in different societies raises the question whether his meteorological observations should be treated as an institutional or as a personal source. An institutional source requires an institution, which can be defined as a body in a leading position of regulating or performing an official function. Thus, this infers a certain formality, and the institution would therefore be in charge of the meteorological measurements or observations.[140] Studer, however, was not supervised but rather supported by the Oekonomische Gesellschaft. Therefore, the source was created by an individual and not by an institution. This is further supported by the fact that the observations and measurements ended with the observer himself. The source contains characteristics such as gaps but also the time of reporting, which is tied to the author.[141] The meteorological observations started with Studer’s interest and knowledge, contain gaps due to his absences, and necessarily ended when he was no longer capable of pursuing his passion due to health reasons. Conclusively, the meteorological observations by Studer are a direct source of historical climatology and contain both observations and measurements. It belongs to the archives of a society and as a personal source, it is dependent on the author himself.

3.2.2. Condition and Location of the Source

As mentioned earlier in the introduction, the availability and accessibility of the source are crucial for this thesis. The meteorological observations by Samuel Studer are all safely kept in his hometown: the Burgerbibliothek in Bern. The observations spanning from 1779 to 1827 are contained within five volumes, under the shelfmark Mss. Hist. Helv. XX. 5.1-5.5. All volumes are in the form of leather booklets and are in excellent condition. The pages are still in remarkable shape and can easily be read. The only hurdle when reading the diaries are papers containing further notes, which have been attached retrospectively. The content and purpose of these notes will be stated later when explaining the content of the source. The handwriting

[139] Cf. Pfister 2018: 37.
[140] Cf. ibid.: 38.
[141] Cf. ibid.: 39.

indicates that it was Studer himself who wrote these notes. Already at first sight, when opening the booklets, one can notice the great care Studer had used to note his observations. Each page of observations contains a neatly hand-drawn table, where the observations have been tracked. In general, the readability of the writing is excellent. Occasional smearing of ink or ink stains or poorer readability due to limited space are to be expected but are a minority. However, when the writing is compared over the entire period of his observations, one can notice a worsening of the readability toward the end of his observations. As mentioned in Chapter 3.1, Samuel Studer eventually had to give up his observations due to bad eyesight. This condition can be recognized in the handwriting of his observations in 1827, as he wrote less neatly and was not able to write as straight and overall as neatly as he had in the past.[142]

3.2.3. Language, Linguistic Peculiarities, and Dating

A common source of error in historical climatology is the dating. The advantage of sources from the archives of a society is their high temporal resolution.[143] This makes it all the more important to know the exact dating. Most dating problems arise from the simultaneous use of the Julian and the Gregorian calendars in the Old Confederation.[144] Before 1582, the Julian calendar, introduced by the Roman emperor Julius Caesar, had been in use. However, one year consisted of 365 days and 6 hours and was thus short by 11 minutes and 36 seconds compared with the astronomical year. In 1582, Pope Gregory XIII propagated a new calendar that eliminated the lag compared with the astronomical year by skipping ten days. In what is now the country of Switzerland, the switch from the Julian to the Gregorian calendar occurred in many steps. Most catholic areas went immediately over to the Gregorian calendar. Protestant territories, including Bern, adopted the new calendar only on 1/12 January 1701. Another calendar was introduced between 1793 and 1805 by the French revolution.[145] Thus, checking the date of a source as the meteorological observations by Samuel Studer is worthwhile, as failure to correct for the accurate calendar can introduce grave errors. The source luckily follows the Gregorian calendar. This can be verified due to the leap years and the Easter dates listed by Studer[146] were checked and correspond to the dates of the Gregorian calendar.
Special attention should further be given to the name of the month of February. Studer did not use the common German term “Februar,” but rather titled the month with “Hornung,” which is

[142] Cf. e.g.: Studer: Meteorologische Betrachtungen: BE01_Studer_1820-1827_088; all images can be found in the digital annex B. The data names correspond to the designations used for the CHIMES project.
[143] Cf. Mauelshagen 2010: 38.
[144] Cf. Pfister 1988: 3.
[145] Cf. Gutzwiler 2018.
[146] Cf. Studer: Meteorologische Betrachtungen: BE01_Studer_1797-1807_004.

a German word meaning "horn" and was commonly used in the observed time. The term probably alludes to the fact that this month has fewer days; it stems from the old Frisian word horning actually meaning the one not conceived in the marriage bed, and thus can be understood as the one who has come too short.[147] However, other research on this term can lead to many interpretations. Important for this study, however, is that with the term "Hornung," the month of February is meant. Generally, the source is written in German, but some of the glued-in notes are written in French.[148]

3.2.4. Gaps and Changes of Location

The meteorological observations and measurements were all taken at the Burgerspital in Bern. However, Studer moved to Büren an der Aare in 1789 for professional reasons. In 1796, he returned to Bern and continued his observations and measurements at the Burgerspital in Bern. This change in location would make an evaluation over the entire 48 year period rather difficult, especially as nothing is known about the observations and measurements conducted in Büren an der Aare. The notes in his diaries, however, continued on as before. The period evaluated in this thesis—1807-1818—contains many gaps, especially during the summer months. In the evaluations of the temperature, air pressure, and days of precipitation, these gaps will play an important role because much less data are available during the summer months. Studer was known for traveling to the mountains during the summer. Hans Häberli did a lot of research on Studer and wrote an article about his life in the *Berner Zeitschrift für Geschichte und Heimatkunde*. He relied on numerous sources about Studer, which can be found in the Burgerbibliothek, carried out extensive research on the subject of Studer, and also included a time line of his main excursions.[149] However, little is known about the exact date of these travels. A comparison with the missing values in the source can indicate when the excursions took place. Studer mostly traveled in July and August. In the study prior to this thesis, the missing values were compared to the known excursions and thus they were assigned to the known travel destinations given by Häberli, whenever possible. Thus, for this study, the missing values will only be included if it is important for the data. However, they will not be explained further or assigned to the excursions.[150] In the preliminary study, it was further concluded that based on the known excursions, Studer had in some cases a substitute who conducted the

[147] Cf. Duden.
[148] Cf. e.g.: BE01_Studer_1797-1807_004.
[149] Cf. Häberli 1959: 79.
[150] Cf. for more details Hari 2019.

observations and measurements for him. While this aspect will not be investigated further in this study, the assumption will not be excluded because it is very plausible as it was common.[151]

3.3. Content of the Source

3.3.1. Three Daily Measurements

Studer's meteorological observations consist of a table (on a double-sided page) for each month of observations (see *Image 3.1*). The table is always drawn very neatly. A header clearly indicates the content of the columns. The first column on each page specifies the day of the month. Next to the number, a symbol indicates the day of the week. The second column is designated to the lunar phase, but it does not always contain an entry. After those first columns, the measurements and observations start. Studer measured and observed the weather three times a day. The morning and afternoon measurements and observations consist of five columns; for the night, there are only four columns. The first column indicates the time of the measurement, usually in quarter-hour steps. The measuring times will be further evaluated as part of this study.

[151] Cf. Pfister 2019: 1349.

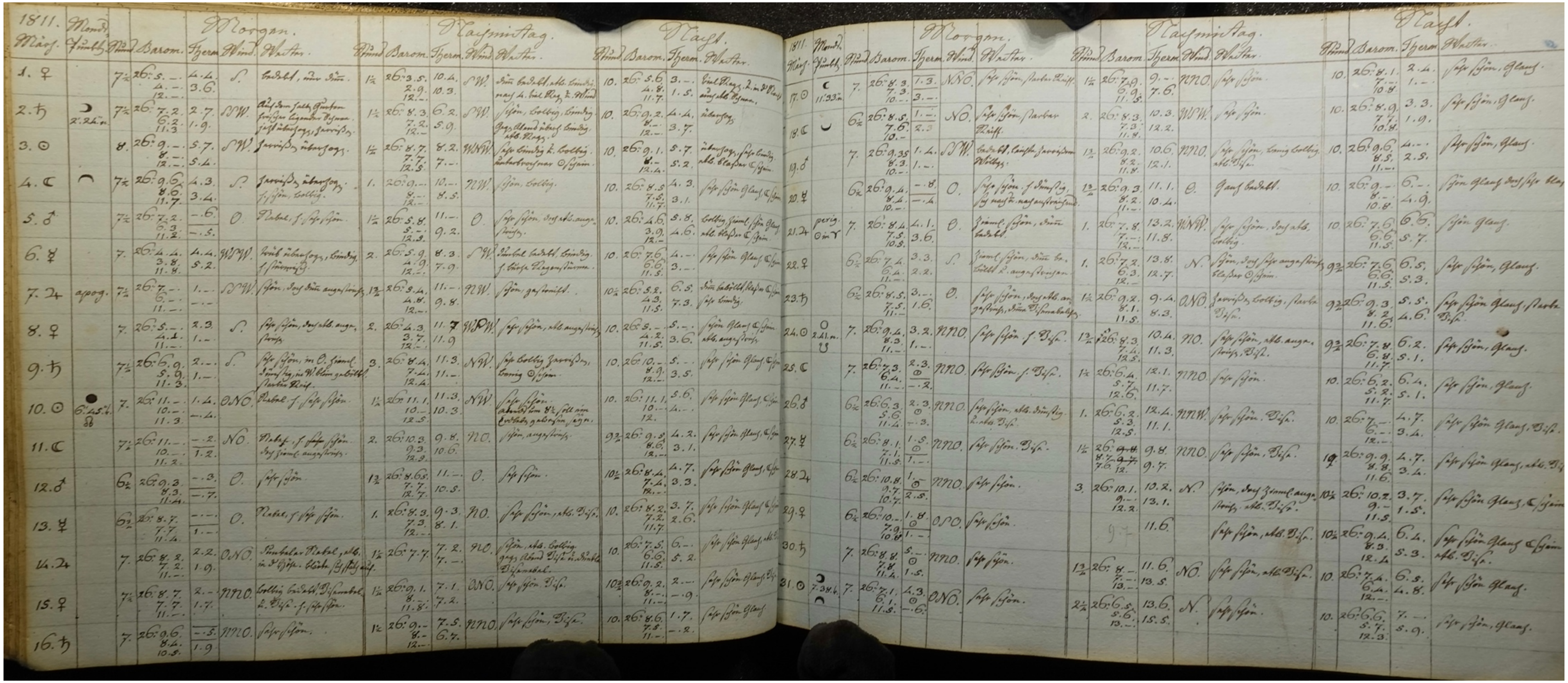

Image 3.1: Photocopy of the meteorological observations by Samuel Studer of March 1811. This image serves as an example to illustrate the structure and the overall presentation of the source.[152]

[152] Cf. Studer: Meteorlogische Betrachtungen: BE01_Studer_1808-1819_044.

The second column entails the barometric readings. The air pressure was given in the unit of Paris inch. Thus, the first number indicates the inches measured and the second number shows the Paris lines. The third line of this field yields the control temperature measured in the room of the barometer in °Ré.[153] In the first volume, Studer made entries about processes he had noticed. For example, he noted that the atmosphere seems to have periods of different weight. Further, the barometric measurements seem to vary little over the course of two to three months. He also observed a connection between rain events and air pressure: Whenever the air pressure fell, it would rain at the lowest air pressure point, and only when air pressure would rise again the sun shine again.[154] These notes underline Studer's interest in the weather patterns and his ability to understand the processes based on his observations. It further shows that Studer made connections between his measurements and observations and tried to understand processes based on these connections.

The third sub-daily column contains the temperature measurements in °Ré. He had installed three thermometers in different directions to measure the air temperature. The first was facing east, the second one west, and the third south. He explained that due to the position of the house a north-facing thermometer was impossible.[155] The temperature and air pressure measurements will be an essential part of this study and will thus be analyzed in more detail in Chapter 4. For temperature, however, the tertiary measurements will not be considered further. As mentioned before, this thermometer was facing south and was thus often exposed to direct sunlight. Whenever a thermometer was directly exposed to the sun, he put a circle with a dot in the middle right next to the measurement to indicate its invalidity.[156] Thus, they were already not considered for the digitization as part of the CHIMES project. For the period of 1807-1818, the tertiary measurements were not even written down by Studer during the years 1807-1812. Even during the period from 1813 to 1818, the tertiary value was frequently missing. Already a first impression of these measurements shows their bias: they often deviated from the other two measurements by 10°Ré or more, especially in the afternoon. Another important aspect to understand the source is how Studer recorded negative values. Whenever a temperature measurement was below zero, Studer drew a line above the measurement.

[153] Cf. Studer: Meteorologische Betrachtungen: BE01_Studer_1779-1786_006.
[154] Cf. ibid.: BE01_Studer_1779-1786_004.
[155] Cf. ibid.: BE01_Studer_1779-1786_006.
[156] Cf. e.g., ibid., 2-7 of October 1814: BE01_Studer_1808-1819_087.

In the next column, Studer indicates the direction of the wind by using the common abbreviations for the four cardinal points. This column, however, is missing for the night observations, which is why the night observations only have four rather than five columns. The wind observations were not equally consistent over the period of 1807-1818. In addition, the source does not contain information on how this observation was made. These observations will not be part of the evaluation in this study.

The last sub-daily column is for his observations of the current weather conditions. While the extent of these notes varies greatly, the consistency of these observations is extraordinary. Christian Pfister pointed out Studer's remarkable ability of observation and differentiation: He was able to distinguish between different types of clouds and used different terms to describe them.[157] Generally, the observation column contains a lot of valuable information on the weather conditions. These could certainly be analyzed at length. However, this study will mainly focus on the precipitation events that Studer mentioned in his observations.

3.3.2. Phenological Observations, Earthquakes, and Others

Besides meteorological measurements and observations, observers have often investigated other aspects of nature. Frequently, the early instrumental measurement series also included phenological observations and botanical classifications.[158] Studer certainly did not focus on phenological observations. The only reference to phenology can be found in between the rows of the table in the month of April or May of each year. This is the start of the blossoming of the cherry trees (*Table 3.1*).[159] It is unknown if a cherry tree was near his observation station or if Studer noticed their blossoming due to their significant appearance.

[157] Cf. Pfister 1975: 45.
[158] Cf. Pfister et al. 2019: 1349.
[159] Cf. e.g., Studer: Meteorologische Betrachtungen: BE01_Studer_1797-1807_131.

Table 3.1: Collection of the dates of cherry tree blossoming according to the notes made by Studer over the course of 1807-1818.

1807	1 May
1808	8 May
1809	5 May
1810	24 April
1811	NA[160]
1812	5 May
1813	20 April
1814	2 May
1815	6 April
1816	9 May
1817	10 May
1818	26 April

On the first page of the third volume, Studer collected several notes as well as prints on Easter dates and on earthquakes. The Easter dates of the years 1797 to 1812 are collected on one print. As mentioned in a subsection above, the dates have been checked and verified with the Gregorian calendar. He also handwrote the Easter dates of the years 1813 to 1825. On the same page, Studer collected the dates of earthquakes that had been detected in Switzerland. On a glued-in piece of paper, he handwrote the dates of earthquakes that had not been felt in Bern. In French, he further listed earthquakes that had been reported from 563 to 1816. Here, he did not just name the place but also described, for example, how far away the earthquake could be felt and other indications about its strength and implications.[161] Notes on earthquakes can be found throughout all the volumes.[162] In the fourth volume, he even handwrote an extract from the *Gazette de Lausanne* published on 28 March 1817.[163] Evidently, Studer had a great interest in earthquakes. The earthquakes were checked with the earthquake catalog of Switzerland. Some earthquakes, for example, the one of 12 May 1802, could indeed be found in the database. However, not all have been included in the database.[164]

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160 Not announced
161 Cf. e.g., Studer: Meteorologische Betrachtungen: BE01_Studer_1797-1807_004.
162 Cf. e.g., ibid.: BE01_Studer_1808-1819_110.
163 Cf. ibid.: BE01_Studer_1808-1819_165.
164 Cf. Schweizerischer Erdbebendienst 2011.

On the last page of the third volume, Studer described the course and occurrence of the phenomena of the solar eclipses on 11 February 1804, and 16 June 1806.[165] Studer was very interested in the lunar phases, so he dedicated the second column of this observation table to the lunar phase observations. The first volume contains a legend to the symbols. On the same page, he further explained the symbols he used to indicate what day of the week it was as well as a legend to the zodiac signs.[166]

While studying the source written by Samuel Studer, it is evident that he did not just take measurements but also thought about mean values, maxima, minima, as well as monthly trends. On the second page of the third volume, one can find the table of the yearly maximum and minimum barometric and thermometric measurements, in addition to other notes.[167] At the end of every volume, he summarized the measurements by drawing graphs. He drew the barometric measurements from the first barometer and further drew the weighted mean temperature—which included doubling the afternoon temperature (see Chapter 4.1.3)—and drawing it onto the barometric scale.[168] As he described, the graph contains the month, the day, the lunar position, the barometric and thermometric measurements, as well as the weather conditions, each of which represented with different dots in a box. A description of the meaning of the different shading can be found in the first volume.[169] This further illustrates Studer's interest in long-term processes and connections between the measurements and observations he made. Evidently, he was interested in the measurements to make those connections and not just for the sake of measuring something.

[165] Cf. Studer: Meteorologische Betrachtungen: BE01_Studer_1797-1807_151.
[166] Cf. ibid.: BE01_Studer_1779-1786_082.
[167] Cf. e.g., ibid.: BE01_Studer_1797-1807_005.
[168] Cf. ibid.: BE01_Studer_1779-1786_006 for further examples.
[169] Cf. ibid.: BE01_Studer_1779-1786_007.

4. Temperature, Air Pressure and Precipitation Records

After having reviewed the source critically, the data can now be evaluated further and undergo the homogeneity assessment. As mentioned in Chapter 2, this procedure mainly follows the guidelines provided by Aguilar et al.[170] The first step of the homogeneity assessment is the metadata analysis and quality control. First, the metadata analysis will be conducted by closer inspection of the instruments Studer used for his observations. In this step, the measurement schedule of Samuel Studer will be considered and investigated. Chapter 4.2 will then analyze the temperature measurements and the remaining steps of the homogeneity assessment will be performed. In addition to the procedure suggested by Aguilar et al., a trend analysis will be applied. In Chapter 4.3, the same procedure will be followed for the air pressure measurements. However, the data will be processed more elaborately before the homogeneity assessment, although the homogeneity assessment will be explained in less detail, because it will follow the same process applied before for temperature. Finally, in Chapter 4.4, the precipitation observations will be taken into account and will be converted from literal to quantified observations.

4.1. Metadata on Measurement Instruments and Schedule

When dealing with early instrumental measurements, the assessment of the instruments used should be an essential part of the metadata analysis. Thus, questions about the exact location, position, type, and fixation of the instruments—among many other questions—should be asked. While the answers to these questions might not be clear when elaborating Studer's measurements, in this section as much information as possible on the instruments will be collected. The general history of the instruments will only be elaborated when necessary or thought to be purposeful. For detailed histories about the thermometer[171] and barometer,[172] Middleton should be examined. Next to the instruments themselves, the time of measurements and observations can also highly influence the data. Therefore, the measurement schedule will also be investigated.

[170] Cf. Aguilar et al. 2013.
[171] Cf. Middleton 1966.
[172] Cf. Middleton 1964.

4.1.1. Thermometer

The invention of the thermometer itself provides material for discussion. Galileo Galilei is considered to have invented the air thermometer back in 1593[173] or 1597.[174] However, as it was very sensitive to atmospheric pressure and had no scale, it was also described as a thermo-barometer[175] or thermoscope.[176] Later, a medical doctor named Santoro Santorini eliminated the influence of the pressure with the help of a compass, by adding or subtracting the diurnal pressure variation.[177] The invention was based on the discovery that liquids are subject to thermal expansion. Only in 1642 did Evangelista Torricelli, the court mathematician of the Grand Duke of Tuscany, invent "the true liquid-in-glass thermometer"[178] using a scale in Galileo degrees, probably to honor his contribution to this invention in the same year Galileo died.[179] Unfortunately, hardly anyone could afford the instrument. Therefore, the invention needed to be adapted. The instrument was to be built with a glass tube with a bulb, filled with a thermometric liquid, the choice of which was crucial because it needed a high expansion coefficient yet could not be allowed to freeze or to adhere to the glass during the measurements.[180] Thus, mercury became more popular for this purpose than, for example, spirit of wine, which had been used previously.[181] The advantage of mercury compared with other liquids is that it is more easily cleared of air and thus bubbles can be avoided. Further, compared with spirit of wine, it is most suitable for measuring great temperature differences and follows constant expansion and contraction for all temperatures. On the contrary, spirit of wine created great comparability problems.[182]

The fate of Réaumur's thermometric scale is rather complicated[183] and does not serve much purpose to this study. However, because Studer followed the Réaumur scale, it needs to be mentioned that it was general practice to define it by the freezing point of water (0°Ré) and the boiling point of water (80°Ré). The mercury thermometers were then uniformly graduated between these two lines.[184] Conducted experiments, however, have proven that the mercury thermometer gives values that are too low for these calibration points; the greatest difference is

[173] Cf. Camuffo 2002a: 297.
[174] Cf. Pfister 1988: 50.
[175] Cf. Camuffo 2002a: 298.
[176] Cf. Camuffo 2018: 84.
[177] Cf. Camuffo 2002a: 298.
[178] Cf. Camuffo 2018: 84.
[179] Cf. ibid.
[180] Cf. ibid.
[181] Cf. Camuffo 2002a: 313.
[182] Cf. ibid.
[183] Cf. Middleton 1966: 84.
[184] Cf. ibid.: 86.

almost 2°C.[185] Another difficulty was the calibration of the instrument, as the freezing point and the boiling point of water under normal pressure, as suggested by Réaumur, were used.[186] Already the term "freezing point" is too imprecise, because Réaumur thought of it as the degree cold enough for water to freeze, however, Fahrenheit used forced freezing by employing ammonia salt. Thus, the freezing point could lead to an uncertainty of 3-5°Ré.[187] In addition, the boiling point was poorly defined because it was not constant. One reason was that the atmospheric pressure, which could influence the boiling point and thus the "normal pressure," was also fairly imprecise.[188] The Royal Society suggested some solutions to this problem, which will not be elaborated further here. The above-mentioned imprecisions illustrate problems that have occurred with thermometers and general instrumental measurements. In most cases, Studer unfortunately hardly commented on the used instruments or the underlying conditions of the measurements. Because he did not give enough information to take these errors into account, perfect calibration will be assumed for his thermometers.

The goal of the Oekonomische Gesellschaft Bern was to collect measurements so the results of different places could be compared. Hence, uniform instruments were needed. In a meeting in 1759, they had decided to purchase thermometers with mercury instead of the widespread spirit of wine thermometers, and to follow the Réaumur scale. Another option would have been the Fahrenheit scale, which was less commonly used at that time.[189] The instruments were then distributed amongst different observers.[190] Samuel Studer did not indicate the type of thermometer he used. The conclusion that he used mercury thermometers is considered appropriate, as it was common in his society. Karl Lombach, who made instrumental measurements partly at the same time as Studer (1777-1789) at the Burgerspital, used mercury thermometers.[191] However, there is no evidence for correspondence between the two men concerning their measurements. From the measurement values, it can be deduced that the measurements were given in °Ré.

According to Christian Pfister (1988), old temperature measurements can contain four different sources of error that need to be considered.[192] Besides the type and scale of the instrument, a

[185] Cf. Deluc 1772: 293.
[186] Cf. Camuffo 2002a: 314.
[187] Cf. ibid.: 315.
[188] Cf. ibid.: 316.
[189] Cf. Pfister 1975: 23.
[190] Cf. ibid.: 52.
[191] Cf. ibid.: 51.
[192] Cf. Pfister 1988: 50.

source of error is the instrument itself, which can lead to, for example, a shift of the zero position. A highly influential source of error can also be the location and positioning of the instrument. Lastly, Pfister mentions the influence of the city as a source of error.

The alterations that the scale might undergo stem from the material that was used to make them. Usually, the scale was made from wood, often attached with an iron wire.[193] Thus, air temperature itself, but mainly the effects of relative humidity on the wood, can alter its length. As it was not possible to measure the humidity content of the air in the early 19th century, classifications were used instead of measurements. With a realistic expansion coefficient of 0.2%, the error would be 0.5°C for a wood board with a length of 1 m.[194] Thus, this rather small error can be considered negligible, especially because neither the length nor the age of the wood used for Studer's instruments is known. The effect of non-linearity in the thermal expansion of mercury should also to be mentioned. This effect is expected to be quite small and only as much as a deviation of -0.11°C for temperatures around 40°C. Moreover, the non-linear response of thermometers is accentuated by irregular expansion of the glass container.[195]

A member of the Oekonomische Gesellschaft Bern, Benjamin Carrard,[196] recommended in 1763 that the thermometer should be positioned outside and should face north so it would be shielded from the sun. Furthermore, there should not be any walls close by that would shield the thermometer, because then the sunrays would be reflected back to the thermometer and show temperatures that are not equivalent to the real air temperature.[197] Consequently, next to position, exposure is also a crucial factor that can influence the accuracy of a thermometer. Radiation as well as ventilation can further affect the measured temperature. Besides direct sunlight, indirect or scattered radiation can affect the temperature reading and induce systematic errors. The extent depends greatly on the time of day and year and can lead to a deviation of as much as 2.5°C.[198] Systematic errors occurring from reflection from nearby objects and wrong positioning of the thermometers were known in the community of observers and networks; indeed, the issue had been mentioned already in 1654.[199] However, it was not until the 19th century[200] that screens were developed due to these errors from scattered and reflected

[193] Cf. Camuffo 2002a: 318.
[194] Cf. ibid.: 319.
[195] Cf. Rivosecchi 1975, quoted from: Camuffo 2002a: 322.
[196] Cf. Rytz 2005.
[197] Cf. Pfister 1975: 52.
[198] Cf. Böhm et al. 2010.
[199] Cf. Middleton 1966: 209.
[200] Cf. Chenoweth 1993: 1792; according to Böhm et al. 2010: 63: 1850-1870; Middleton 1966: 219: 1835.

radiation. Ventilation can be a cause for a systematic error in temperature readings. A lack of ventilation can increase the monthly average minimum by 0.5-1.9°C.[201] These potential sources of systematic errors are enhanced in urban areas and are the fourth source of error mentioned by Pfister in his study conducted in 1988.[202]

A crucial part of this metadata analysis is to see how Studer dealt with these potential sources of error and to what extent he was aware of them. Interestingly, the position of the thermometer is the one piece information he commented on the most, as there is an additional sheet of paper glued on the third page of his first volume of observations where he elaborates important information on the thermometer and barometer.[203] As the separate sheet of paper was glued on top of the second half of December 1779 observations, it can be assumed that they had been written either later or at the very beginning of his observations. Ultimately, however, this timing is of no further importance. More valuable for the evaluation is the information written on the paper as well as the implied information on what Studer considered to be important to note.

According to the statements on this additional sheet, Studer had put a total of three thermometers into operation, one each facing east, west, and south. He mentioned that due to the position of the house, he could not attach a thermometer facing north. Regarding the quality or rather exposure of the thermometers, he stated that the values of the three measuring instruments barely deviated by 0.5-1°Ré, if the conditions were overcast and wind still for a few consecutive days. However, a ray of sun or a light wind increased or decreased the same exposed thermometer by one or several °Ré.

From here on, Studer only mentioned the two thermometers facing east and west. He explained, that the problem with the east-facing thermometer was its attachment to a sandstone wall, a typical material used for walls in the city of Bern. The sandstone wall was warmed up by the sun in the morning, which led to higher and thus biased values. Studer mentions a bias of 1°Ré or more, even for the evening measurements. The west-facing thermometer, on the other hand, was attached to wood, which according to his comments does not react as much to warmth and cold as sandstone does. According to Studer, because most houses in Bern were built with sandstone, it was hard to estimate the true air temperature of the city. Interestingly, he was already interested in knowing the mean daily temperature. To calculate the mean, he would

[201] Cf. Chenoweth 1993: 1792.
[202] Cf. Pfister 1988: 50.
[203] Cf. Studer: Meteorologische Betrachtungen: BE01_Studer_1779-1786_006.

choose the afternoon temperature of the three thermometers that he found to be the most plausible, which was usually the thermometer facing west. He then worked out a weighted mean temperature. He doubled the afternoon temperature and also added the most plausible of the three morning and evening measurements.

In the eleven years of his measurements examined in this thesis, only two temperatures per day were recorded in most cases. Therefore, it can be assumed from the information in Studer's notes that they were the two more elaborated thermometers facing east and west, because already in the description information on the south-facing thermometer is missing. He must have known that these values would be too biased by the direct radiation this thermometer would have received. As screens had not yet been developed, it is clear that all values stem from unscreened thermometers. Interestingly, Studer himself marked each measurement with a circle and a dot in the middle if this measurement was taken in exposure to direct sunlight. For the digitization of the observations by the CHIMES project, these values were not considered and, hence, have been left out of the data set and appear as "NA" in the evaluation. This fact should be kept in mind for the following quality control, where the two thermometers will be compared and elaborated further.

In summary, the metadata of the temperature measurements are fairly limited but, nevertheless, extremely valuable. It is known that Studer had installed three thermometers at the Burgerspital, each facing a different direction. He was further aware of the direct sun insolation as a possible source of error and had thus marked the values affected by direct sunlight with a symbol to show their invalidity. Additional valuable information stems from his notes that declare on what kind of surfaces the thermometers were attached and the implications this had on the temperature readings.

4.1.2. Barometer

The measurement of atmospheric pressure has had a long history. To give an overview of the vast number of instruments that have been available in the past is neither possible nor reasonable. However, it started with the famous experiment conducted by Evangelista Torricelli in 1643.[204] It did not take long for the barometer to become a commercial product that was sold to a wide range of people and networks.[205] During the relevant period for this study, the beginning of the 19th century, there were three main types of mercury barometers in use: the siphon barometer, the Fortin barometer, and the fixed-cistern barometer, which was the most commonly used. As indicated by the name, the mercury is exposed to the air pressure in the cistern. A vertical thin glass tube is closed at the upper end to create a vacuum. At the bottom end, it is immersed in mercury. Especially in the early days of the barometer, the reference level of the scale was always affected by an error because the zero level was dependent on the height of the mercury in the column and, thus, dependent on the actual atmospheric pressure at the time of calibration. If the calibration was made on a day when the atmospheric pressure was low, then the zero level would be higher, and vice versa for a high-pressure day. This source of error, however, also depends on the diameter of the tube: the thinner the tube, the more underestimated the reading. Furthermore, the error was much greater for unboiled tubes. However, the practice of boiling the tubes was introduced only later in the 1840s. Another source of error is the sliding of the scale. The scales have been attached differently over time. At first, the scale was commonly attached with an iron wire, resulting in a drift. Eventually, the scale was directly marked on the glass tube, thus eliminating the error caused by sliding.[206] The lack of correction, however, likely introduced an error of less than 1 hPa and will therefore be neglected in the following analysis.[207] A more important error to be corrected for is the corresponding temperature. The barometers were often equipped with a thermometer because the observers were aware that the air pressure needed to be adjusted by the corresponding temperature.[208] The use of this correction temperature will be elaborated in much more detail throughout the homogeneity assessment of air pressure.

Similarly to Chapter 4.1.1 regarding the thermometer, it is now essential to provide knowledge about the barometer that can be gained from the metadata found in Studer's meteorological observations. It is not possible to narrow down Studer's barometer to a specific type; however,

[204] Cf. Middleton 1964: 22.
[205] Cf. Brugnara et al. 2015: 1028.
[206] Cf. Camuffo, Cocheo, Sturaro 2006: 497.
[207] Cf. Brugnara et al. 2015: 1033.
[208] Cf. ibid.: 1031-1032.

Studer mentioned the use of two barometers. The result of the primary barometer was always noted on the top line of the barometric reading column. In addition, the measurement of the second barometer was recorded on the second line and had a control function for the primary barometer and will thus be referred to as secondary or control barometer. The third measurement in the "barometer" column of his measurements belongs to the control thermometer, which was attached next to the barometer. The barometer was located in a room, the exact location of which is unfortunately unknown.[209] However, from the control temperature measurements, it can be concluded that these instruments were placed in a unheated and poorly ventilated room, which are fairly undesirable conditions for the location of meteorological instruments.[210] Thus, the adjustment of the temperature the barometer was exposed to will be an essential step of the quality control and data processing. Studer further indicated he used a mercury barometer. The mercury height was measured in Paris inch with an accuracy of 1/12. Overall, for the barometric readings, the essential metadata about the instruments was provided by Studer. In contrast to the thermometer, Studer noted the type of instrument, as well as the scale used.

4.1.3. Measurement Schedule

Before the measurements can be analyzed further, it is important to take note of the measuring times. As elaborated before, Studer measured and observed three times daily. The first reading was always conducted in the morning, the second in the afternoon, and the last at night. Studer himself mentioned the importance of these measurements, namely for the mean daily temperature. The way he calculated the mean was by first choosing the one afternoon measurements of the three that seemed to be the most accurate, which was usually the thermometer facing west. He then doubled this number and added the morning and night measurements that he felt were the best. Even though he does not mention it, one can assume that he then divided this number by four. He weights the afternoon temperatures to better characterize the day. He mentions that he chooses this method because the morning and evening temperatures can differ widely.[211] The method he chose was the calculation of the *trimean.* According to Wilks, the afternoon temperature represents the median and thus receives twice the weight as the upper and lower quartile (*Equation 4.1*).[212]

[209] Cf. Studer: Meteorologische Betrachtungen: BE01_Studer_1779-1786_006.
[210] Cf. Moberg et al. 2002: 193.
[211] Cf. Studer: Meteorologische Betrachtungen: BE01_Studer_1779-1786_006.
[212] Cf. Wilks 2011: 26.

$$Trimean = \frac{q_{0.25} + 2q_{0.5} + q_{0.75}}{4} \qquad (Equation\ 4.1)$$

Even though he did not mention this statistical method, he seemed to grasp the concept. An advantage of the trimean is indeed the reduced sensitivity to outliers by removing a specified proportion of the largest and smallest observations; thus, it is a very resistant measure of location.[213] Another method suggested in 1831 by Kämtz used a similar method, but instead of weighting the afternoon measurements, the night measurement would be weighted to obtain a reasonably good approximation for a daily average.[214] Even though Studer did not follow this method, it also underlines the importance of three daily measurements to obtain a daily mean temperature, which seemed to be already well established in the early 19th century. In fact, many early instrumental measurement series of the second half of the 18th century had been conducted at least twice a day, at similar points of time, because it was also known that a consistent measuring time is important for temperature as well as air pressure measurements.[215] An issue with the Studer series is the inconsistency in the measuring times.

The digitized measuring times first had to be checked as the transcription was a fairly big source of error. The errors were usually simple typing errors, either of an erroneously typed digit or a comma in the wrong place. The possibly erroneous measuring times (often noticed because they did not follow the quarter-hour pattern Studer used) were compared with the original source and corrected if necessary. In addition, the minimum and maximum time stamps were compared to the time stamps indicated in the source. A plot of the corrected measuring times in the morning is shown in *Figure 4.1*.

[213] Cf. ibid.: 26.
[214] Cf. Kämtz 1831: 102.
[215] Cf. Cocheo, Camuffo 2002.

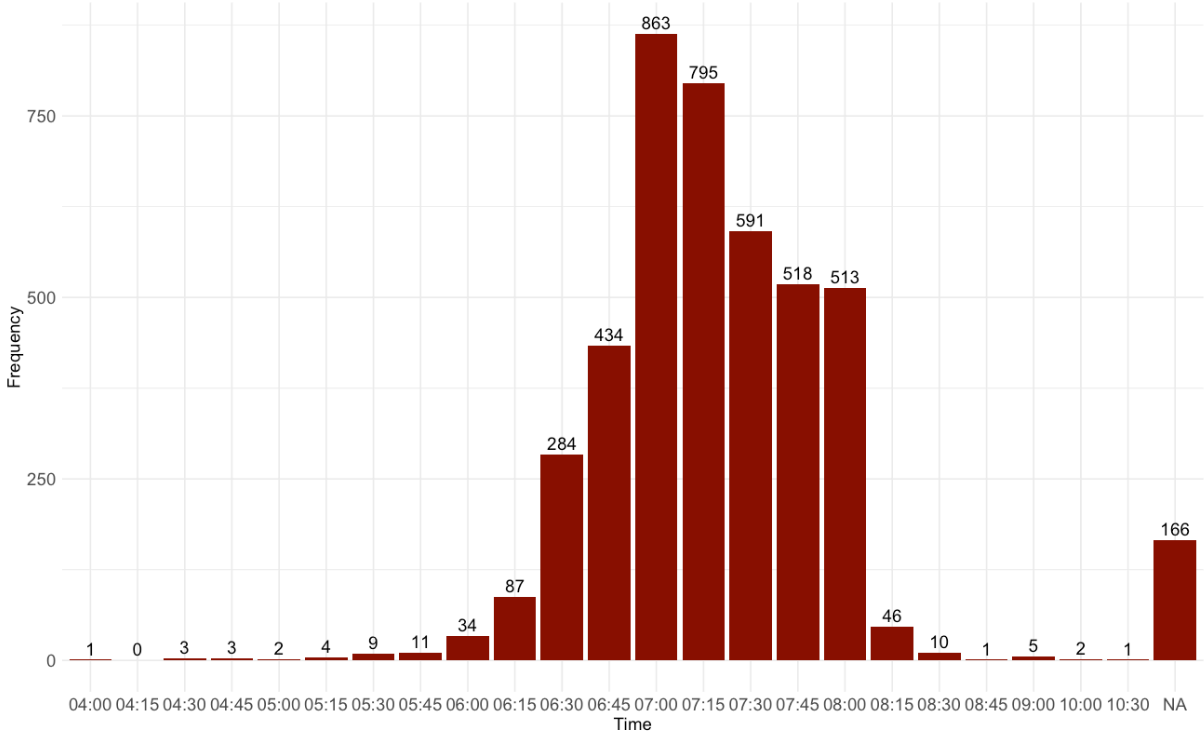

Figure 4.1: Barplot of the measurement and observation times made by Studer in the morning.

Studer noted the measuring times with a precision of 15 minutes. The earliest he ever measured in the morning was at 04:00 and the latest at 10:30. Omitting the NA values, 20.46% of the measurements were taken at 07:00. The hour between 7:00 and 08:00 includes 77.78% of the measurements over the course of the eleven years analyzed in this thesis. Thus, measurements were taken over a time span of 6 hours for the morning measuring times. This poses some difficulties. The morning temperature is supposed to catch the minimum temperature of the day. However, the temperature can change a lot between early morning and late morning, and generally over the course of 6 hours. The missing values will be dealt with later in this study.

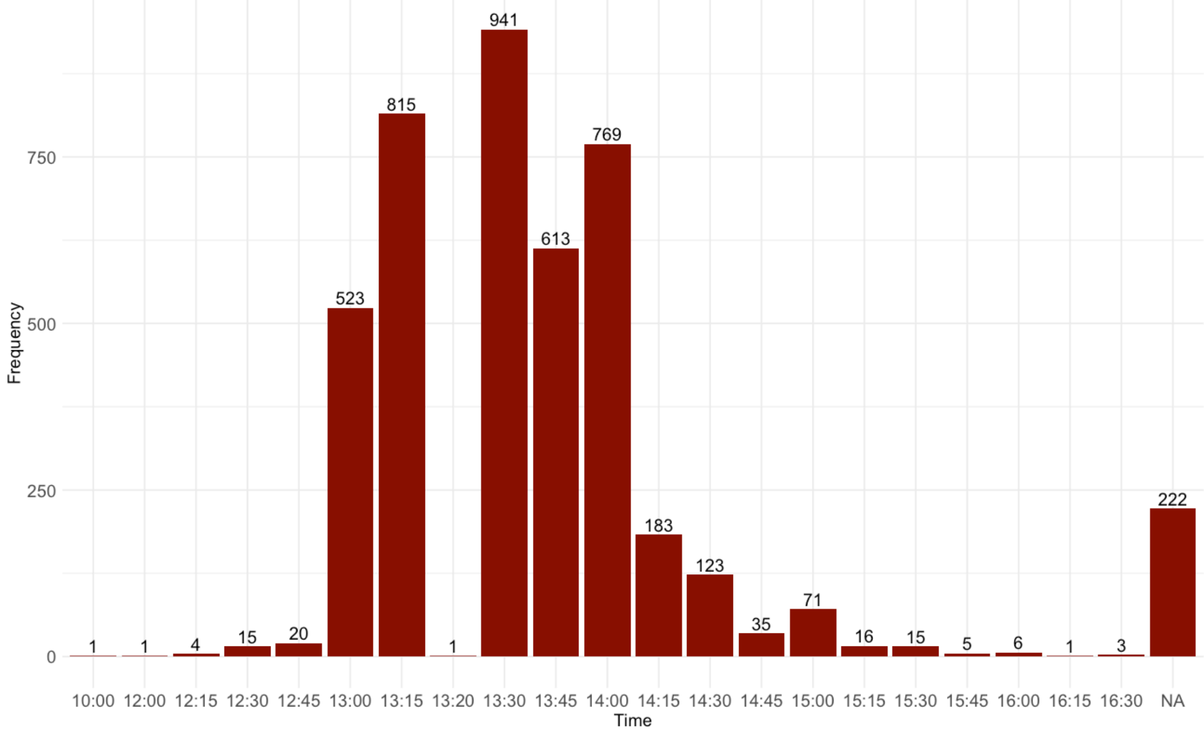

Figure 4.2: Barplot of the measurement and observation times made by Studer in the afternoon.

As presented in *Figure 4.2*, the large time span was not only a characteristic of the morning measurements: The afternoon measurements spanned 6.5 hours. There are several features of this graph. First, the earliest afternoon measurement taken during the investigated period was at 10:00, which is earlier than the last morning measurement taken by Studer. The digitization was also checked with the original source in this case and confirmed: Studer noted 10:00 as the afternoon time on 15 June 1813, and the time was, therefore, not corrected. An overlap between the morning and afternoon measurement and observation times is certainly not ideal and does not fulfill the criteria of a consistent measurement schedule. Another irregularity is the afternoon measuring and observation time is 13:20 as it does not fall into the quarterly hour pattern. Indeed, Studer noted $1\frac{1}{3}$ as the measuring time of the afternoon of 21 December 1808. Overall, 87.98% of all afternoon measurements and observations (omitting the NA entries) between 1807 and 1818 were made within the hour of 13:00-14:00.

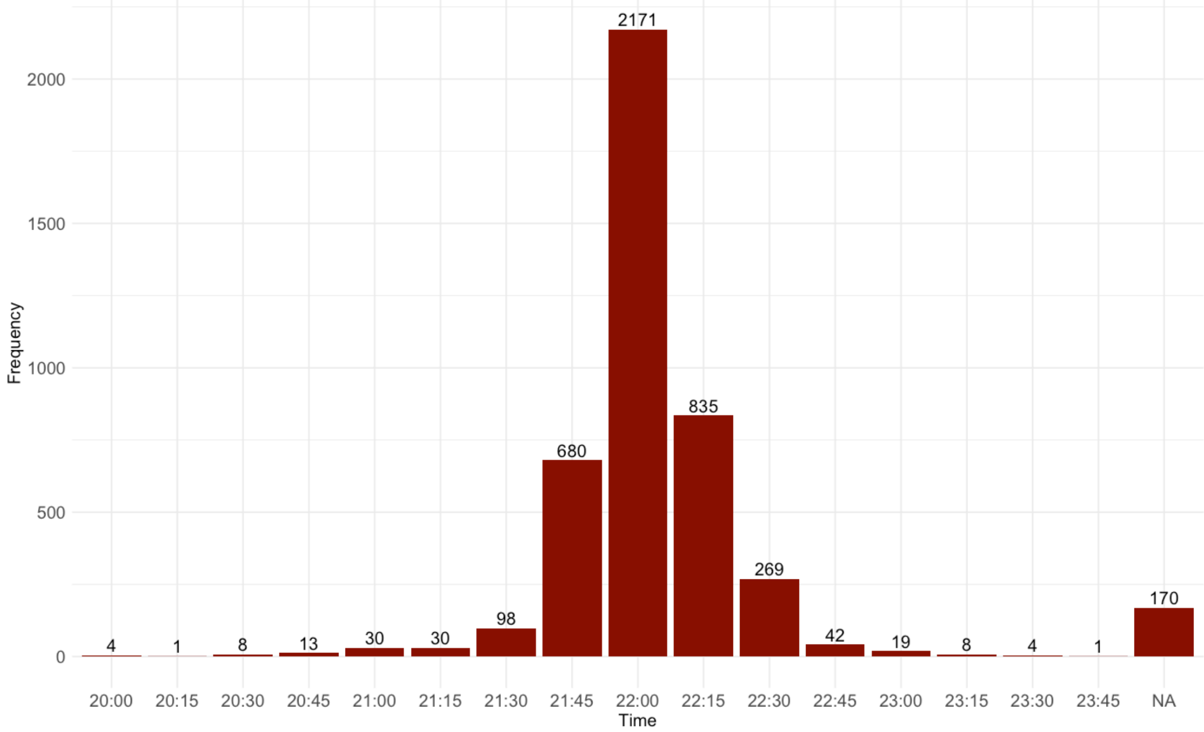

Figure 4.3: Barplot of the measurement and observation times made by Studer at night.

Samuel Studer was most consistent with measuring at night (*Figure 4.3*). The time span over which he recorded his observations and measurements is only 3.75 hours. Overall, 51.53% of all measurements at night were taken at 22:00 (NA entries omitted).

This short elaboration of the measurement and observation times shows that he was not consistent and especially not consistent enough to calculate the daily mean temperature following the trimean method or the method suggested by Kämtz, as for both methods, the measurement and observation times would have had to be more consistent. Thus, the daily mean can only be calculated when considering the local climatology. The average daily cycles of the temperature and pressure have to be considered and included in the calculations. The modern cycle of Bern Bollwerk (2001-2018) was used to calculate the daily mean temperatures, applying corrections for the daily cycle. The trimean[216] was then calculated, which resulted in the daily mean temperatures used for further evaluations and corrections in this thesis. This approach was not be applied for pressure. Rather, the mean was calculated by simply averaging the three measurements. Hence, the measurement and observation times from here on are no longer be relevant for this study.

[216] Cf. also Begert, Schlegel, Kirchhofer 2005.

4.2. The Temperature Measurements

The temperature measurements have already been the subject of the preliminary study. Even though the preliminary study certainly questioned the quality of these data, no further efforts were made to check systematically the temperature measurements for errors in the recording itself or later on in the digitization process. Thus, a crucial step forward compared with the preliminary study was to check for errors in the already evaluated temperature measurements. Additionally, a longer period will be taken into account. Moreover, the evaluation of the temperature measurements promises new insights into the measurements and new results for the overall study. Because the temperature is the first variable to be evaluated in this chapter, it will not have been corrected previously. By contrast, the pressure measurements will be influenced by the evaluation of the temperature measurements. Chapter 4.2 will thus be the most detailed and extensive sub-chapter, as all homogenization steps need to be explained in more detail.

4.2.1. Data Processing, First Impressions, and Quality Control

Samuel Studer measured the temperature in °Ré. Thus, the temperature data first need to undergo a unit conversion to the metric system. *Equation 4.2* was used for the conversion from °Ré to °C:

$$T_C = \frac{T_R}{0.8} \qquad \text{(\textit{Equation 4.2})}$$

Here, T_R is the temperature in °Ré. This step was implemented in Microsoft Excel, before loading the data into R. Following the unit conversion, a first impression of the data can best be obtained by illustrating the monthly mean temperatures with boxplots. For this purpose, the raw digitized data made available by the CHIMES project was entered into R. At this point, the temperature recordings had only been converted to °C according to *Equation 4.2.* The monthly means were calculated based on the daily means, which were obtained by applying *Equation 4.1* to the data. The monthly means were not calculated if the criteria set by the WMO were not satisfied, as this would have yielded artificial outliers. Thus, no monthly mean was obtained if eleven or more days of measurements were missing or if values were missing on five or more consecutive days.[217]

[217] Cf. WMO 2017: 8.

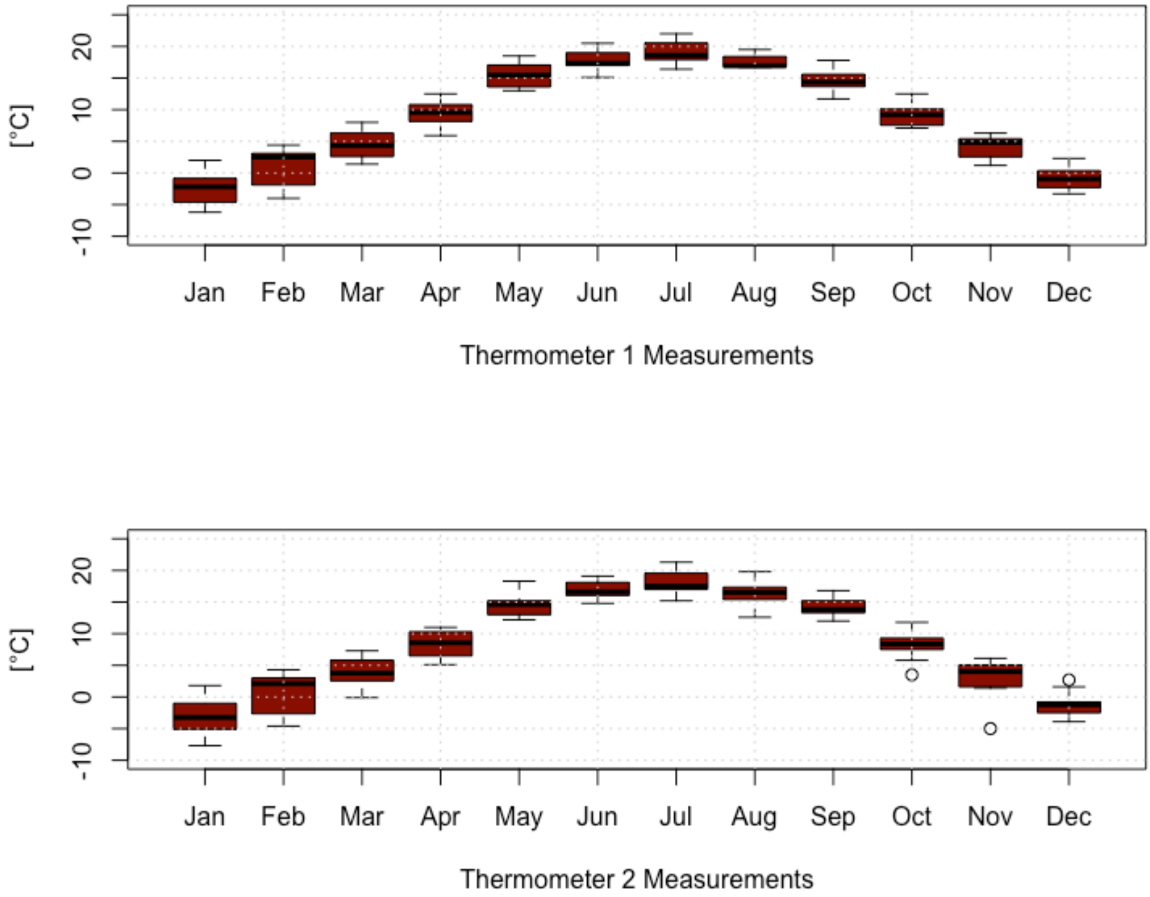

Figure 4.4: Boxplots of monthly mean temperatures. The upper boxplot presents the monthly mean temperatures obtained from the primary thermometer, whereas the lower plot shows the results obtained from the secondary thermometer.

The outliers in *Figure 4.4* are purposely not labeled, as at this moment it is not a concern of when exactly they occurred. However, their presence in the secondary thermometer and their absence in the primary thermometer needs to be addressed. The three plotted outliers were all within the last three months of the year. These outliers indicate particularly warm or cold months. However, as no quality control has been conducted so far, the outliers could also stem from faulty measurements or faulty digitization of the measurements. Besides outliers, information on the general annual cycle can be obtained from the graph, for example, the expected sinusoidal temperature curve, following the according seasonality.

For the quality control, the individual sub-daily measurements have to be considered. The first step is to perform a gross error check on the measurements. Physically impossible values—and thus obviously erroneous values—are flagged and checked with the original source. For temperature, values below -273.15°C are considered to be physically impossible.

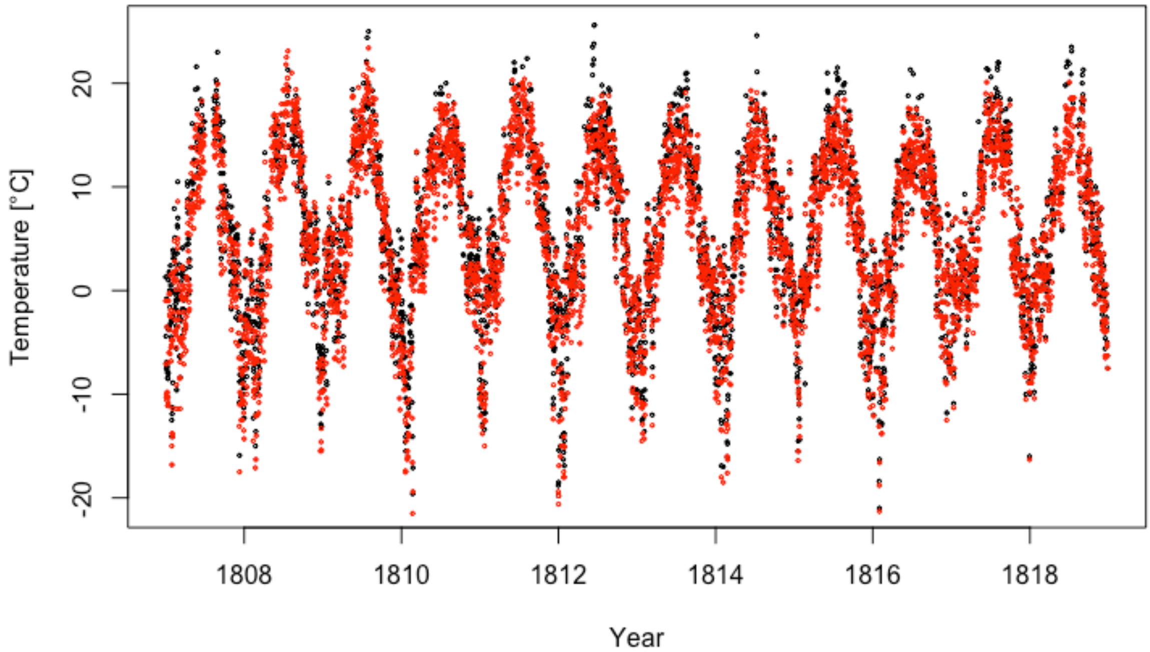

Figure 4.5: Plot of the morning temperature measurements over the period of 1807-1818. The measurments from the primary thermometer are shown in black, and the measurments from the secondary thermometer are shown in red.

A simple plot of all values from each thermometer for each part of the day was made and the summary measures[218] were calculated. The *summary* function in R then indicates the minimum and maximum values, as well as the mean and the median, the first and the third quartiles, and the number of NA entries. Generally, this gives a great first impression of the sub-daily measurements and is helpful to identify obvious erroneous and even impossible or implausible measurements. As an example, in *Figure 4.5*, the morning temperature measurements from both thermometers are plotted. The summary measures indicated a minimum at -21°C and a maximum at 25.6°C. Thus, all values are within the physically possible range. Furthermore, the data were checked for physically implausible values. For temperature, all values outside the range of -80°C and 60°C were considered physically implausible. As *Figure 4.5* shows, there were no physically implausible values outside the predefined range for the morning temperature

[218] Cf. Wilks 2011: 25-28; the numerical summary measures according to Wilks include measures of location, spread, and symmetry. In the context of this thesis, the summary measures are the results computed in R, when the function *summary* is used.

readings measured with the secondary thermometer. The procedure was repeated for all sub-daily measurements. Because this process is rather straightforward, it will not be illustrated in further graphs in this section. Neither physically impossible nor physically implausible values were found for any thermometer or for any time of day.

After the range check, the quality control employed the full length of the series by performing a variance check. Here, all values exceeding ± four standard deviations were flagged for further inspection. No values for the primary or the secondary thermometer exceeded this threshold; thus, no values were flagged. Further, a difference check as well as a consecutive value check were run. Values that differed by more than 25°C on consecutive days as well as consecutive values that were equal four or more times in a row were flagged for further inspection. The difference check once again did not result in any flagged values. However, the consecutive day check flagged four values in the night temperature readings, measured by the primary thermometer, for further inspection. No values were flagged for the secondary thermometer. The four flagged values of the primary thermometer were immediately inspected. The dates of these values could easily be detected in R: from 30 November to 3 December 1813. The temperature values of -2.1°C were checked with the original source, which confirmed the values. Thus, there were no errors made in transcription or processing. Given the precision of the scale that was read and the truncation to the first decimal point, this is considered to be possible and plausible; thus, the values were not corrected and were kept in the dataset.

Overall, the quality control did not indicate any errors that needed to be corrected after the above-mentioned tests had been conducted. In total, only four values were flagged during the quality control, which is an indication of the precision of the handling of the data by the contributors to the CHIMES project. The data was digitized precisely and had already been cross-checked by others. Furthermore, it can be said that Samuel Studer worked precisely and, regarding temperature, he made no obvious errors. Even if, for example, the four flagged values during the consecutive value check were erroneously written down by Studer, they are still within a reasonable range, as the values before and after these four night measurements all supported the plausibility of the values.

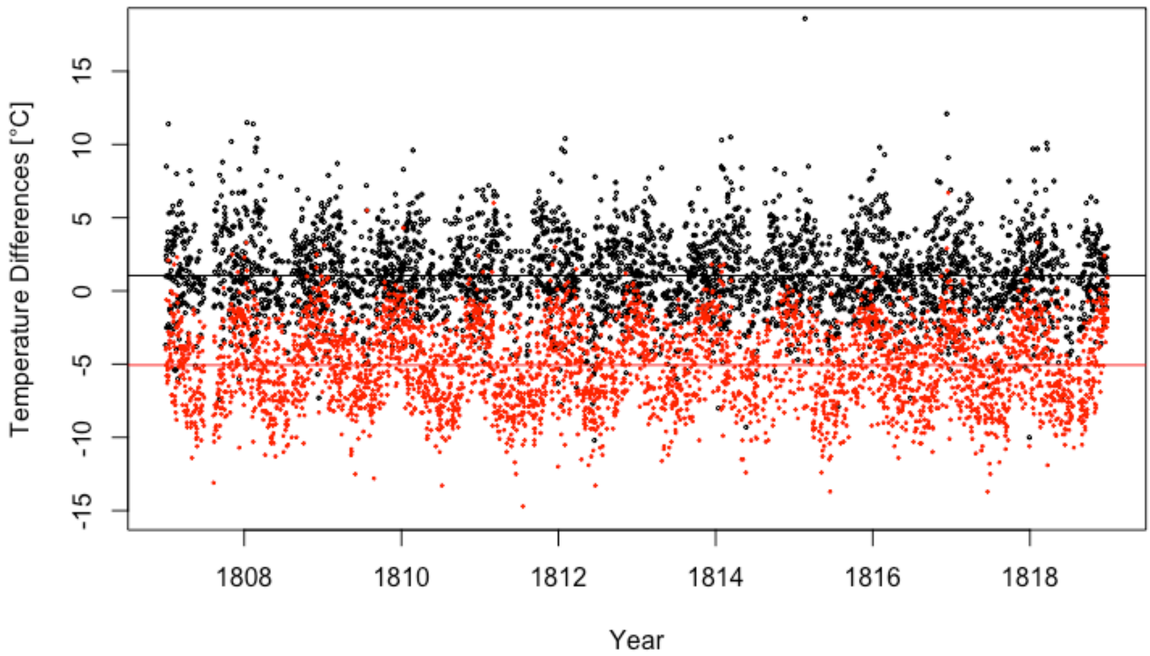

Figure 4.6: Plot of the differences between the night and morning temperature measurements (black) and the differences between the night and afternoon measurements (red). The black line indicates the mean value of all differences between the night and morning measurements, and the red line the mean value of all differences between the night and the afternoon measurements.

So far, the quality control has shown that the data have been handled with great care, but it is still possible that the data include errors. For example, transcription errors that are not drastic enough to be detected with the checks outlined by the WMO guidelines could still be undetected. Thus, the quality control will be taken further than the WMO guidelines dictate, with the aim to inspect further values that seem suspicious. For this purpose, *Figure 4.6* shows the differences between the night and the morning as well as between the night and the afternoon measurements. This can be helpful to detect suspicious measurements, especially if the difference is unusually large. The differences between the night and the morning measurements are larger than between the night and the afternoon measurements. However, there are still quite striking values evident: The differences above 15°C and below -10°C need to be inspected further. The largest difference of 18.8°C between the night and the morning temperatures was recorded on 11 January 1812. A comparison of the data with the source showed that it was indeed an error in transcription, as the night value should have been negative, but was transcribed as being positive. On 20 February 1815, there was a difference of 18.6°C. The comparison of the transcription with the original source revealed a typing error. The morning value was noted to be -7.2°Ré but was supposed to be -2.2°Ré. Subsequently, all temperature values of this reviewed day were then compared with the original source. This endeavor revealed a large string of errors.

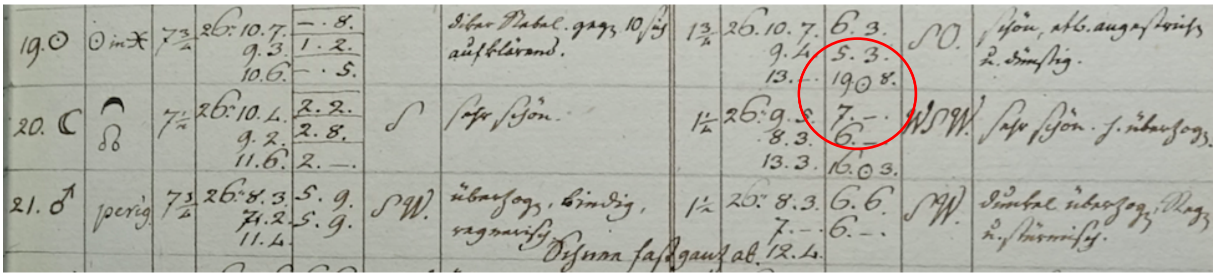

Image 4.1: Photocopy of the results of 19-21 of February 1815.[219] *Columns 4-7 indicate the morning measurements and observations, while columns 8-12 indicate the afternoon measurements and observations.*

The image of the original source (*Image 4.1*) shows the morning as well as the afternoon measurements. It is worth taking a closer look at the afternoon measurements of 20 February 1815, highlighted with a red circle. According to the raw digitized data, the primary afternoon temperature measurement was highlighted as NA. However, the original source shows that a temperature was measured, and this value seems to be fairly plausible when compared with the secondary thermometer measurement of the same day. The transcriber made a mistake by considering the circle with the dot in the middle to be for the value below the symbol instead of above or within the note of the value. A gross check of this error through the data revealed that this was indeed a systematic error made over the entire evaluated period during the digitization. Thus, it was evident that the transcription, especially of the afternoon measurements, had to be revised and the NA entries needed to be inspected and compared with the original source.

[219] Cf. Studer: Meteorologische Betrachtungen, 19-21 of February 1815: BE01_Studer_1808-1819_091.

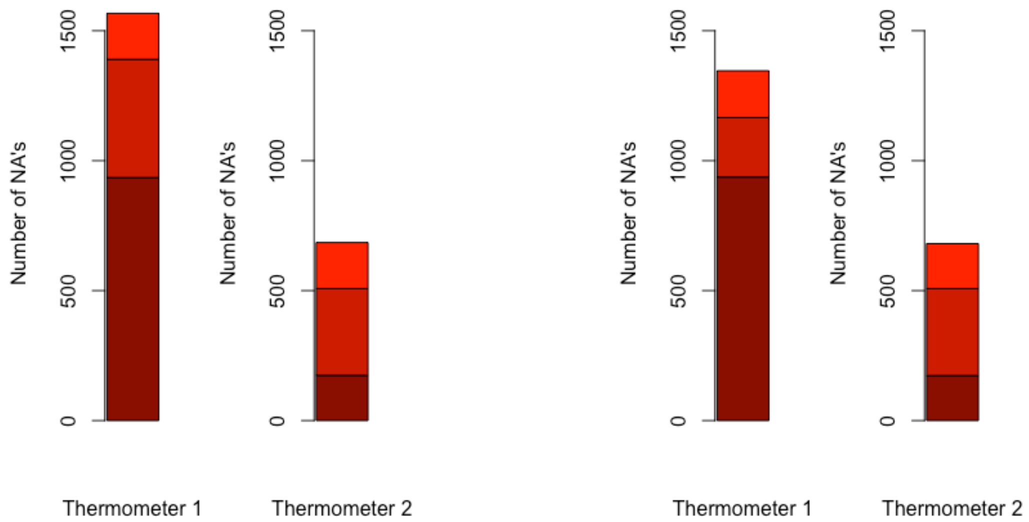

Figure 4.7: Barplots of missing values before (left) and after quality control (right). The dark red color indicates all missing values for the morning readings, the medium red color indicates missing values for the afternoon, and the light red color indicates the missing values for the night.

After the systematic error explained above had been identified, the digitization was corrected for the entire period of 1807-1818. For the primary afternoon thermometer, as many as 226 additional measurements could be included in the data with this correction (see *Figure 4.7*). As this inspection was rather tedious and time-consuming, all evident digitization and transcription errors were corrected in this step, regardless of the source of errors or the targeted measurement (thus, digitization errors of pressure values were corrected). But not just afternoon measurements that were considered to be missing in the raw data were found. The number of missing values changed for each sub-daily category and for both thermometers. This change was due to the discovery of an entire month of new data, namely the July 1807 data, among other small transcription errors. The missing month, unfortunately, did not further stand out before, as most NA's can generally be found in the month of July.[220] However, a large part of the month in 1807 was indeed measured and observed by Studer.

Beyond the missing values, the evaluation of the differences plotted in *Figure 4.6* revealed further systematic errors, in addition to small and rather unique errors made during the digitization process. The lowest difference of -12.3°C could also easily be corrected when

[220] For further elaboration on the missing values, see: Hari 2019.

compared to the original source, as the morning temperature reading was actually distorted by direct solar radiation and, consequently, should have been left out of the digitization. Another striking difference was the disparity between the night and morning temperature measurements on 16 June 1812, which amounted to -10.2°C. The review of this possibly erroneous value revealed another potential systematic source of error in the digitized version of Studer's data.

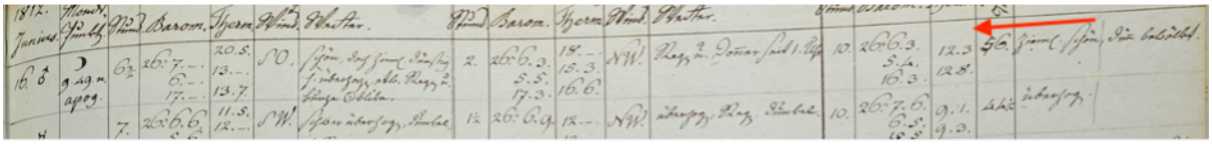

Image 4.2: Photograph of the results of 16 June 1812. The red arrow points towards the erroneous digitization.[221]

The investigation of the original source showed that the temperature measurements were digitized for the wrong thermometer. *Image 4.2* shows that Studer left a larger blank space on top of the afternoon temperature measurements (column 15), indicating that the uppermost value should belong to the secondary and not the primary thermometer, as had been included in the digitized data. In this case, the error was corrected.

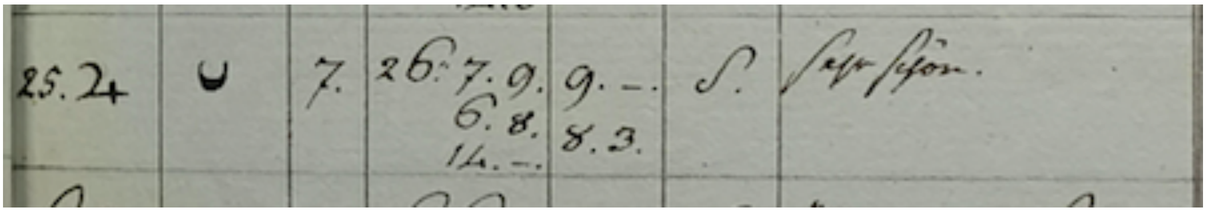

Image 4.3: Photograph of the morning measurements and observations of 25 June 1812.[222]

However, in many cases it is not clear to which thermometer the measurements belonged. For example, in *Image 4.3.*, the first temperature measurement seems to be almost on the same line as the first air pressure measurement, but there is still a larger gap above this value, and thus it is impossible to clearly state to which thermometer the value belonged. Therefore, the values were only corrected in the cases where the temperature differences were larger than 15°C or smaller than -10°C.

Further corrections were made at the beginning of May 1814. At the end of the April 1814 observations, a note could be found that the thermometer facing east—the primary

[221] Cf. Studer: Meteorologische Betrachtungen, February 1815: BE01_Studer_1808-1819_059.
[222] Cf. ibid.

thermometer—had broken and had been replaced in May. The measurements of 1-5 of May 1814, therefore, had to belong to the secondary thermometer. From the afternoon of 5 May three measurements were recorded again. One can assume that Studer had already received his new thermometer, even though in the mentioned note, he stated that he did not receive a new thermometer until 9 May 1814.[223]

Finally, the difference of -10°C on 29 December 1817 was reviewed. This time, no digitization error could be found. The weather conditions fit the temperature measurements well, as according to Studer, it was overcast during the day but then it was a clear and cold winter night. The differences between the night and afternoon temperature measurements were also reviewed. In general, there were more negative differences calculated. However, this is fairly plausible and was also supported by the comparison of the original source with the digitized data. Some large differences could also be attributed to digitization errors. These were also corrected as part of the general digitization correction. In the other cases, the weather conditions caused large differences between the night and the afternoon temperatures. The largest temperature gradients in the summer were often associated with thunderstorms, according to the observation notes by Studer. Therefore, it was not surprising to find most of these large differences in the summer months. Conclusively, this comparison was not as helpful to find erroneous values as was the computed differences between night and morning temperatures.

The last part of the quality control aimed to compare the two thermometer measurements and eventually select the more reliable readings for the subsequent steps of the homogeneity assessment. The preliminary study concluded that the secondary thermometer was more reliable and accurate: The primary, east-facing thermometer was missing many values in the morning because it was directly exposed to solar radiation. This pattern was, however, the opposite for the afternoon and night measurements (*Figure 4.7*). Overall, however, there were fewer missing values for the second thermometer.

To decide whether this evaluation should be pursued with both thermometers or if it should be narrowed down to only one, as had been done in the preliminary study, the metadata should be taken into account. Samuel Studer himself mentioned in his notes that the east-facing thermometer was more biased because it was attached to a sandstone wall, which stored the heat over the day and thus resulted in higher values. The west-facing thermometer, on the

[223] Cf. Studer: Meteorologische Betrachtungen, May 1814: BE01_Studer_1808-1819_081.

contrary, was attached to wood, which stored less heat and thus provided more accurate measurements, especially in the evening.[224] Therefore, similarly to the preliminary study, it was decided to only consider the secondary, west-facing thermometer for this study.

4.2.2. Breakpoint Detection and Homogeneity Adjustment

Early instrumental measurement series are valuable sources of information that can be used for further climate research. However, a prerequisite for the data is to be homogenous, thus capturing only variations in climate and not variations caused by, for example, the repositioning or the replacement of an instrument. As the quality control for the temperature values has shown, many errors can be introduced to a time series by erroneous digitization or ambiguous notations. Not discussed so far are variations in the data introduced by Studer through the replacement or relocation of instruments. Before statistically checking for the breakpoints, the metadata should be assembled,[225] and it needs to be checked for notes on further information about the instruments, and thus for hints about possible breakpoints. Indeed, some metadata on the instruments is provided in the source. However, a challenge is determining which thermometer was replaced. Nevertheless, it is necessary to determine if Studer meant the east-facing thermometer—the thermometer not considered further in this thesis—or if he meant the west-facing thermometer. A hint about a broken thermometer in 1814 has been already discussed in the quality control section.

Studer further noted replacements of a thermometer on the following dates: 6 November 1809, 11 February 1810, 1811 (exact date unknown), and 6, 16, and 25 May 1812. There are only vague hints about which direction the replaced thermometers were facing. The replacement in 1809, however, must have been the east-facing thermometer. Studer wrote that the replaced thermometer was positioned on the arbor facing the botanical garden, which lies northeast of the Burgerspital. In 1811, the thermometer on the arbor had to be replaced due to renovations on the building. Overall, the dates should be kept in mind for the statistical breakpoint detection, as they will hopefully match the metadata. It is also possible and likely that only major replacements were noted, and not all relocations or other adjustments. Generally, any major replacement or relocation could have introduced a bias in the measurement series and would thus reflect non-climatic variations that need to be corrected to have a homogenous time series. The instruments themselves in the period of early instrumental measurements could have

[224] Cf. ibid.: BE01_Studer_1779-1786_006.
[225] Cf. Aguilar et al. 2003: 31.

introduced further biases. The main difficulty of homogenizing a series like the one from Studer is the lack or incompleteness of the metadata. In conclusion, it is unlikely for all biases to be noticed.

A suitable reference series for the Craddock test (see *Equation 2.2*) should have experienced the same climate oscillations as the candidate series. Unfortunately, when dealing with early instrumental measurements, the choice of reference series is rather limited. Ideally, a reference series would capture an atmospheric state similar to the candidate series and therefore should not be affected by different local weather patterns. The distance in the sense of climatology and the general geographical distance should ideally be as small as possible. However, the challenge is already to find a reference series that covers the same period as the candidate series. Moreover, it is not always clear what type of processing the reference series has undergone. Therefore, it is an advantage to take all reference series for the temperature measurements from the same database. The Global Historical Climatology Network (GHCN) database[226] was chosen for this endeavor. The web application run by the WMO is a scientific tool that provides a vast amount of climate data and analytical tools.[227] For the temperature reference series, the filter was set to "adjusted" data. These data have already undergone a homogenization process and are thus suitable as a reference series.[228] Thus, the following temperature series with monthly mean temperatures were chosen: Basel/Binningen, Geneva-Cointrin, Strasbourg, Karlsruhe, and Milan. In addition, the temperature series of Basel/Mulhouse and Zurich from the CHIMES project were chosen.

First, the correlation of each series was calculated. Following Fessehaye et al., reference series with a correlation coefficient of less than 0.6 were rejected.[229] In addition, reference series were only accepted if they included the years 1807-1818.

[226] Cf. Lawrimore et al. 2011.
[227] Cf. Climate Explorer 2020.
[228] Cf. Menne et al. 2018.
[229] Cf. Fessehaye et al. 2019: 5218.

Table 4.1: Pearson correlation coefficients for the reference series and the candidate (Studer) series.

Reference series	Pearson correlation coefficient
Basel/Mulhouse	0.84
Basel/Binningen	0.78
Geneva	0.84
Zurich	0.20
Karlsruhe	0.80
Strasbourg	0.79

The correlation coefficients shown in *Table 4.1* of both Basel stations, Geneva, Karlsruhe, and Strasbourg all indicate a moderately strong linear relationship to the candidate series.[230] Only Zurich had to be excluded as a reference series, because Pearson correlation coefficient only indicated a weak linear relationship. The Zurich series is similar to the Studer series. The measurements were taken by Feer in 1807-1827 and the series was digitized as part of the CHIMES project.[231] However, no further work has been done on this series. It has also not been homogenized. Therefore, it is not a surprise that the correlation is much lower than the other series, which have already undergone a homogeneity assessment. It is important to add, however, that much potential can be seen in the Zurich series relative to the Studer series: It also covers partially the same time period and is generally a very long measurement series, as Feer measured from 1807 to 1827. There are also measurements for 1838 available.

[230] Cf. Wilks 2011: 55.
[231] Cf. Pfister et al. 2019: 1351.

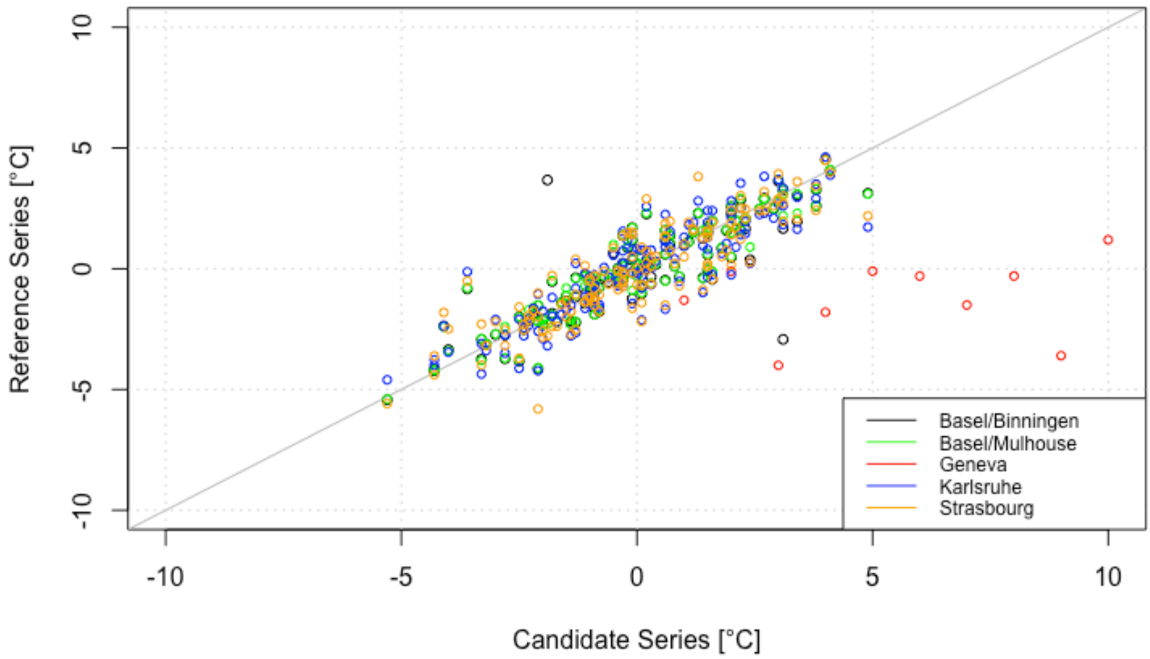

Figure 4.8: Scatterplot of the temperature correlations between the reference series and the candidate (Studer) series.

In addition to the correlation coefficients in *Table 4.1*, the linear relationships were graphically checked (*Figure 4.8*). A scatterplot is a common tool to display paired data and allows for an easy evaluation of features such as a linear relationship.[232] The data for this purpose is illustrated using a Cartesian coordinate system, where the coordinates are the values of each member of the pair.[233] If the Pearson correlation coefficient is 1 for paired data of a reference and a candidate series, the points would fall directly on the grey line in *Figure 4.8* and would have a perfect positive linear relationship. A disadvantage of Pearson correlation coefficient is that it is neither robust nor resistant. It is not robust because a strong but nonlinear relationship may not be recognized, and it is not resistant because it is extremely sensitive to outliers, and thus a single outlying point can lead to an overestimation of the linear relationship. Hence, it was worthwhile to check Pearson correlation coefficients graphically, after they have been computed mathematically. It was also worthwhile in this case because the linear relationship between the Studer series and the Geneva series does not seem to be as strong as indicated by Pearson correlation coefficient. This can be gathered from the many data points lying in the

[232] Cf. Wilks 2011: 50.
[233] Cf. ibid.

fourth quadrant of the coordinate system.[234] The Geneva series was, therefore, also excluded as a reference series. The breakpoint detection was consequently performed with four reference series. As already explained in Chapter 2, the homogeneity has been be checked graphically with the Craddock test. Breakpoints should be compared to the metadata to detect and hopefully to find a cause for the inhomogeneities. In addition, the metadata was also tested for completeness. If breakpoints cannot be explained by the metadata, the information might have never been noted in Samuel Studer's observations.

Overall, the accumulated differences for four reference series were used to detect the breakpoints. To prepare the data for the Craddock test on the temperature measurements, unfortunately, the annual cycle of all stations had to be removed, as it was evident even in the accumulated differences. The cause of this could be a radiation error in the Studer series. When subtracting the annual cycle from the candidate and reference series, the source of error disappeared. A time series can be corrected to many different extents to remove inhomogeneities. One can go as far as removing the urban heat island effects and many more sources of errors from the series. However, the aim of the homogenization here was only to remove obvious breakpoints stemming from, for example, replacement or relocation of measuring instruments. The homogenization conducted here could be seen as incomplete, as little will be corrected overall. However, this thesis aimed to present the time series so far, as it can be used for further climate research. When the Studer series will be reused for future research, the information on the metadata will be crucial. The homogenization procedure will most likely be redone, eventually even with a different method and with different reference series. While the annual cycle was subtracted for the Craddock test to make the detection of the breakpoints easier, the possible radiation error was not corrected, because the metadata does not contain enough information about this aspect.

[234] Cf. ibid.: 52.

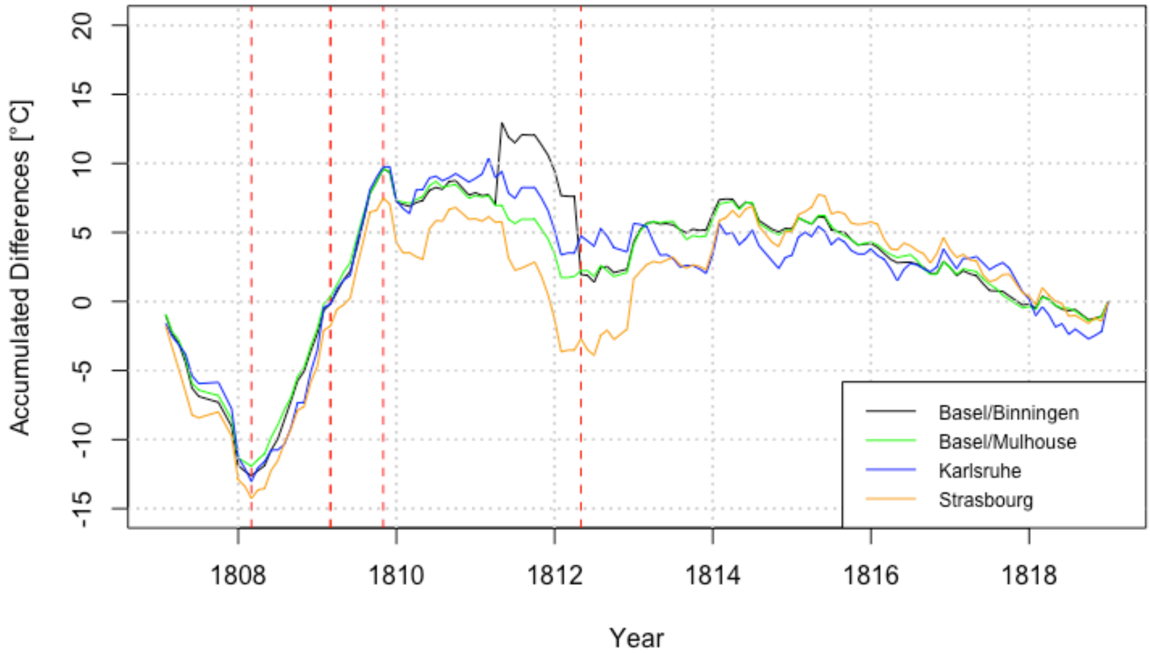

Figure 4.9:Accumulated differences between the reference series and the candidate (Studer) series, calculated with the Craddock test. The red dashed lines indicate the breakpoints.

The graph of the accumulated differences is illustrated in *Figure 4.9*. The most obvious breakpoints can be detected at the beginning of the series and are marked with red lines. The year 1807 seems to be too cold, whereas the two following two years seem to be too warm. Then follows a two-year period of 1810 to 1811 where the series is rather homogenous already. In 1812, there seems to be another breakpoint. The last years of the series are again homogenous.

Table 4.2: Adjustments made to the temperatures of the Studer series based on breakpoint detection.

Period	Corrections [°C]
1807	+1.3193
1808-1809	-0.9349
1810-1811	+0.0799
1812-1813	-0.2166
1814-1818	0

According to the break points found above, the series was corrected as shown in *Table 4.2*. The inhomogeneity of the years 1807 and 1808 was evident even without the support of metadata, as they could be detected in the accumulated differences of all four reference series. Inhomogeneities in 1809-1810 and 1812, on the other hand, could possibly be supported by the metadata. As mentioned above, it is unclear which thermometers Studer replaced. However, it seems to have at least affected the secondary thermometer as well. Either the thermometer was replaced or the measuring circumstances of the secondary thermometer changed as a consequence of the replacement of the primary thermometer. There are other possible explanations for the inhomogeneities detected. It is possible that Studer adjusted the thermometer scale without taking notes on the procedure. The large shift in the first years of the period analyzed in this thesis could have easily been caused by such an action.

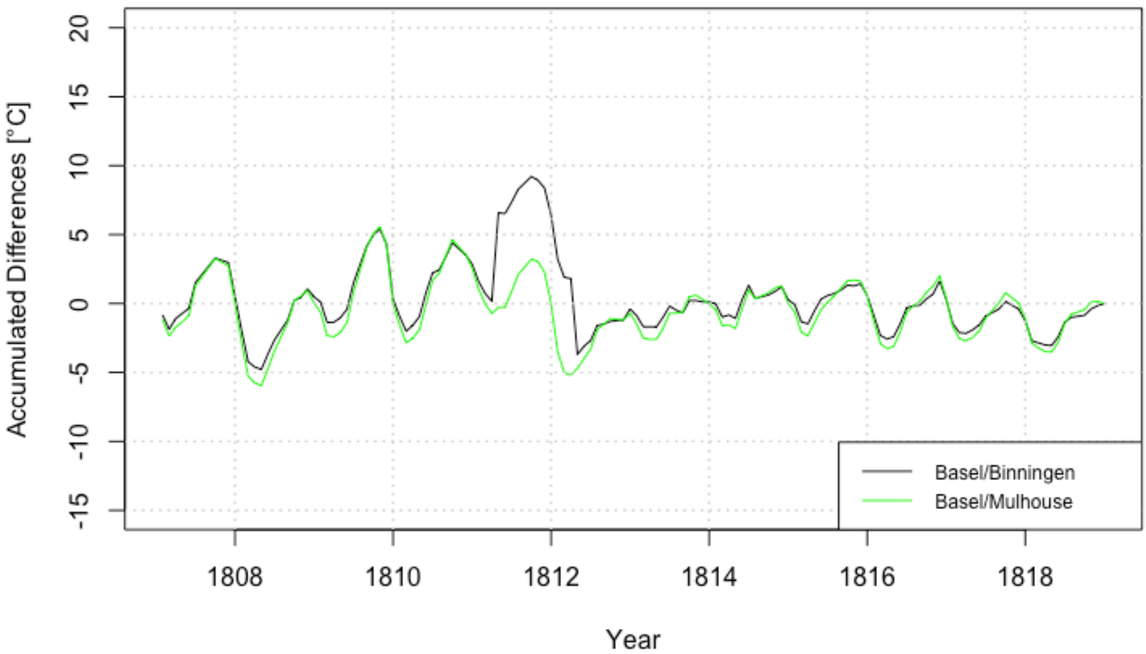

Figure 4.10: Exemplary accumulated differences in temperature after the homogeneity adjustment of the temperature series.

After the homogeneity adjustment, the Craddock test was repeated with the corrected data to check the impact of the adjustments. However, the Craddock test was only repeated with the two Basel reference series (see *Figure 4.10*), as an example. The accumulated differences still do not present a straight line because the differences were calculated without the subtraction of the annual cycle. This was done on purpose to show the above-mentioned annual cycle.

Nevertheless, the curves now oscillate much closer to the 0°C line than before the homogeneity assessment; hence, the data were considered to be sufficiently homogeneous, and further corrections were not needed.

4.2.3. Trend Analysis

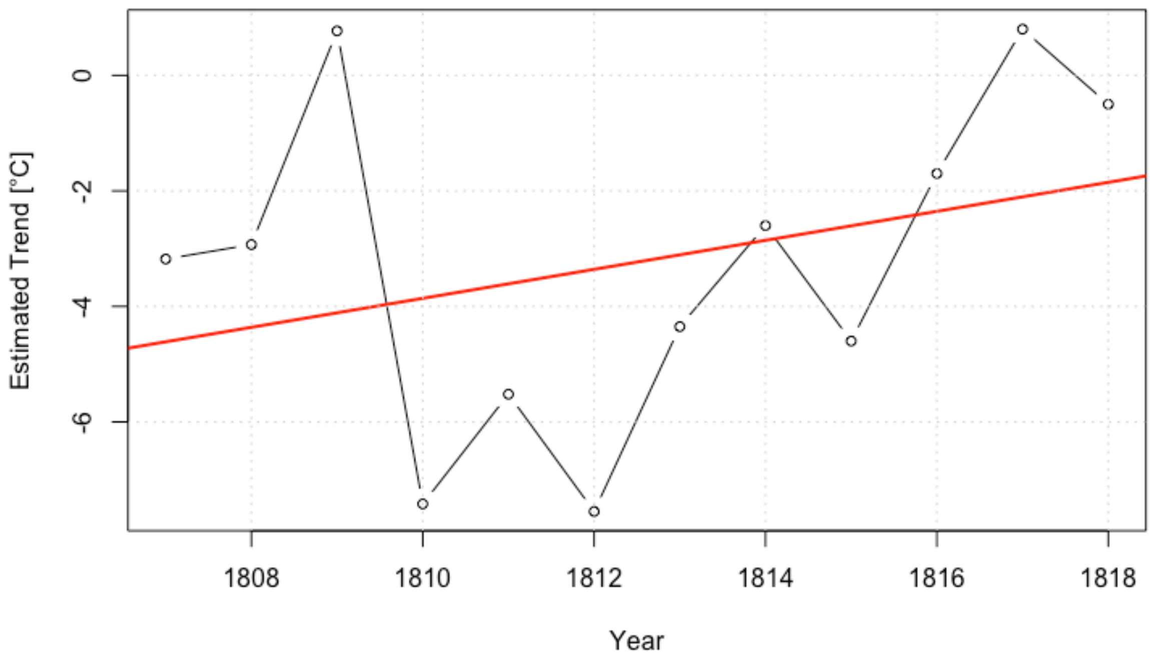

Figure 4.11: Trend detection based on linear regression. The red line indicates the possible trend. The y-axis is based on the estimated trend generated by tren.linreg. The abline (red, solid line) is based on the fitted values.

In addition to the breakpoint detection, the Studer series was subjected to trend analysis using linear regression. H_0 is that the slope $\beta = 0$ (see *Equation 2.3*) and thus the data are not dependent on time and there is no linear trend. H_0 will be rejected at a significance level of 5%. H_A is $\beta \neq 0$ and thus there is some dependence on time. The estimated yearly trend is plotted on the y-axis of *Figure 4.11*. The p-value was 0.31, and thus H_0 could not be rejected. There is no significant trend observable in the series. Linear regression is based on the assumption that the residuals are independent as well as normally and identically distributed, and these assumptions need to be verified.

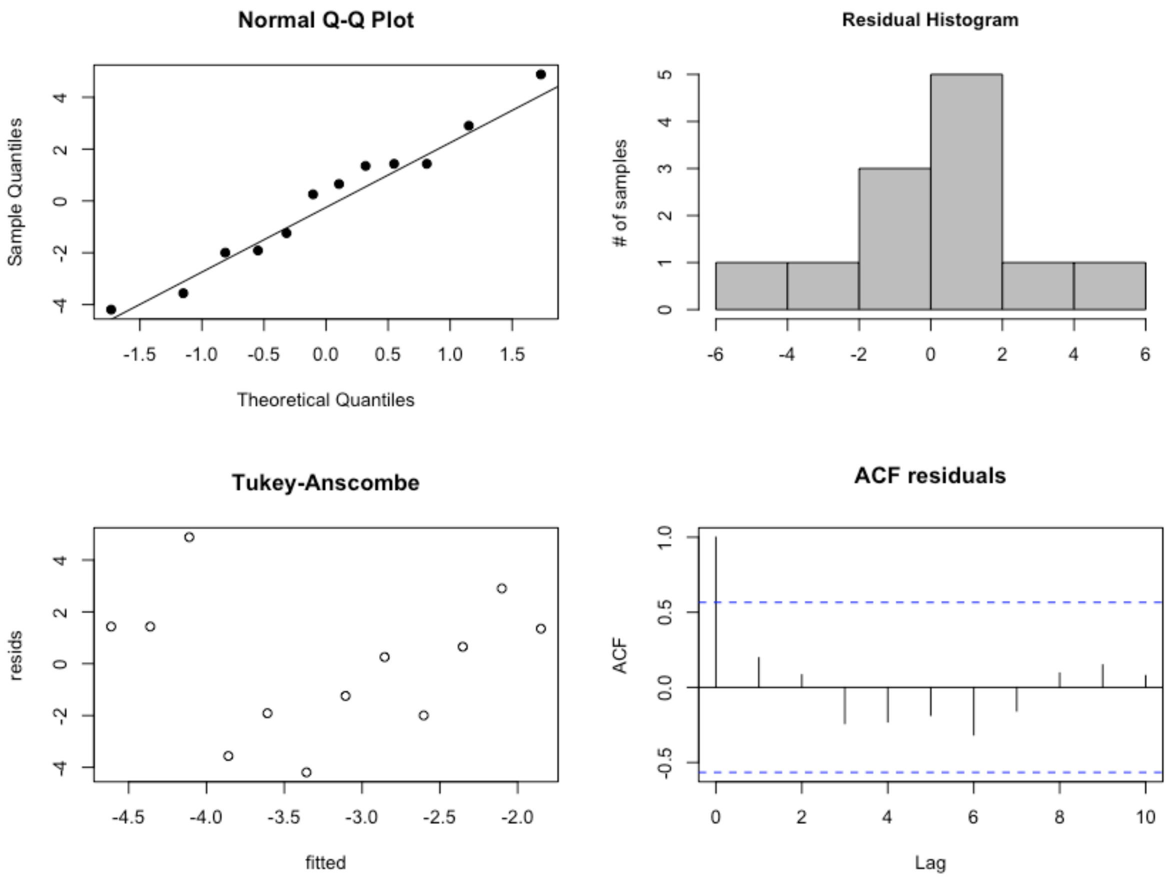

Figure 4.12: Normal Q-Q plot, residual histogram, the Tukey-Anscombe plot, and the autocorrelation function (ACF) of residuals to test for underlying assumptions about the residuals.

The residuals can be tested for the assumptions by the generation of four different plots (see *Figure 4.12*). The Q-Q plot as well as the residual histogram point toward normality. The histogram, however, shows a slight left skewedness of the residuals. The Q-Q plot does not have enough data points to draw the same conclusion. More worrisome, however, is the Tukey-Anscombe-Plot, which plots the residuals against the fitted values. If the underlying assumptions presented in Chapter 2 were correct, the points would ideally fluctuate around a horizontal line. Unfortunately, this is not the case, and the residuals could violate the assumptions. The autocorrelation function proves that there is no serial correlation of the residuals. Except for the Tukey-Anscombe plot, the residuals seem to validate the assumptions. Because the test result might be compromised, it was decided to perform a non-parametric test, namely the Mann-Kendall trend test. For this test, H_0 states that the time series values are independently and identically distributed, while H_A states that there is a monotonic—not necessarily linear—trend.[235] The p-value was 0.19, meaning there is no significant trend and H_0 could not be rejected. Hence, no trend was corrected.

It is worthwhile to think about the implications or possible causes for such a trend. Camuffo provided as possible reason for a positive trend. Especially mercury thermometers can experience a slow rising of the 0°Ré indicator over time. This can be caused by the gradual contraction of the glass tube of the thermometer.[236] This finding could indeed be another indication toward the use of a mercury thermometer by Samuel Studer.

In summary, a trend analysis was conducted, but no significant trend was found and, therefore, no trend was subtracted from the data. The lack of a trend could also be attributed to the small number of available datapoints. For a more conclusive statistical analysis, more datapoints would ideally be available. Nevertheless, the goal of producing a homogenous monthly temperature series was achieved. However, the homogenization process did pose great difficulties. The first challenge was the selection of suitable reference series. The reference series availability is fairly limited as it relies on early instrumental series that are ideally already homogenized.. Hopefully, more series will be available in the future so that more suitable, geographically, and climatically closer reference series to the Studer series can be chosen. Further, the homogenization process was limited by the constraint of the metadata. The availability of information to the replacement or relocation of the thermometers was very scarce and would ideally be vaster. Moreover, the homogenization process could and should go further in future studies to create a homogeneous daily temperature series. This would, however, be an even more problematic endeavor, as the suitable reference series would have to be available in daily or at best sub-daily resolution as well. The homogenization of sub-daily or daily time series will not be further considered for the scope of this thesis, but it can be kept in mind for future time series analysis with early instrumental measurements.

4.2.4. The Corrected Temperature Series

To conclude the homogenization procedure for the temperature measurements, it is worthwhile to present the corrected series (*Figure 4.13*). It can be compared to the temperature series of the second thermometer of *Figure 4.4.*

[235] Cf. Wilks 2011: 166-168.
[236] Cf. Camuffo 2002a: 323.

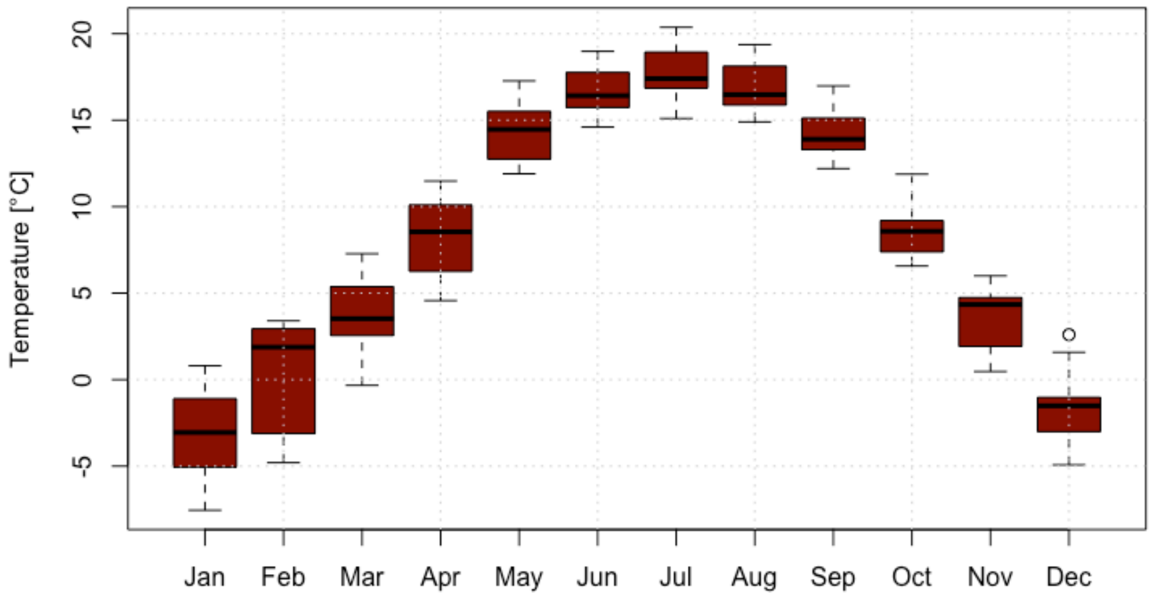

Figure 4.13: Boxplot of the monthly mean temperatures based on the homogenized Studer series.

The outlier in December needs to be addressed. Before the homogeneity assessment had been conducted, three outliers were plotted, all between October and December. Only one outlier remained after homogeneity assessment; it can be attributed to December 1814. The mean temperature of this month was 2.6°C. Only one other month, December 1810, had a positive mean. All other Decembers experienced a negative mean temperature, the coldest being December 1808 with -4.9°C. A disadvantage of only having the monthly means homogenized is that it is not possible to look at homogenized daily temperatures, an endeavor that would give information on the course of this month. However, the original source can always be consulted to obtain additional information. In this case, the period between 11 to 17 December 1814, was warm, with afternoon temperatures always at or above 10°C.[237] Studer mentioned in his observations that a majority of these days were overcast but had generally nice weather. He also mentioned wind on several occasions: On 11 December, when this warmer period started, he even noted observations on strong wind gusts. This weather condition is consistent with *Föhn*, which is a common weather condition for Bern. This is, however, difficult to predict specifically, especially because air pressure has not yet been considered.

[237] Cf. Studer: Meteorologische Betrachtungen, December 1814: BE01_Studer_1808-1819_089.

In addition to the outlier, the temperature ranges in the different months should be considered. Even though they did not significantly change from before the homogeneity assessment, they need to be viewed with great caution. The monthly mean temperatures were calculated considering the WMO guidelines. Thus, if the criteria concerning the amount of missing data in absolute terms and in terms of consecutive days were not fulfilled, the relevant month could not be taken into account. Hence, the monthly mean temperature range does not necessarily reflect the true climatological temperature range, but rather includes an indication about the available data. Studer mostly traveled in the summer, and therefore most of the missing data are from this period. Only the months of July, August, and October were affected by Studer's absence in terms of missing monthly values. For 1807, the monthly mean temperature was missing for all three months. For both August and October, three additional years were missing in the period of 1808-1818. These missing data need to be considered when looking at the boxplots and drawing conclusions about them. This problem will be discussed further in the case study (Chapter 5), because it will be relevant for this application.

4.3. The Air Pressure Measurements

A step forward from the preliminary study is the inclusion of other measurements and observations made by Studer. Besides temperature measurements, early instrumental series often included air pressure measurements. It is another source of information about the past weather and thus a source of additional knowledge about past climate variability. Compared with temperature measurements, air pressure measurements need to be handled a bit differently. The advantage of air pressure is that if it is accompanied by detailed metadata, and it is less problematic because it does not require a certain exposure.[238] On the other hand, air pressure measurements require more elaborative pre-processing because they need to be corrected for variations in temperature and altitude. This data processing procedure will follow the steps applied by Brugnara et al. (2015).[239] The additional steps of the homogeneity assessment will be conducted analogously to the homogenization process of the temperature measurements presented in Chapter 4.2.

4.3.1. Data Processing

As briefly mentioned in Chapter 4.1.2., the air pressure measurements by Samuel Studer were measured in the Paris inch and are complemented by a control temperature measurement in the

[238] Cf. Brugnara et al. 2015: 1029.
[239] Cf. ibid.

room in which the air pressure measurements were taken. The air pressure as well as the according temperature measurements first need to undergo a unit conversion. The temperature can be converted from °Ré to °C using *Equation 4.2*. The air pressure conversion from Paris inch to the in the metric system occurs by the multiplication of a factor of 27.07.

The control temperature measurements could suffer from various errors. Before proceeding further with the air pressure measurements, the control temperature measurements were subjected to a quick quality check. These measurements will be important for the further steps of the data processing of the air pressure measurements. Errors in the control temperatures would therefore have implications on the air pressure measurements.

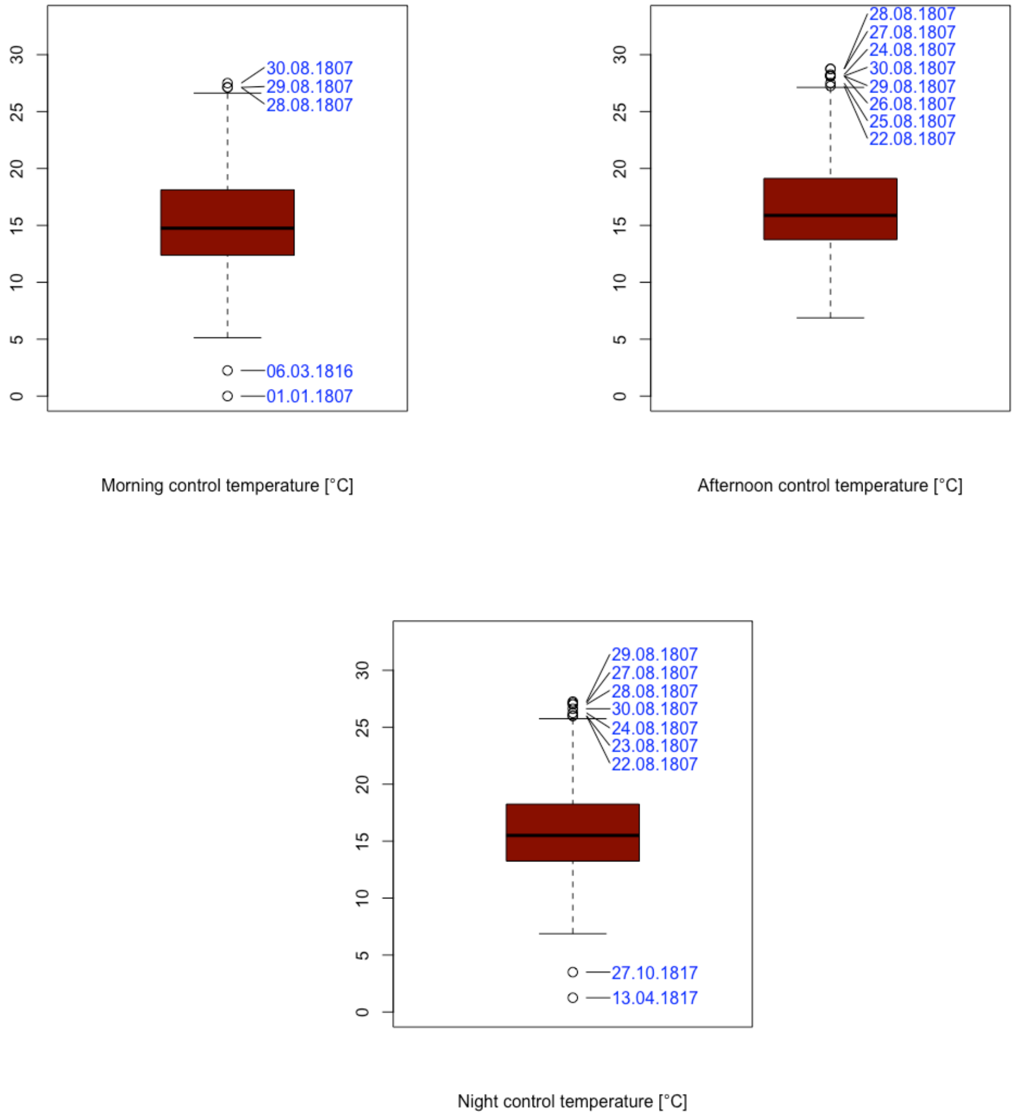

Figure 4.14: Sub-daily boxplots of the control temperature measurements of the air pressure data, including the labeled outliers (in blue).

Boxplots are a helpful tool to depict information about the quartiles of a set of data. As mentioned before, especially the outliers are worth a second look, as they could potentially indicate erroneous or otherwise suspicious values. First, however, the values within the whiskers and a comparison of the three sub-daily plots are interesting (*Figure 4.14*). The median of the sub-daily control temperature measurements is evidently almost equal. This further proves that the measurements were taken in a room and thus the temperatures vary little over the course of a day: The median varies only from 14.8°C (morning) to 15.9°C (afternoon). The night median of 15.5°C thus corresponds to the exact overall mean of the room temperature over all the measurements.

The morning control temperatures have the fewest outliers. The lowest value was measured on 1 January 1807, when it was supposedly 0°C in the room. However, a comparison of the digitized data with the original source concluded that this was an erroneous digitization of the value, and the temperature was actually 10°Ré (12.5°C). The outlier of 6 March 1816 was also due to a digitization error: It was entered as 1.8°Ré (2.3°C) but was really 10.8°Ré (13.5°C). The other outliers of the boxplot of the morning temperatures all stem from the end of August 1807. A comparison with the other sub-daily boxplots in *Figure 4.14* reveals many other outliers from this month. The values were compared with the source and the digitization was correct. The readings stem from a warm period in a summer month. Therefore, it must have been fairly hot in the room, which indicates rather poor interior ventilation. Further outliers can be found when analyzing the evening temperatures. Both the measurements of 13 April 1817, and 27 of October 1817, were correctly digitized, but seem to be faulty readings when compared with the other sub-daily measurements of these days. Thus, these values cannot be used and were marked as NA measurements.

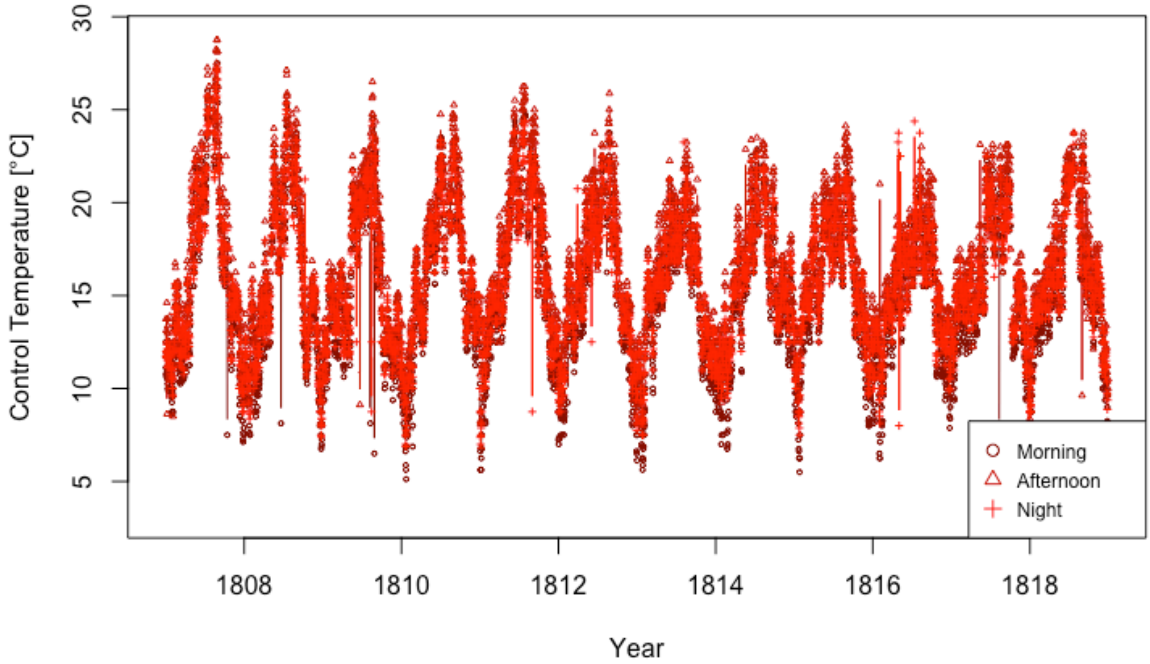

Figure 4.15: Plot of the control temperature measurements of the sub-daily measurements. The colors and symbols are indicated in the legend, however, the general picture is relevant and not the individual values. Thus, colors that fade together were used purposefully for this illustration.

Because it is known that this thermometer was placed in a room, it is worthwhile to understand whether this room was heated. If it were heated, the temperature measurements would not show a seasonality. However, *Figure 4.15* indicates a clear seasonality of the measurements. Therefore, the room was likely not heated, and the control temperature measurements represent the seasonal fluctuations of the temperature, even though it obviously does not correspond to the outside temperature measurements. Nevertheless, the control measurements are important to show to what temperature conditions the barometer was exposed because mercury shrinks and expands depending on the temperature. Therefore, the air pressure measurements need to be corrected accordingly. Hence, the availability of control temperature measurements is of great value.

The control temperature was next used to correct the air pressure measurements. The aim was to obtain measurements in millimeters reduced to 0°C (L_0). The reduction to 0°C follows the international standards and was calculated according to the following equation.

$$L_0 = (1 - \gamma T)L_{mm} \quad (\textit{Equation 4.3})$$

In *Equation 4.3*, γ is the thermal expansion coefficient of mercury at 0°C (1.82×10^{-4} K^{-1}), T corresponds to the correction temperature of the barometer in °C and, L_{mm} is the original measurement in millimeters.

Next, the measurements were converted from the unit of length (mm) to the common air pressure unit (hPa). The calculation follows the hydrostatic equation (*Equation 4.4*).

$$P_0 = \rho g_n L_0 \cdot 10^{-5} \quad (\textit{Equation 4.4})$$

The resulting P_0 corresponds to the absolute pressure in hPa. For ρ, the value 1.35951×10^4 kg m^{-3} is inserted as the density of mercury at 0°C. The standard gravity acceleration g_n is 9.80665 ms^{-2}. L_0 again is the barometric reading corrected for temperature in millimeters.

After these adjustments, the readings were now in the customary air pressure units and had to be corrected for local gravity, because this varies with latitude and altitude. This correction is based on the geographical location of the barometer (*Equation 4.5*).

$$P_n = \frac{g_{\rho,h}}{g_n} P_0 \quad (\textit{Equation 4.5})$$

Because the exact location in the Burgerspital where Samuel Studer took his readings is not known, the geographical coordinates were narrowed down to be as exact as possible, resulting in a latitude of 46.948149 (ρ) and an altitude of 546 m (h).[240] Following *Equation 4.6,* $g_{\rho,h}$, the local gravity acceleration, was calculated as follows:

$$\begin{aligned} g_{\rho,h} = 9.80620 \cdot (1 &- 0.0026442 \cdot \cos(2 \cdot \mathrm{lat}) \\ &- 0.0000058 \cdot \cos(2 \cdot \mathrm{lat})^2) \\ &- 0.000003086 \cdot \mathrm{alt} \end{aligned} \quad (\textit{Equation 4.6})$$

[240] Cf. Worldwide Elevation Map Finder 2021; assuming he measured on the ground floor. As there is no information about where he measured, it will be assumed. In addition, for this calculation a flat terrain around the stations needs to be assumed and can be confirmed. GEOsearch 2021.

Lastly, to allow a comparison of the Studer series with measurements taken in a different geographical location, and thus at different altitude, the data were reduced to mean sea level for synoptic analysis *(Equation 4.7*).

$$SLP = P_n \cdot \exp\left(\frac{\frac{g_{\rho,h}}{R} \cdot h}{T_S + a \cdot \frac{h}{2}}\right) \qquad (\textit{Equation 4.7})$$

Equation 4.7 results in the sea level pressure (SLP) in hPa. For this, the gas constant for dry air R needs to be introduced—it is 287.05 J kg^{-1} K^{-1}—and the lapse rate of a fictitious air column below the station (a) is 6.5×10^{-3} km^{-1}. The equation further requires the outside temperature at the station in K. Fortunately, this is an easy endeavor as Studer measured the temperature outside and these measurements have already undergone a quality control in Chapter 4.2. The measurements of the west-facing thermometer, previously identified as producing the most reliable measurements, were included in the calculation and transformed to K by adding 273.15 to the individual values. This step completed the data processing of the air pressure measurements, and the data were next subjected to the homogeneity assessment procedure.

4.3.2. First Impressions and Quality Control

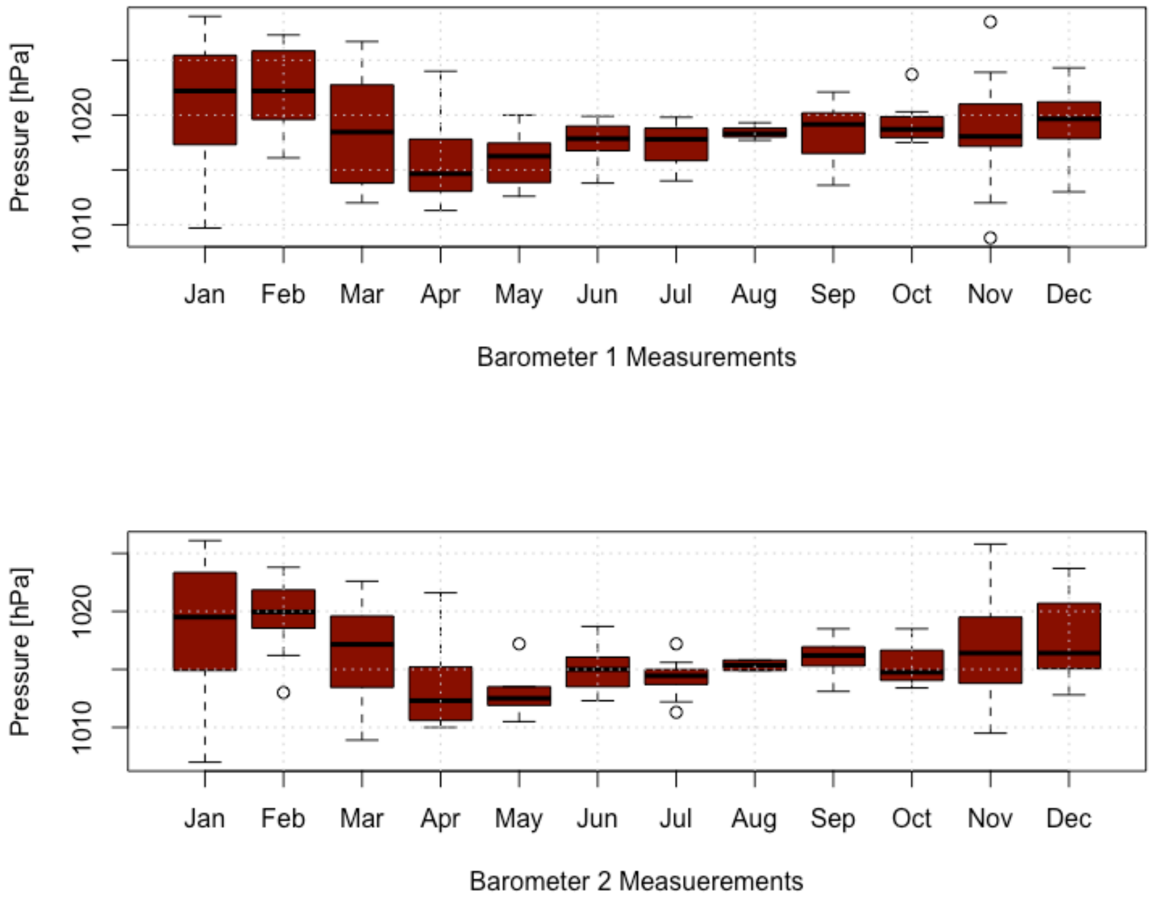

Figure 4.16: Boxplots of the monthly mean air pressure based on the data after the temperature quality control.

A first impression can again best be gained by analyzing the boxplots of the monthly means. The monthly means were calculated based on the daily means produced by averaging the morning, afternoon, and night measurements without adjustment of the daily cycle because this does not have the same implications for air pressure as for temperature. Furthermore, it needs to be noted that a daily mean was accepted even if only one or two measurements of the day were available, because air pressure only varies 1-2 hPa per day in the midlatitudes. This can also be proven by comparing the mean of the morning, afternoon, and night air pressure measurements. For both barometers, they did not vary more than 2 hPa over the course of a day. Dynamic, atmospheric variations were thus not considered. A first impression of the annual cycle of the air pressure measurements confirmed the expectation of air pressure being

the lowest in April for the midlatitudes. Further, it can be noted that, at first glance, both barometers seem to have performed similarly.
Before continuing the analysis, the outliers need to be addressed. The primary barometer seems to have fairly striking high and low outliers in November. Thus, they were examined critically, especially because the minimum outlier is at 1010 hPa and the maximum outlier is at 1026 hPa, which is a fairly large difference. It must be noted, however, that the second barometer includes the uppermost outlier of the primary barometer in the whisker and the lower outlier disappeared. Thus, this issue was examined later to identify the concerning years.

The quality control for air pressure followed the same procedure as the temperature quality control (Chapter 4.2). All air pressure values below 0 hPa and outside 500-1100 hPa were flagged to check for physically implausible values; no values were flagged for further investigation. Next, values exceeding ± four standard deviations were flagged. Over both barometers and all sub-daily measurements, four different dates were flagged for at least one measurement time. All values were verified with the source, and because the values only deviated by small values in absolute terms, they were left in the time series. Lastly, no values were flagged for the difference check (observations differing by more than 40 hPa on consecutive days) or for consecutive values (four or more equal consecutive values in a row).
The quality control did not reveal any further erroneous values, mainly due to the extensive comparison of the digitized data to the original source as part of the temperature quality control. Otherwise, the data would have included erroneous transcriptions and would have lacked the data of July 1807.

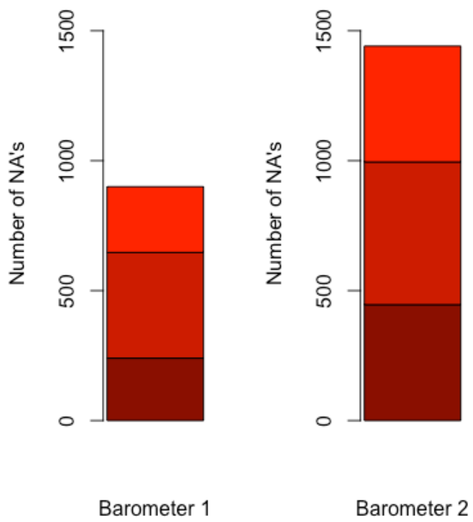

Figure 4.17: Barplots of the missing air pressure measurements after the quality control.

The last part of the quality control entails the comparison of the two barometers and, eventually, the selection of one to continue the study, similarly to how one thermometer was selected for temperature measurements. The decision regarding the barometer was rather easy, especially when considering the metadata. After all, it was already Studer's intention for the first barometer to be the actual barometer and the second one to have a control function.[241] This is also evident when comparing the number of missing values: There are many more missing values for the secondary barometer than for the primary barometer (*Figure 4.17*). Thus, considering the number of NA entries and Studer's noted intentions, the first barometer was used for further evaluation. However, the quality control was still be conducted for both instruments. The homogeneity assessment was therefore only pursued for the primary barometer, and the air pressure measurements from the second barometer were considered further.

4.3.3. Breakpoint Detection, Homogeneity Adjustment, and Trend Analysis

The homogenization process of air pressure measurements poses different obstacles than with the temperature measurements. Air pressure is highly affected by altitude and by temperature; hence, more information is needed than just the barometer measurements to use an air pressure time series as a reference series. Indeed, the concept of air pressure is conceptually harder to

[241] Cf. Studer: Meteorologische Betrachtungen: BE01_Studer_1779-1786_006.

understand than temperature. Because one does not directly feel an air pressure difference, one is also less affected by changes. Furthermore, a main reason that many people have made meteorological observations has been to understand the weather and its impact on agriculture. Pressure is not directly relevant for plant growth and thus it has been less observed, and finding suitable reference series for the breakpoint detection is much harder. This phenomenon is not only due to the lack of reference series per se, but also due to the lack of metadata of the series. Only a pressure series that has been reduced to the mean sea level can be used. The data processing procedure has shown the amount of metadata needed for this reduction. However, the advantage of air pressure measurements is that, unlike temperature, it only varies little on the scale of up to a few hundred kilometers. Therefore, pressure series that are a bit further away from the candidate series could also have been considered as reference series.

A few air pressure series were selected again from the GHCN database, where the available series had already been reduced to the mean sea level. Unfortunately, only two suitable pressure series were available from the database. Unlike with temperature, the data from this database have not been adjusted or homogenized. Inhomogeneities caused by those reference series could be detected and should be kept in mind. From this network, the two stations of Basel/Binningen (also used as a temperature reference series) and Edinburgh were chosen, as they are the two closest series available in the GHCN database. Additional series were gathered from the CHIMES and IMPROVE projects. These pressure series were then also reduced to the mean sea level, which required additional data. Because the exact location of the stations was mostly unknown, they were approximated as best as possible. As for the temperature reference series, only air pressure series that covered the entire period of 1807 to 1818 were considered. In addition to the aforementioned stations, the following three were included as reference series: Zurich, Geneva (CHIMES), and Milano (IMPROVE).

Table 4.3: Pearson correlation coefficients for the reference series and the candidate (Studer) series.

Reference series	Pearson correlation coefficients
Basel/Binningen	0.93
Geneva	0.94
Zurich	0.16
Milan	0.79
Edinburgh	0.13

Pearson correlation coefficients were calculated as had been done with temperature. They were expected to be higher than for the temperature because the air pressure have been adjusted to the mean sea level and are generally less affected by orography. Pearson correlation coefficients of the stations are listed in *Table 4.3*. The reference series that yielded a correlation of less than 0.8 had to be excluded, namely Edinburgh—its distance proved to be too large—and the Zurich series with the observations by Feer. Of note, the Zurich series also had to be excluded for temperature, and thus the quality of this series may not be very good. After all, this series has not been homogenized, which makes it additionally unsuitable as a reference series. Therefore, only the stations in Basel/Binningen, Geneva, and Milano could be considered as reference series. Although there are only three reference series, they represent stations from the north, south, and west relative to the Studer series for the breakpoint detection. Moreover, the high correlations with especially the Basel and Geneva series indicate the quality of the Studer series.

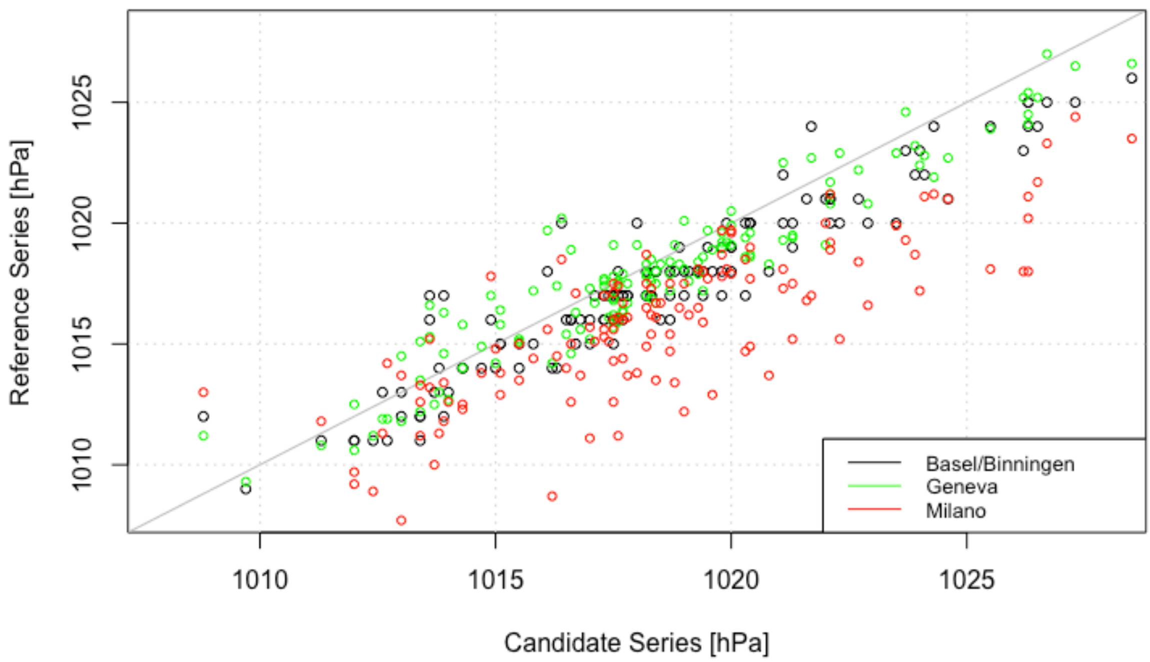

Figure 4.18: Scatterplot of the air pressure correlations between the reference series and the candidate (Studer) series.

All three reference series considered for the breakpoint detection according to their Pearson correlation coefficients to the candidate series are plotted again in *Figure 4.19* to check the correlations graphically. The Basel/Binningen as well as the Geneva series have a positive linear relationship to the candidate series. The scatterplot, however, shows that the Milano series should only be considered carefully. While the correlations are indeed positively and linearly aligned, there is a shift away from the line of perfect correlation. As breakpoint detection with only two reference series was considered to be too unreliable, the Milano series was still considered. Otherwise, it would have been impossible to disentangle what inhomogeneities would have been caused by the candidate series and what other breakpoints would have been caused by the reference series themselves.

In general, the breakpoint detection for pressure followed the same procedure as for temperature (Chapter 4.2.2). However, the annual cycle was not removed from the candidate or the reference series. A first impression of the cumulative differences revealed that this approach was not necessary for the three reference series that were considered for the Craddock test.

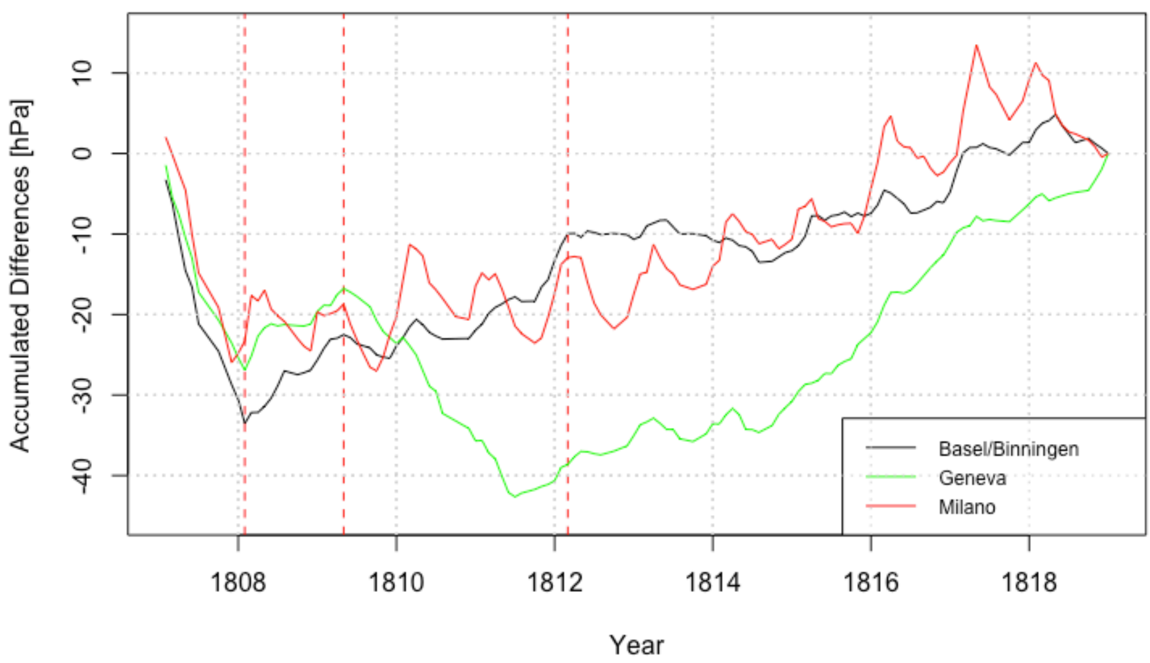

Figure 4.19: Accumulated differences in pressure between in the reference series and the candidate (Studer) series, calculated with the Craddock test.

The availability of only a few pressure reference series makes the disentanglement of the variations caused by only the climate versus variations caused by other circumstances very difficult. An even more important aspect is to consider the available metadata. However, the information on the instruments proved by Samuel Studer is even scarcer for the barometer. From Studer's notes it is known that the barometer had an issue on 23 January 1808: It had to be repaired after it was damaged by an air gust. This breakpoint was also detected in all reference series and is highlighted by a dashed red line in *Figure 4.19*. Unfortunately, those were the only clear notes on changes that had been made to the barometer. Another breakpoint in 1809 was supported by the Geneva and the Basel/Binningen reference series and was therefore also considered for correction. However, the two reference series signaled corrections in the opposite direction. Hence, it was essential to also include the Milan series, even though it is far from a perfect reference series due to its large climatological distance relative to the Studer series. The Milan series supported the upward trend of the accumulated differences in the years 1810 and 1811. The correction was therefore made according to the Basel/Binningen series.

So far, it is very noteworthy that the breakpoints seem to be almost identical to the breakpoints detected in the temperature series. It is thus possible that Studer readjusted or made other changes to the barometer whenever he had an issue with a thermometer. For this reason, a further breakpoint was considered in 1812. Because Studer always seemed to adjust something in the barometer when he replaced a thermometer, it seems plausible that the same happened in 1812, when there were issues with the thermometer no less than three times. For the period of 1812-1813, the accumulated differences of the Geneva series still deviated greatly from the accumulated differences of the other series, so the corrections were again based on the Basel/Binningen series.

The breakpoint detection is based on many assumptions, and unfortunately Studer provided very little metadata regarding thermometer and barometer adjustments. Indeed, there are only hints about the relocation or replacement of the instruments for the period considered in this thesis, and only one of his volumes contains information about adjustments. It is highly unlikely that the thermometers did not have to be replaced or relocated in the large period not considered for this study. For further research on the Studer series, it would be very difficult to include the entire series, as a homogenization will be even more difficult with no metadata at all on thermometer relocation, adjustment, or replacement. This is an important interim finding of the evaluation of the Studer series.

Table 4.4: Adjustments made to the pressure measurements of the Studer series based on breakpoint detection.

Period	Corrections [hPa]
1807	+3.5887
1808-1809	-0.0968
1810-1811	-0.3113
1812-1813	+0.0654
1814-1818	0

The applied corrections are listed in *Table 4.4*; they followed the periods of the temperature homogenization due to the identical breakpoints, as mentioned above. All corrections were eventually based on the Basel/Binningen series. For the first two differences, the corrections of Basel/Binningen and Geneva only deviated by a little. For the later periods, however, it was important to correct according to the Basel/Binningen series, as only the Milan series also supported those corrections. Overall, the largest correction had to be conducted in the first period, which can be explained by the metadata mentioned above. After the corrections had been applied, the Craddock test was repeated analogously to the temperature homogenization and proved the homogenization procedure had been rather successful.

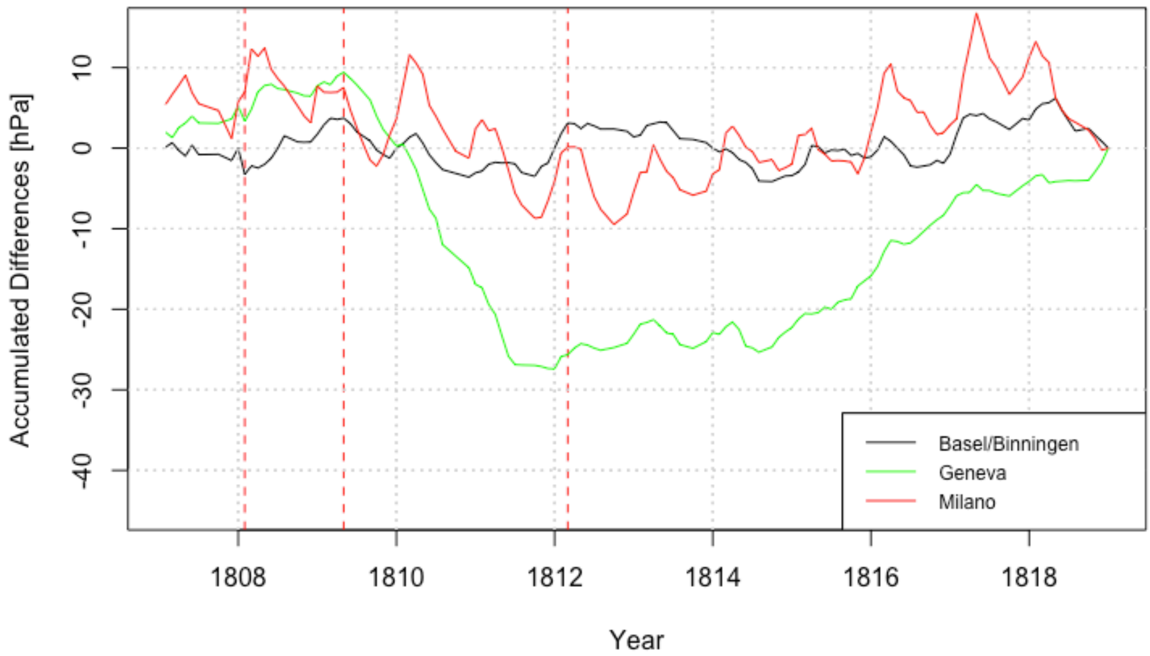

Figure 4.20: Accumulated differences in pressure between the reference series and candidate (Studer) series, after the data adjustment.

As for the temperature series, the Craddock test was repeated and showed especially promising results for the Basel/Binningen series. In addition, the accumulated differences with the Milan series seem to oscillate much closer to the 0 hPa line now and thereby support the conducted corrections. The Geneva series, however, still shows a large dip in 1809, which is probably caused by an inhomogeneity in the Geneva series itself. As this inhomogeneity was only visible in the Geneva series and not supported by the two other reference series, no further corrections were considered.

It needs to be mentioned again that the homogenization conducted in this study is far from perfect. Other and more reference series could have been chosen. Further, the corrections could have been made with shorter periods. However, for the purpose of this study, the applied homogenization procedure was considered to be sufficient and fulfilled the aim of the study. Nevertheless, as with the temperature series, the homogenization process could be perfected and expanded by, for example, taking the sub-daily measurements and a larger period into account. For the purpose of a sub-daily or already daily homogenization, however, more data and more metadata would be needed. In the case of the Studer series, this just seems not to be available.

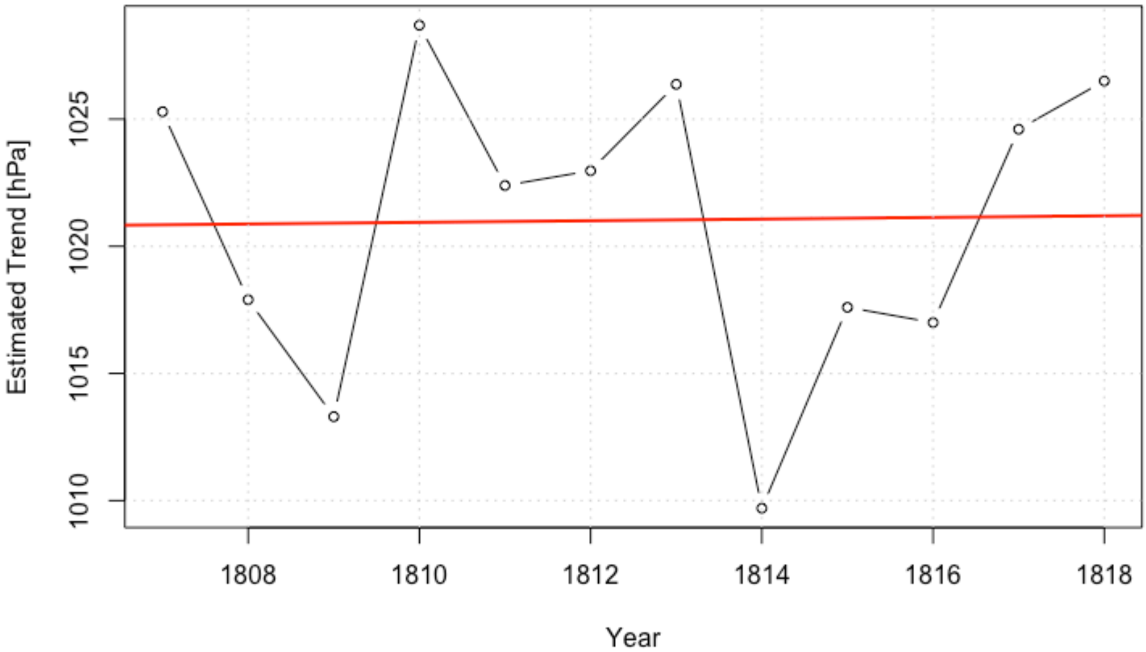

Figure 4.21: Trend detection for the pressure measurements based on linear regression. The red line represents the fitted values.

As for the temperature series, a trend analysis was conducted for the pressure series. The graphical check for a trend based on the line of the estimated yearly trend indicates no significant trend. The calculated p-value was 0.95; thus, H_0 could not be rejected and there is no significant trend. The result for the Mann-Kendall trend test produced the same conclusion. Consequently, the trend analysis for the pressure series will not be further elaborated as the procedure was thoroughly explained for the temperature measurements.

4.3.4. The Corrected Pressure Series

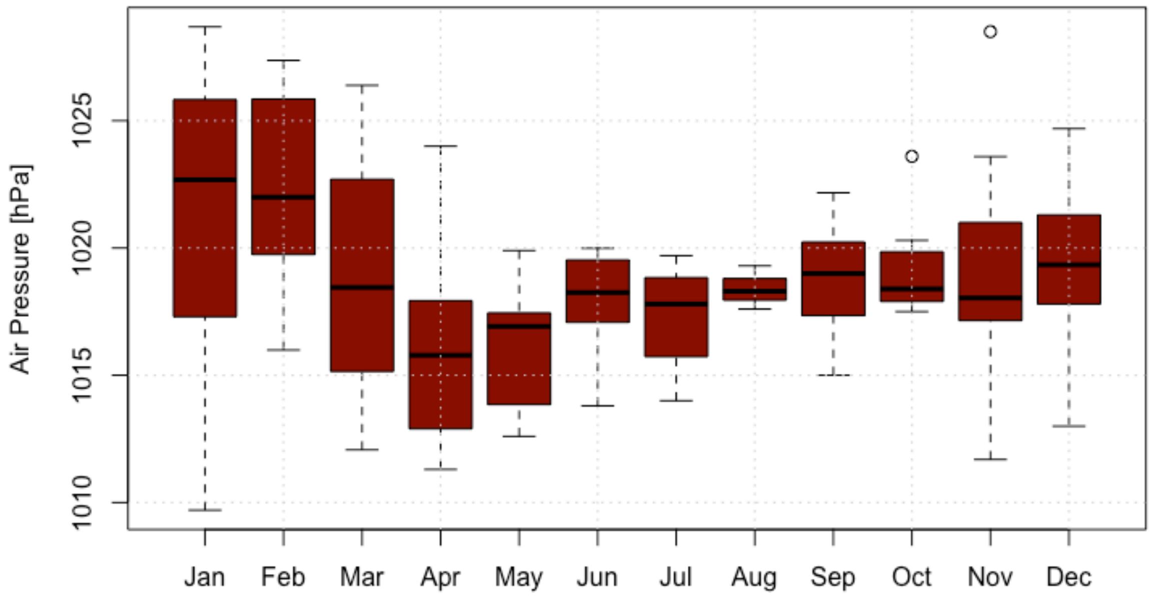

Figure 4.22: Boxplot of the monthly mean air pressure based on the homogenized Studer series.

The homogenization process has now been completed for the Studer pressure series. On the basis of the monthly boxplot, the series will now be reviewed, and outliers will be discussed. The pressure ranges are especially large at the beginning of the year and are much smaller during the summer months. The month of April showed the lowest pressure median, as can be expected. Overall, the annual cycle of the pressure measurements observed in the Studer data looks similar to what was recorded by MeteoSwiss for the period of 1961-1990, even though the absolute values are not comparable because the Studer values are still reduced to mean sea level.[242] The monthly mean values were again only calculated if the WMO criteria were met. The basis of the data for some of the months is even worse for pressure than it was for temperature. The August means could only be reported for the years 1809, 1815, and 1816. The information given by the boxplots must therefore be considered with great care. Luckily, the other months are missing for fewer years: Only one year is missing for the month of July, and only five years for October. There was an outlier detected for the latter month. The monthly mean of October 1809 was 1023.6 hPa. However, considering that the boxplot to be made up of only seven instead of twelve values, an outlier is not a surprise. When comparing the outlier

[242] Cf. MeteoSwiss 2021a.

to the boxplot of November and December, it is evident that for these months, the outlier would have been included in the whiskers. The value is therefore not worrisome. The November outlier can be assigned to November 1817 (1028.5 hPa). Comparison with the original source is much less straightforward with the pressure measurements than with the temperature measurements, mainly due to the very uncommon unit that was used at the time of data collection. The highest pressure values were measured from 17 the 20 November 1817. The weather conditions according to Studer's observations were mainly overcast but do not stand out at all when compared with the rest of the month.[243]

The homogeneity assessment of Studer's pressure measurements was performed for the first time in this study. There were many difficulties during this process. The breakpoint detection was especially problematic for several reasons. On the one hand, there are few suitable reference series that are comparable to the Studer series and have already been homogenized. The breakpoint detection further showed the problem of a lack of metadata in Studer's meteorological observations. With reference series that are more suitable—and thus have more available metadata—the homogeneity assessment could certainly be improved in future studies with the Studer series. Therefore, the corrected pressure measurements should be considered with caution. The aim of this study is, after all, to present the Studer data and to show both its shortcomings and its potential. The result of the process was a homogenized Studer pressure series, which can be used for further evaluation. Therefore, the aim was fulfilled.

4.4. The Precipitation Observations

Precipitation is an important climatic element for the human and terrestrial ecosystems. Unfortunately, early instrumental precipitation series are very rare. Precipitation varies much more spatially than temperature and air pressure; hence, a much greater density of stations is needed to capture and measure all precipitation events. Most stations measuring precipitation were only established in the twentieth century.[244] Gimmi et al. provided a reason for the lack of early instrumental precipitation series. Rain gauges were neither standardized nor manufactured in large quantities in the period of early instrumental measurements. Thus, local craftsmen had to design them on their own.[245] A further difficulty was the measuring schedule followed by the observers of early instrumental measurements. Precipitation events can often occur for just a short period of time. Thus, even very attentive observers can miss an event or

[243] Cf. Studer: Meteorologische Betrachtungen: BE01_Studer_1808-1819_125.
[244] Cf. Gimmi et al. 2007: 185.
[245] Cf. ibid.: 186.

not note it at the time of the usual measurements. Especially in the summer, short-lived rain showers occur and quickly evaporate. On the other hand, Lamb apparently orally pointed out that precipitation events in the winter can be overseen easily, due to the long duration of darkness.[246] In general, the observers could not take into account short events that had occurred at night and had evaporated by the morning.

Because quantitative measurements of precipitation in the early instrumental measurement periods were rare, it has to be inferred from systematic daily weather observations that often accompany early instrumental observations.[247] In this study, the qualitative observations, including precipitation records by Studer were used. As indications of precipitation events could only be found in the descriptive data, which had not been digitized as part of the CHIMES project, the descriptive data had to be evaluated thoroughly. Precipitation observations were then only categorized into "rain" or "no rain" using the binary codes 0 and 1, respectively. The sub-daily observations were summarized to achieve daily data. These were then accumulated into the months and compared with the Gimmi et al. data. The authors of that study had estimated the monthly precipitation totals of Bern by creating categories according to the expected precipitation total, based on several observations made in Bern during the period of 1760-1863. The Studer data were also included in this study. The evaluation of the Studer precipitation for this study here, however, was not conducted based on the Gimmi et al. estimations of precipitation totals but was compared to it. However, the number of days when precipitation occurred was not always in agreement with the Gimmi et al. data. Months that differed were checked again with the original source and corrected if needed. However, only a few mistakes were found and corrected. If Studer only mentioned rain drops, it was not considered to be a precipitation event, as precipitation is commonly considered to start at a threshold of 1 mm.[248] The data was further compared with the Euro-Climhist database, where the descriptive sub-daily data have been summarized to daily descriptions.[249] As the author of this dataset, Christian Pfister is indicated. However, nothing is known about the procedure that led to these entries. The database entries did not match the evaluation of the descriptive data conducted for this specific study or the Gimmi et al. precipitation data. Many precipitation events are missing in the Euro-Climhist database. It was only used to compare and to find possible transcription errors and was not included in further evaluation. All analyses based on

[246] Cf. Pfister 1988: 55.
[247] Cf. Gimmi et al. 2007: 186.
[248] Cf. MeteoSwiss 2021b.
[249] Cf. Euro-Climhist, retreived data: 01.01.1807-31.12.1818.

precipitation have been conducted specifically for this study and have been checked by comparing the monthly counts to the Gimmi et al. data and the daily data to the Euro-Climhist database.

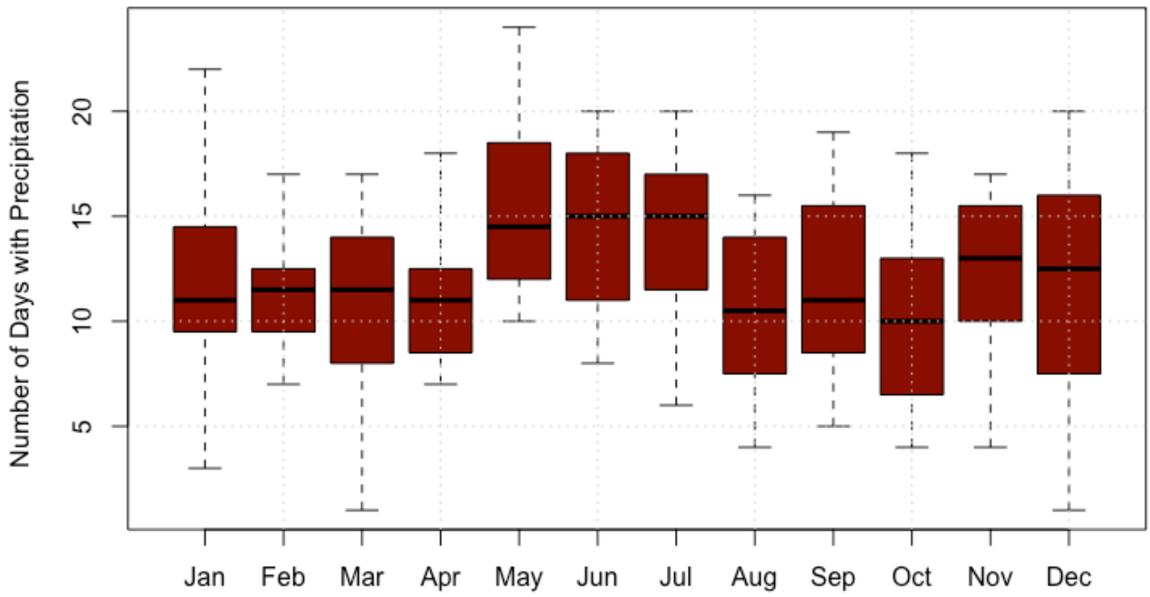

Figure 4.23: Boxplot of the mean number of precipitation events per month.

As with air temperature and pressure, it is also worth plotting the mean precipitation days as a boxplot to get a first impression. The seasonal cycle of precipitation is not as well defined as for the other two variables. The highest number of days with precipitation can be found from May to July. Most precipitation usually occurs in the summer in Switzerland, with a large gradient between April and May.[250] This can also be seen in *Figure 4.23*. The median precipitation days in April according to the Studer data was 11. By contrast, the median precipitation days in May was 14.5. June and July had the highest medians, with 15 precipitation days each.

As mentioned before, summer is when most precipitation occurs in Switzerland. Moreover, when not considering the amount of precipitation but the number of precipitation days, more precipitation days should be detected in the summer because short rain showers are very common for this season. It is surprising that the number of precipitation days seems to be much

[250] Cf. MeteoSwiss 2021b.

lower for August compared with May, June, and July. The problem with only considering the total number of precipitation days in a month is that NA entries are not considered. As elaborated previously in this study, Studer was often traveling in August, and he made fewer measurements for this month. Thus, the boxplot of the August precipitation days is expected to be much lower, as often only half of the days were even observed. This problem could be confirmed when comparing the Studer observations to data provided by MeteoSwiss. For the period of 1961-1990, there was an average of 10.9 precipitation days for the month of August.[251] In the Studer data, the mean was 10.5 precipitation days, just below the MeteoSwiss value. However, over all the years, Studer observed a mean of 12.1 precipitation days per month. Thus, the mean of the August observations would be expected to be higher than the mean of the MeteoSwiss data. Using the number of precipitation days per month, therefore, only works when considering Studer's absences or following the WMO guidelines and not calculating monthly means if eleven or more days are missing during a month and observations are missing for a period of five or more consecutive days during a month.[252] The same thresholds should be applied for count parameters. In addition, the number of days in a given month should be converted to a ratio or percentage.[253] For this purpose, the number of NA entries had to be reevaluated because they could differ for the observations compared to the measurements. The observations were thus only considered if all three measurement times included an observation. Further, the sub-daily observations were only considered if at least one temperature and air pressure value was noted. Otherwise, the observation made was also considered as an NA entry, as it is unclear whether this observation was made in Bern or where Studer had traveled. In the case of a substitute who measured and observed for Studer in times of his absence, it seems more likely that the measurements and the observations were conducted, and the substitute would not just have written down an observation.[254] Further, if only, for example, the afternoon measurements were missing but the observations had been made, it is likely for Studer to have noted the observation based on memory. As elaborated above, it is especially likely to miss a short precipitation event in the summer. Hence, these observation days were excluded entirely to get a picture as accurate as possible. In the end, the NA entries based on observations were gathered from the original source. The results can be found in the table in Annex A.1.

[251] Cf. ibid.
[252] Cf. WMO 2017: 7.
[253] Cf. ibid.: 8.
[254] Cf. Studer: Meteorologische Betrachtungen, October 1807: BE01_Studer_1808-1819_124.

The results of the observation evaluation again revealed the largest number of missing values in the summer months, especially in July and August. In the period of 1807-1818, five July and six August monthly mean values had to be excluded as they did not fulfill the WMO criteria.[255] For the calculation of the percentages of precipitation days per month, in addition to the missing values in each month, the leap years also had to be considered. Considering the number of days with precipitation expressed as a percentage seems to be a less straight forward method, however, the results are much more accurate and reliable. The average percentage of precipitation days based on all monthly mean values was 42%. The three summer months plus the commonly precipitation-rich May were above this average. July had the highest monthly average, with 53%.

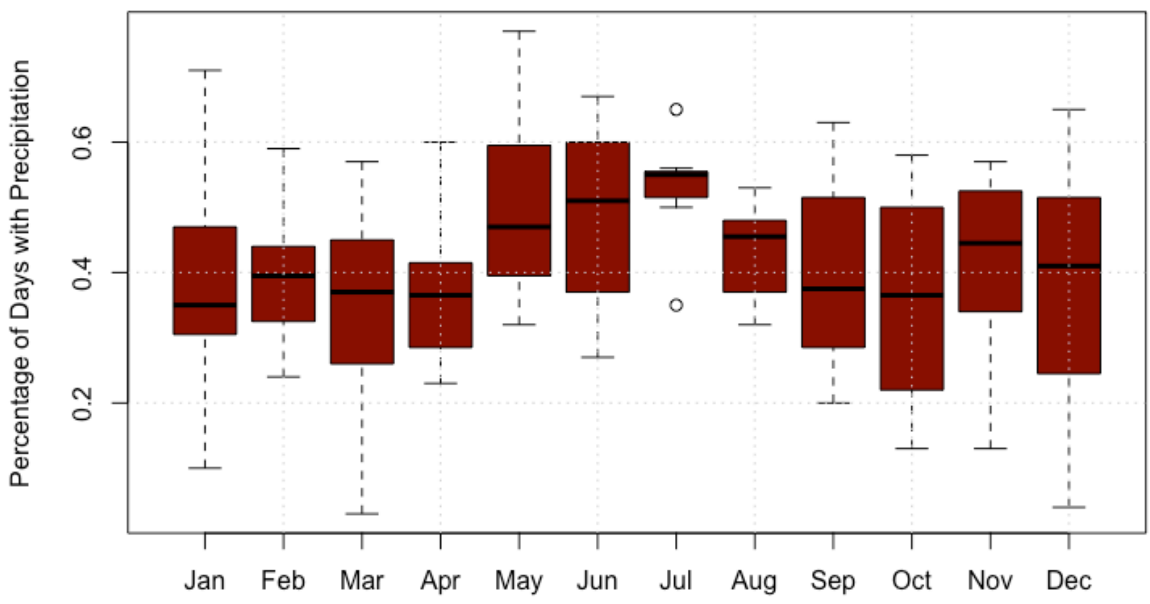

Figure 4.24: Boxplot of the percentage of days with a precipitation event per month.

The percentages can again be illustrated as boxplots (*Figure 4.24*). The size of the boxes of varies throughout the year. It needs to be pointed out again that the boxes of July and August are especially small due to the lack of data. The outliers that can be found in July are, therefore, not surprising. The lower outlier is due to a drier-than-average July in 1811. As a reference, the yearly average was 41% of precipitation days. The upper July outlier indicates 65% of precipitation days out of the observed days. Indeed, Studer observed the entire month, hence,

[255] Cf. WMO 2017: 8.

there were no missing values. Out of the 31 days, precipitation observations were made on 20 days. The largest ranges were observed in the months of January and December, each with a range of 0.61. The minimum of January were three precipitation days without any missing value in 1810, and thus 10% of precipitation days, and the maximum was 71% in 1814. In December 1818, precipitation was only observed on one day. As the last three days of observations were missing, this is equivalent to 4% of precipitation days in this month. The years after the Unknown Eruption and the Mount Tambora eruption will be analyzed in Chapter 5. The precipitation evaluation has so far given a first impression of the data itself and of the way the Studer observations had to be handled.

5. Case Study: Impacts of the Unknown Eruption and the Mount Tambora Eruption

This study so far has homogenized and investigated temperature, air pressure, and precipitation measurements and observations by Samuel Studer separately. Now, the information gathered about the data will be put to use to perform a case study. As mentioned in the introduction, the aim of this thesis was to finish what had been started in the preliminary study to determine whether the effects of two volcanic eruptions can be detected in Studer's data and how they can be compared. Hence, the research started in the preliminary study has been finalized and concluded.

The decade of 1810-1819 was the coldest decade of the past 500 years according to climate records.[256] The impact of the volcanic eruptions in 1808 (Unknown Eruption) and 1815 (Mount Tambora eruption) have been attributed as the primary causes for this cold phase.[257] However, as will be further elaborated in Chapter 5.1, the volcanic eruptions were not the only reason for this cold phase. At first, the climatic effects of volcanic forcing will be explained. Next, the effects of solar irradiance and the Dalton Minimum will be taken into account. Then, an introduction into the Unknown Eruption and the Mount Tambora eruption will be given. A brief summary will explain what is known about the eruptions and what implications on climate they had. In addition to the effects on temperature and air pressure in central Europe, the precipitation patterns will be discussed. In Chapter 5.2, the results of the hypothesis tests will be presented to answer the research questions concerning the volcanic eruptions.

5.1. Climatic and Historical Background

5.1.1. The Effects of Solar and Volcanic Forcing

The climate at the beginning of the 19th century was influenced by different external forcing. Solar forcing will only be mentioned briefly because it still had an important influence on the climate of the period. The period of 1807-1818 falls into a 60-year period of low solar activity named the Dalton Minimum; this cold period lasted from 1780 to 1840.[258] Anet et al. showed that the negative temperature anomaly could not only be explained by the two major eruptions that took place in this time. A part of the cooling had to be attributed to the Dalton Minimum.[259]

[256] Cf. Cole-Dai et al. 2009: 1; Guevara-Murua et al. 2014: 1707.
[257] Cf. Chenoweth 2001: 2963.
[258] Cf. Anet et al. 2014: 921.
[259] Cf. ibid.: 939.

Together with solar variability, volcanic forcing was one of the most important external factors in pre-industrial times to affect the global climate on interannual time scales.[260] The "Year Without a Summer" in 1816, following the Mount Tambora eruption on the Indonesian island of Sumbawa, is likely the best-known example of the climatic impact of volcanic eruptions.[261] The climatic impact is mostly caused by volcanic stratospheric aerosols.[262] A volcanic eruption ejects sulfur compounds in gaseous forms into the stratosphere, which then oxidize to sulfuric acid, forming aerosols.[263]

The resulting mechanisms increase back scattering of incoming solar radiation, leading to a cooling of the earth's surface.[264] The extent of the effect depends on location as well as seasonality. The global cooling effect is greatest at locations in the tropical areas, because the shortwave radiation balance is most negatively affected, and the residence time of the ejected aerosols is the longest.[265] The transport of stratospheric aerosols due to the Brewer-Dobson circulation is impacted by the seasonality of the eruption.[266] The largest effect occurs during the season when the incoming surface shortwave radiation is high, and it mainly affects the boreal summer.[267] Furthermore, solar and terrestrial infrared radiation is absorbed by the formed stratospheric aerosol layer, leading to a warming of this layer. This feedback is strongest for the tropical regions.[268] So, what determines whether a volcanic eruption leads to a warming or cooling and whether it has a strong or weak effect? First, the geometry and size of the produced aerosol matters. Cooling as a result of scattering of solar radiation depends on the quantity of aerosols, whereas the absorption of infrared radiation depends on the aerosol mass.[269] Aerosols with larger mass are more efficient in absorption, but they have shorter lifetimes.[270] Second, the eruption needs to be large enough for sufficient amounts of sulfur to reach the stratosphere to cause significant cooling in the troposphere and on the surface.[271] Once in the stratosphere, the aerosols are transported in the meridional direction.[272] Volcanic aerosols have the longest residence time if the eruption occurs in the tropics, as they are then transported

[260] Cf. Arfeuille et al. 2014: 359; Brönnimann 2015: 123.
[261] Cf. Cole-Dai et al. 2009: 1-3.
[262] Cf. Arfeuille et al. 2014: 359.
[263] Cf. Brönnimann 2015: 123.
[264] Cf. ibid.: 133.
[265] Cf. ibid.: 127-134.
[266] Cf. ibid.: 133-134.
[267] Cf. Arfeuille et al. 2014: 359; Brönnimann 2015: 127-128.
[268] Cf. Arfeuille et al. 2014: 359; Brönnimann 2015: 128.
[269] Cf. Brönnimann 2015: 133.
[270] Cf. Raible et al. 2016: 572.
[271] Cf. Cole-Dai et al. 2009: 1; Raible et al. 2016: 132-133.
[272] Cf. Brönnimann 2015: 133; Raible et al. 2016: 572.

by the stratospheric meridional circulation until they reach the troposphere again in the mid-to-high latitudes.[273]

The composition of polar ice cores has been analyzed to quantify volcanic forcing before 1833.[274] Stratospheric volcanic aerosols are washed out in the troposphere and end up in the polar ice cores. From the analysis of Greenland and Antarctica ice cores, the amount of sulfur injected into the stratosphere as well as the aerosol optical depth can be estimated.[275]

In contrast to boreal summers, tropical volcanic eruptions trigger a boreal winter warming due to increased pressure over the subtropical North Atlantic and the Mediterranean Sea, causing circulation anomalies.[276] Changes in the equator-to-pole temperature gradient in the lower stratosphere leads to a change in the stratospheric circulation, causing enhanced westerlies in the winter hemisphere.[277] This explanation is only a simplification of the complex processes, but as the focus of the case study is mainly on the summer period, it will not be explained in more detail. The effect on the summer precipitation in Europe, however, deserves further comment. Summer precipitation can increase over south-central Europe following a tropical eruption as a result of weakened Asian and West African monsoons.[278] This phenomenon leads to a weakened northern Hadley circulation over Africa and Europe. The Atlantic storm track experiences a southward shift due to convection as a result of a weakened descent in the subtropics.[279]

5.1.2. The Unknown Eruption

As mentioned above, the decade of 1810-1819 was extraordinarily cold. A cause for this climate extreme is the eruption of the Mount Tambora in 1815, which will be elaborated further in Chapter 5.1.3. However, the beginning of this cold decade, in particular the years 1810 and 1811, also presented below-average temperatures. This anomaly cannot be explained by an eruption that occurred in the middle of the decade.[280] Furthermore, high concentrations of sulfuric acid have been found in the polar ice cores in Greenland and Antarctica in the 1809-

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[273] Cf. Brönnimann 2015: 133.
[274] Cf. Arfeuille et al. 2014: 360; Brönnimann 2015: 134; Raible et al. 2016: 576.
[275] Cf. Brönnimann 2015: 134; has been done in e.g., Arfeuille et al., 2014.
[276] Cf. Brönnimann 2015: 129.
[277] Cf. ibid.
[278] Cf. ibid.: 131.
[279] Cf. ibid.: 132.
[280] Cf. Cole-Dai et al. 2009: 1; D'Arrigo, Wilson, Tudhope 2009: 52; Guevara-Murua et al. 2014: 1707.

1811 snow layers.[281] As both polar ice cores contained the signal of a volcanic eruption and the deposition had occurred essentially simultaneously at both poles, it was determined that a large, stratospheric eruption had to have occurred in the tropics, as only then could the volcanic aerosols have been distributed to both hemispheres.[282] Unfortunately, direct eye witness accounts are missing for a volcanic eruption from 1800 to 1814.[283] The eruption has thus been named either the AD 1809 eruption[284] or the Unknown Eruption.[285] Some research has been done to investigate whether two coincidental eruptions of similar magnitude led to the signal at both hemispheres. The Unknown Eruption was estimated to have been at least magnitude 6 on the Volcanic Explosivity Index (VEI).[286] The initial studies hypothesized that the Unknown Eruption was not a single eruption; instead, two volcanic eruptions in the high latitudes of both hemispheres produced the sulfate deposition in both the Greenland and the Antarctica ice cores.[287] More recent studies, however, have shown that it was a single eruption.[288] Guevara-Murua et al. took indirect eyewitness accounts of atmospheric effects into consideration. They excluded Latin America as a possible location because the two eyewitnesses were Latin American scientists based in Colombia and Peru.[289] The exact date of the eruption is also an open question. Chenoweth gave the earliest estimate for the eruption with the range from March to June 1808, based on negative anomalies in tropical air temperatures in 1809.[290] A few years later, February 1809 (± 4 months) was suggested based on the polar ice core records.[291] The indirect eyewitness accounts helped Guevara-Murua et al. to locate the eruption in the tropics and provided evidence that the eruption is unlikely to have occurred earlier than late November 1808. They were able to narrow down the eruption date to 4 December 1808 (± 7 days).[292] Based on this knowledge, this study will refer to this event as the Unknown Eruption and will assume the eruption took place on 4 December (± 7 days). Finally, the assumed magnitude of the eruption needs to be mentioned. The Unknown Eruption is assumed to be one of the most sulfur dioxide (SO_2)-rich stratospheric eruptions in the last 500 years. Its sulfate contribution is

[281] Cf. Cole-Dai et al. 2009: 1-2.
[282] Cf. ibid.: 1.
[283] Cf. ibid.: 1; Guevara-Murua et al. 2014: 1708.
[284] Cf. Dai, Mosley-Thompson, Thompson 1991.
[285] Cf. Mosley-Thompson, Mashiotta, Thompson 2003.
[286] Cf. Guevara-Murua et al. 2014: 1708.
[287] Cf. Yalcin et al. 2006.
[288] Cf. Cole-Dai et al. 2009; Guevara-Murua et al. 2014; D'Arrigo, Wilson, Tudhope 2009: 53.
[289] Cf. Guevara-Murua et al. 2014: 1709.
[290] Cf. Chenoweth 2001.
[291] Cf. Cole-Dai et al. 2009.
[292] Cf. Guevara-Murua et al. 2014: 1713-1714.

estimated to have yielded almost twice of what had been released by the Mount Pinatubo eruption in 1991, which was also categorized as VEI 6.[293]

5.1.3. The Mount Tambora Eruption

In contrast to the previously discussed Unknown Eruption, many facts are known about the Mount Tambora eruption. The event had global socioeconomic as well as climatic consequences.[294] A vast amount of research has been done on this eruption, but this sub-chapter will only summarize the main event as well as the major aspects of the magnitude of the effects the eruption had. This summary is far from complete and cannot include the extensive research that has been done on this topic.

Mount Tambora is situated on the Indonesian island of Sumbawa and had been considered extinct until 1812.[295] The reason for why so much is known about the Mount Tambora eruption is the availability of written records on the eruption. Java had been under British control since 1811, at which time Sir Stamford Raffles had been appointed Lieutenant Governor.[296] In his history of Java[297] and his memoirs,[298] he gave insights into the nature and implications of the eruptions.[299] The event started on Wednesday, 5 April 1815.[300] The people on Sumbawa were concerned about the volcanic activities and, eventually, the government authorities in Bima sent someone to investigate the site. Over the next two days, even stronger eruptions would follow. Unfortunately, the representative sent by the government was never able to report on the eruption, as he was one of the people killed by the devastating eruption.[301] Thousands of people were immediately killed and tens of thousands would die on Sumbawa and neighboring islands in the following months due to starvation and disease.[302] The eruption went down in history as one of the largest and deadliest.[303] Compared with the above-mentioned Unknown Eruption, it emitted twice the amount of sulfate and was categorized as VEI 7.[304] The mountain was assumed to have had a height of more than 4300 m,[305] but today it only measures as much

[293] Cf. Guevara-Murua et al. 2014: 1708.
[294] Cf. Oppenheimer 2003: 231.
[295] Cf. ibid.: 232-233.
[296] Cf. Stothers 1984: 1192.
[297] Cf. Raffles 1817; quoted from Oppenheimer 2003: 232.
[298] Cf. Raffles 1830; quoted from Oppenheimer 2003: 232.
[299] Cf. Oppenheimer 2003: 231.
[300] Cf. ibid.: 233.
[301] Cf. ibid.: 234.
[302] Cf. Raible et al. 2016: 570; Oppenheimer 2003: 249.
[303] Cf. Stothers 1984: 1192.
[304] Cf. Guevara-Murua et al. 2014: 1708.
[305] Cf. Stothers 1984.

as 2850 m.[306] The following year, 1816, has been known ever since as the Year Without a Summer.[307] Extreme weather was observed especially in northeastern North America as well as in Europe. Severe frost in the summer shortened the growing season as well as total crop failure leading to famine.[308] The socioeconomic impacts were devastating. In addition to the climate anomaly and the resulting socioeconomic impacts, Europe was just starting to recover from the Napoleonic wars, and thus the already bad situation was enhanced. John Post called it the "Last Great Subsistence Crisis in the Western World" and described it to have come at a very inopportune time, as Western societies had no chance to settle after the war years.[309]

The Mount Tambora eruption led to a cooling of approximately 0.5°C on the global scale.[310] In Switzerland, Geneva was most affected and experienced the largest negative temperature anomaly of the summer of 1816.[311] Auchmann et al. concluded that the Year Without a Summer was mainly an afternoon phenomenon, as the difference in the mean afternoon temperature was 3.8°C for 1817 relative to their chosen reference period.[312] In addition to examining temperatures, Auchmann et al. also included pressure, cloud cover, wind speed and direction, as well as daily precipitation measurements. In terms of frequency, there were three times as many low-pressure situations recorded in Geneva compared with their chosen reference series. High-pressure situations in the summer of 1816 were completely absent.[313] Wegmann et al. further studied the impact of the Mount Tambora eruption on precipitation. They concluded that the summer precipitation in Europe increased in the Year Without a Summer as a result of changes in the Hadley cell and a weakened African monsoon, as a result of decreased convection over the Sahel-Sudanese region.[314] In general, the global water cycle was slowed down as a result of the cooling and thus less convection occurred.[315]

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[306] Cf. Oppenheimer 2003: 241.
[307] Cf. Stommel, Stommel: 1979.
[308] Cf. Oppenheimer 2003: 244.
[309] Cf. Post 1977.
[310] Cf. ibid.: 325.
[311] Cf. ibid.: 326.
[312] Cf. ibid.: 328.
[313] Cf. ibid.: 331.
[314] Cf. Wegmann et al. 2014; Brönnimann 2015: 131-132.
[315] Cf. Wegmann et al. 2014: 3685.

5.2. Results

5.2.1. Temperature

The years following the eruptions would be expected to be colder than average as elaborated in Chapter 5.1. Thus, the two years following each of the eruptions are the focus of this case study.

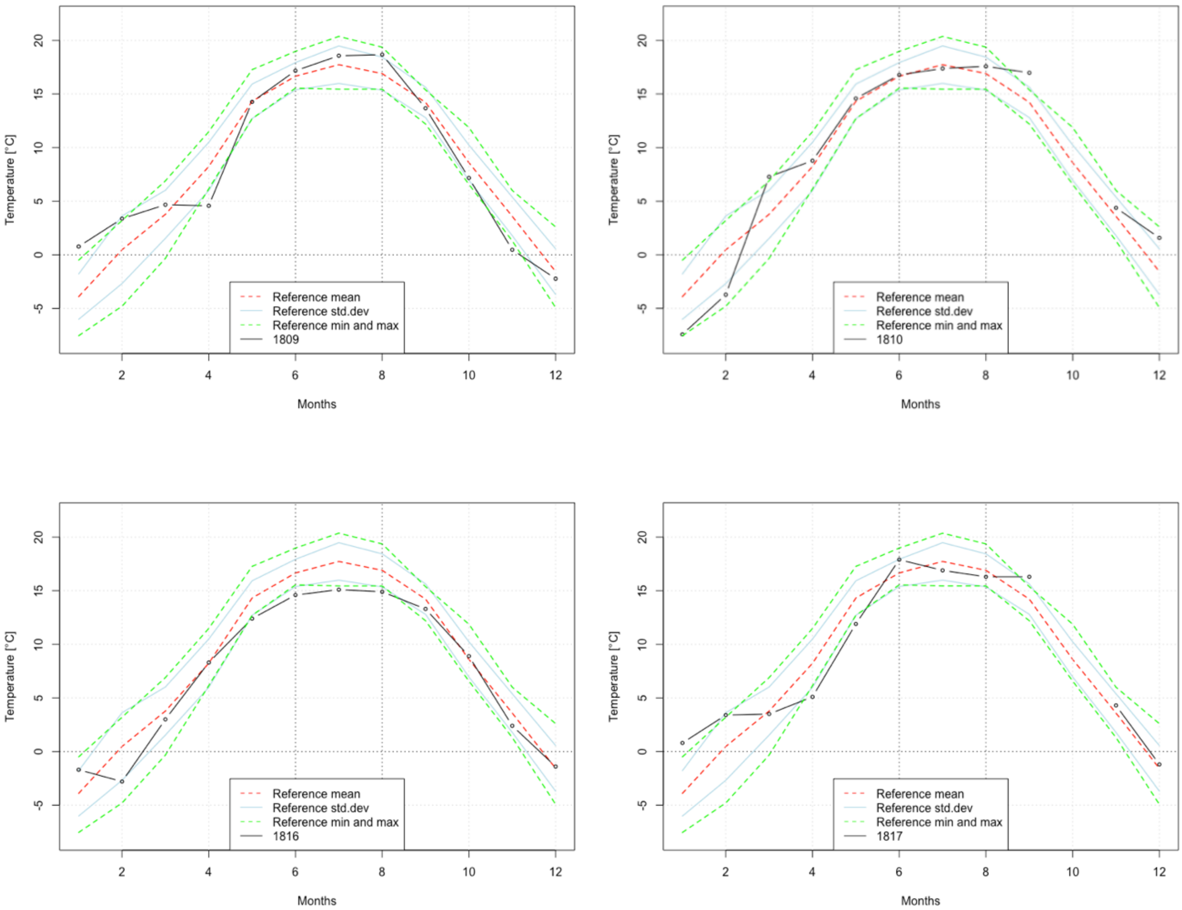

Figure 5.1: Time series of the monthly temperatures for 1809, 1810, 1816, and 1817 (solid black line). The light blue (solid) lines denote ± one standard deviation from the mean; the green (dashed) lines show the minima and maxima for the reference period (1807-1808, 1811-1815, and 1818). The red (dashed) line indicates the reference mean temperature. The horizontal grey (dashed) lines denotes the 0°C line. The vertical grey (dashed) lines highlight the summer period.

The period of Studer's observations and measurements evaluated, 1807-1818, are also the base period of this case study. The volcanically perturbed years following the eruption were removed from the base period of 1807-1818. The remaining years of the base period form the reference period (1807-1808, 1811-1815, and 1818) to which the perturbed years have been compared individually. When first looking at 1809 and 1810, the years following the Unknown Eruption, the monthly temperature means are around the mean of the reference period but also below and even above the plotted minima and maxima of the reference series. The plots in *Figure 5.1* generally show that the summer months did not seem to be colder than the reference period. The picture is different for 1816 and 1817, the years following the Mount Tambora eruption. It can also be considered as fortunate that in those four inspected years, all summer months were available. As noted in Chapter 4 this would not have been the case for many other years. Thus, it is possible to conclude whether the perturbations caused by the Unknown Eruption and the Mount Tambora eruption can be detected in the Studer series. For this purpose, the anomalies were calculated and analyzed.

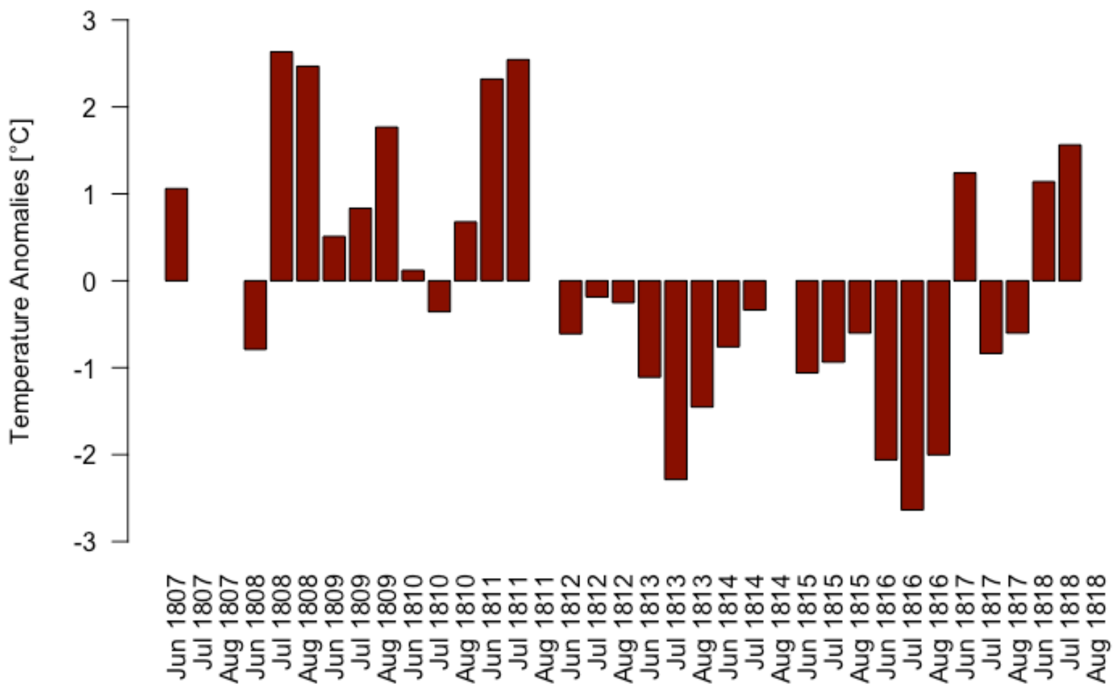

Figure 5.2: Barplot of the temperature anomalies of the summer months for the period of 1807-1818.

As shown in *Figure 5.2*, summer temperature anomalies seem to be mainly positive in the period of 1807-1811, and mainly negative afterward. The plot further shows the missing values. The reference period is already rather short with only eight years. From these years, three August means are missing. Thus, besides testing for the significance of the impact on the summer temperatures, the same will be done for half-year periods. This approach will also allow drawing a conclusion about the winter months, even though the focus will be set on the summer months, as indicated by the research questions.

The summer months were with a one-tailed Student's t-test using a 95% confidence interval. H_0 states that the summer months of the years following the eruptions were not colder than the reference period and the mean temperature anomalies were not lower. H_A states these years experienced colder summer months and the mean temperature anomalies were lower.

The p-values of the years 1809, 1810, 1817 were > 0.5; thus, H_0 could not be rejected for those years.[316] The p-value of 1816 was 0.000015 and H_0 could be rejected: The mean summer temperature anomalies of 1816 were significantly lower than the same months of the reference period. For the same test based on half-year measurements, the fall and winter months (September-February) were taken as one half of the year and the spring and summer months (March-August) as the other half of the year. The p-value for the period September 1809 to February 1810 was 0.01 and thus H_0 could be rejected: There were higher mean temperature anomalies for this period compared with the reference period. For the other years, H_0 could not be rejected. For the period spring and summer months, only the period from March to August 1816 proved to have significantly lower mean temperature anomalies than the reference period. Before drawing an overall conclusion, the same procedure was repeated for air pressure and precipitation.

5.2.2. Air Pressure

Auchmann et al. checked for the frequency of weather types in 1816 and found an absence of high-pressure situations in the Year Without a Summer (1816) and three times as many low-pressure situations.[317] Nevertheless, the Studer series was checked for low-pressure situations in the years after the eruptions. The method regarding the reference period is the same as for the temperature (Chapter 5.2.1).

[316] The detailed results of the case study can be found in the annex under A.2.
[317] Cf. Auchmann et al. 2012: 330-331.

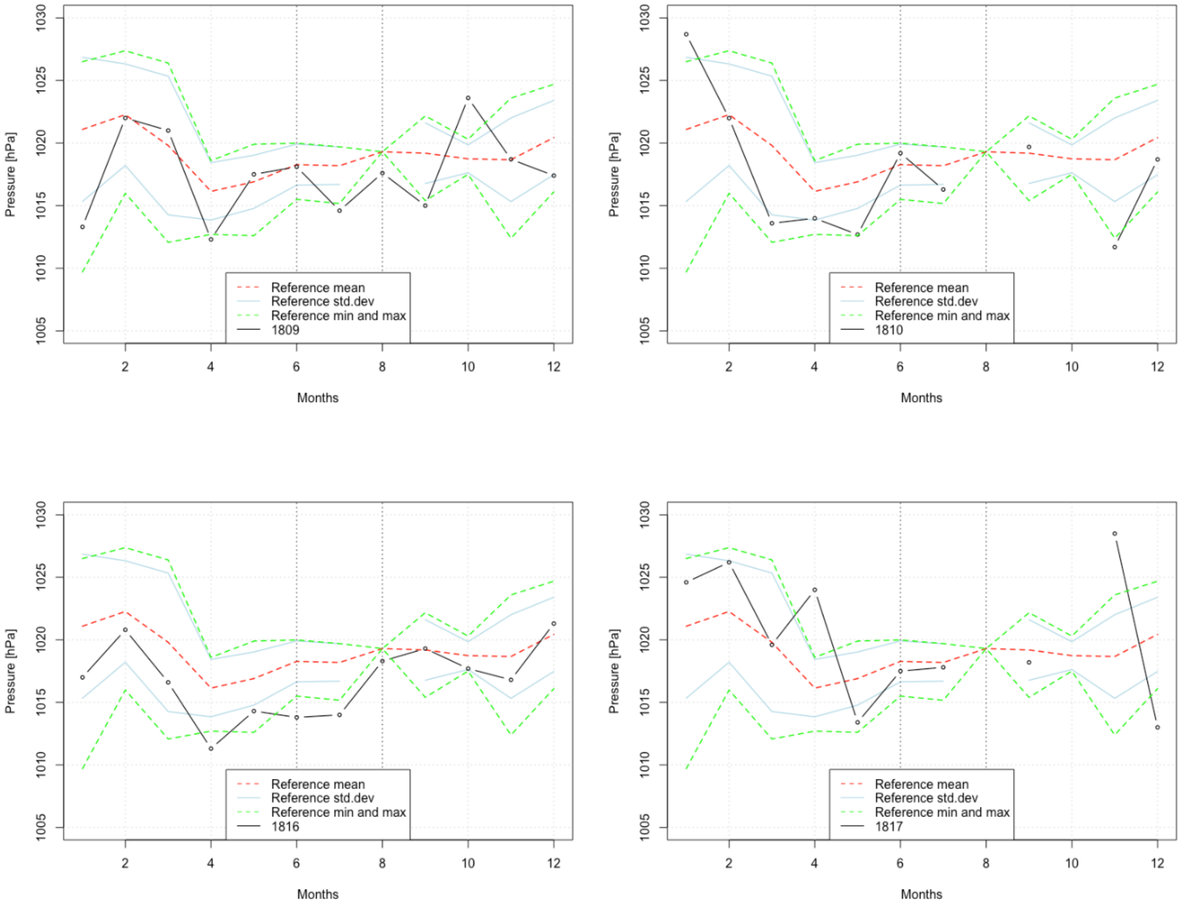

Figure 5.3: Time series of monthly pressure for 1809, 1810, 1816, and 1817 (solid black line). The light blue (solid) lines denote ± one standard deviation from the mean; the green (dashed) lines show the minima and maxima for the reference period (1807-1808, 1811-1815, and 1818). The red (dashed) line indicates the reference mean air pressure. The vertical grey (dashed) lines highlight the summer period.

The plotted monthly air pressure means of the perturbed years against the reference period are much more difficult to interpret (*Figure 5.3*). In 1809, eight monthly means were lower than the respective mean of the reference period. The period from July to September was even lower than the minima of the reference period. However, the month of August seems to be rather problematic in this case, as the minimum of the reference period is equivalent to its maximum. The problem is due to the large amount of missing August air pressure measurements. Only one mean of the month of August could be computed; thus, the reference mean for August solely depends on the year 1815. For 1810, the situation is even worse because there is no air pressure measurement for the August of this year either; 1817 has the same issue. The other summer months were not as problematic because there are fewer missing values. In the case of air pressure, it is even more worthwhile to conduct a Student's t-test for the summer months as well as half-year periods.

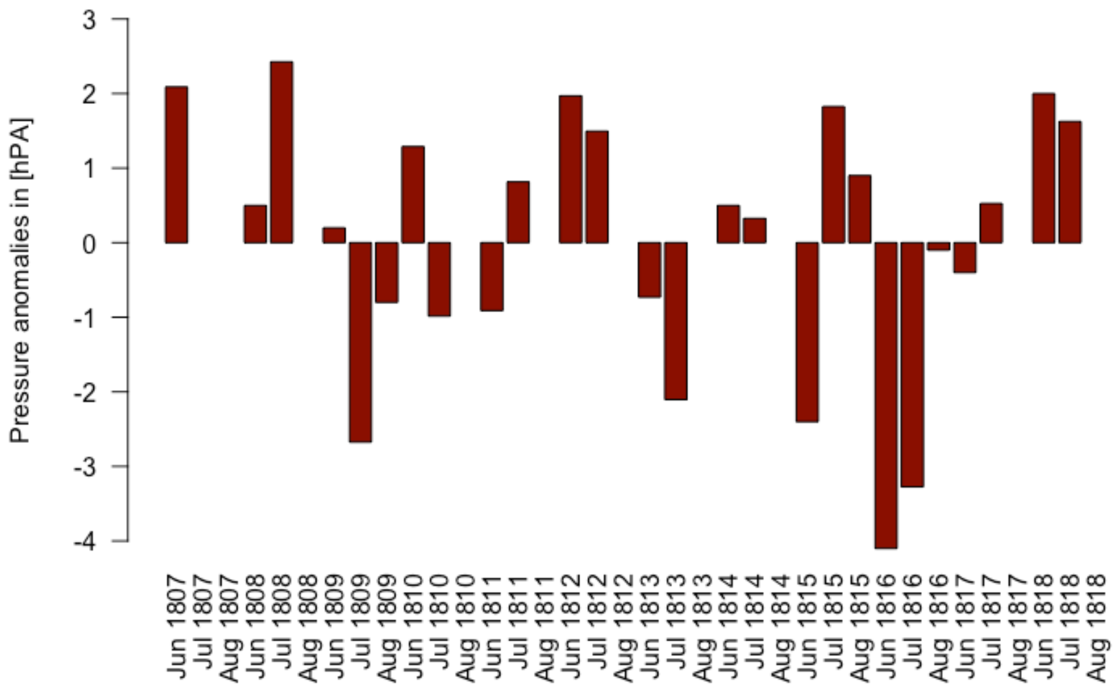

Figure 5.4: Barplot of the air pressure anomalies of the summer months for the period of 1807-1818.

The pressure anomalies of the summer months illustrated in *Figure 5.4* are not stringent. The very low pressure anomalies in June and July 1816 are outstanding; otherwise, there is no clear pattern. The abundance of missing monthly data is very evident again. The hypothesis testing was performed analogously to the procedure used in Chapter 5.2.1. H_0 is that the monthly pressure anomalies were greater than or equal to the respective reference period in 1809, 1810, 1816 and 1817. H_A states that the air pressure anomalies of the years following the eruptions were lower than in the reference period. The one-sided Student's t-test was again conducted with a 95% confidence interval. For the summer month anomalies, H_0 could not be rejected as the p-values were > 0.05. The Student's t-tests computed for the period of September to February also yielded p-values > 0.05 and thus H_0 could not be rejected. Only the period of March-August 1816 had significantly lower pressure anomalies than the reference period (p-value = 0.0026) and, therefore, H_0 could be rejected.

5.2.3. Precipitation

In Chapter 4.4, the percentage of precipitation days were computed by considering the missing days. Therefore, the same hypothesis testing procedure using in Chapters 5.2.1 and 5.2.2 was used to evaluate the percentage of precipitation days. The percentage of precipitation days is expected to be higher in the years perturbed by volcanic eruptions than in the reference period.

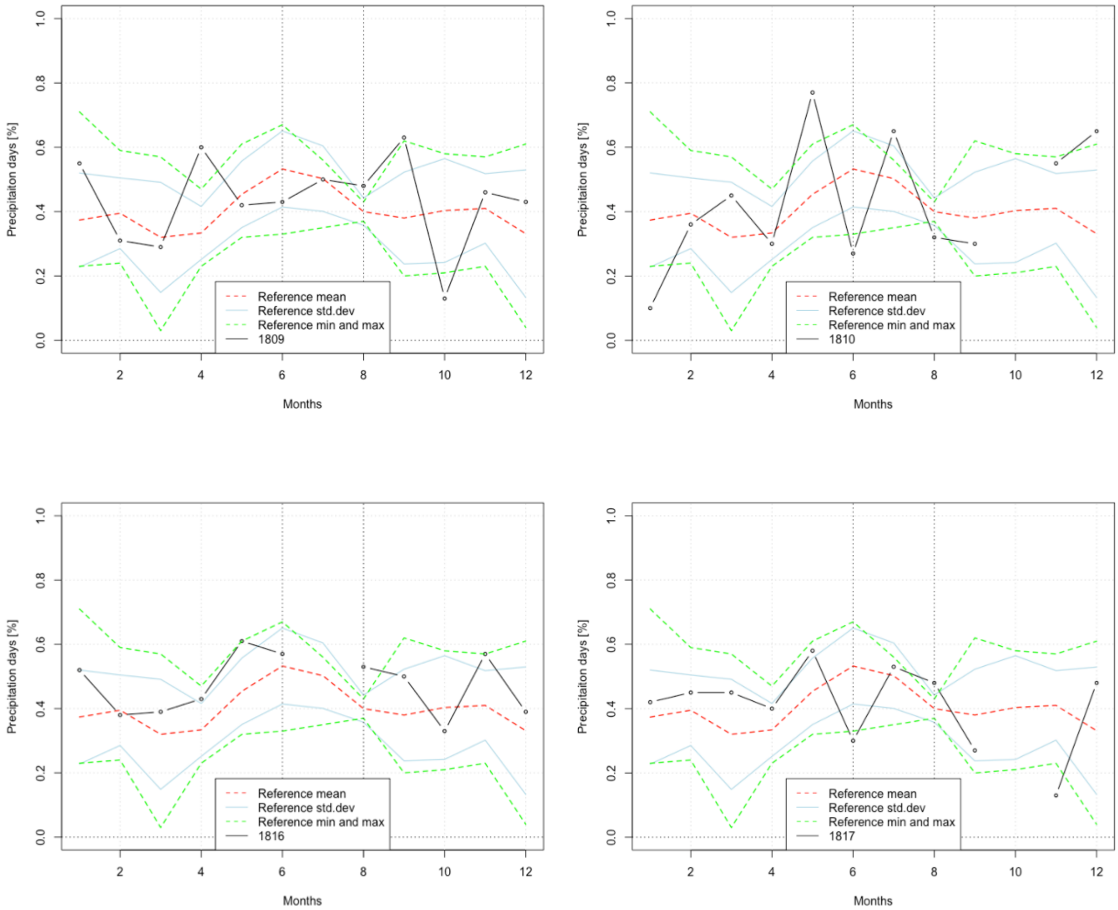

Figure 5.5: Time series of monthly percentage of precipitation days for the years 1809, 1810, 1816, and 1817 (solid black line). The light blue (solid) lines denote ± one standard deviation from the mean; the green (dashed) lines show the minima and maxima for the reference period (1807-1808, 1811-1815, and 1818). The red (dashed) line indicates the reference mean. The vertical grey (dashed) lines highlight the summer period.

The percentage of precipitation days in the reference series indicates that the summer months have the most precipitation days. The years perturbed by the volcanic eruptions suggest percentages of precipitation days below and above the reference mean, and thus it is difficult to assess the impacts in these years. Strikingly, however, the mean percentage of precipitation days for 1809, 1810, and 1817 were higher than the respective mean and the mean + one standard deviation. The means for 1809 and 1810 were even higher than the respective maxima of the reference period. From the evaluation of temperature and pressure, the volcanic perturbations were only seen in the 1816 data. Thus, it is unfortunate that the July percentage of precipitation days is missing for this year. The anomaly of this month would have been very interesting to compare to the other years. Nevertheless, the Student's t-test was first conducted for the summer months and then for the two half-year periods. H_0 is that the anomaly of the precipitation day percentages was lower for the two years following the Unknown Eruption and the Mount Tambora eruption. This hypothesis was expected to be disproven. H_A states that the anomalies were higher for the years following the volcanic eruptions compared with the reference period. The p-value for the summer months of 1816 was 0.007139; hence, H_0 could be rejected. The p-value for March-August of 1816 was 0.0004843, so H_0 could be rejected. All other hypothesis tests resulted in p-values > 0.05 and thus H_0 could not be rejected. The anomalies of the percentage of precipitation days for the summer of 1816 were, conclusively, significantly higher than during the reference period.

5.3. Case Study Conclusion

This case study concentrated on the years following two major volcanic eruptions, the Unknown Eruption and the Mount Tambora eruption. Both eruptions had impacts on the global climate; indeed, the year following the Tambora Eruption in 1816 has gone down in history as the Year Without a Summer. The cold and wet conditions during this time led to a socioeconomic crisis, which was also evident in Switzerland. Therefore, this case study evaluated the impact of those eruptions on the basis of the Studer data. This case study, therefore, has tied in directly with the preliminary study, where the aim was also to detect and to compare the impacts of those volcanic eruptions based on the Studer series.[318] The monthly mean values of 1809, 1810, 1816, and 1817 were compared with a defined reference period. Moreover, the data were tested for significant anomalies based on the summer season as well as half-year periods. There were significantly lower temperatures in 1816 for the summer as well as the half-year (March-August) period. The climatic impacts of the Unknown Eruption that led to lower temperatures could only be detected in the period from September 1809 to February 1810. Compared with the preliminary study, the variables were extended to air pressure as well as to precipitation. Air pressure was significantly lower in March-August 1816. The precipitation anomalies were computed based on the percentage of precipitation days. Higher percentages of precipitation days were expected, especially for the summer months

[318] Cf. Hari 2019.

following the volcanic eruptions. There was a significant difference for the summer of 1816, based on only the summer itself as well as the half year period from March to August.

To conclude the case study, the climatic impacts of the Mount Tambora eruption were detected in the Studer data in the summer based on the mean temperature, air pressure, and precipitation values only in the year following the eruption and not in 1817. For the Unknown Eruption, there were significant temperature anomalies for only September 1809 to February 1810. In general, the Mount Tambora eruption could be detected much more clearly than the Unknown Eruption in the Studer data. There were no significant results two years after either eruption (1810 and 1817, respectively). The same conclusion was made in the preliminary study, however, it was important to prove statistically the assumptions that had been made in the preceding study.

6. Conclusion and Outlook

The focus of this study was the meteorological observations by Samuel Studer. As an early instrumental measurement series spanning 48 years, the series contains valuable climatological data. In the first part of this study, the source was critically reviewed, and the author was introduced, especially the motivation behind the sub-daily measurements and observations that were investigated. Studer was one among many who had grown curious to explore physically and to explain their environment. Many societies were founded in midst of this Enlightenment utopia. These societies encouraged their members to collect data about their environment, including meteorological observations. Studer was a highly involved member of the Oekonomische Gesellschaft, which can be seen as a forerunner of the Swiss Natural Research Society, which later in the 19th century would establish the first nationwide network with standardized measuring instruments. Nevertheless, the Oekonomische Gesellschaft Bern had already suggested the use of consistent instruments and units. The founders of these societies were driven to learn more about nature to improve their knowledge about agriculture to avoid a food supply crisis. At the core of their motivation was the urge for more scientific knowledge. Meteorological observations were mainly important for this purpose: Forecasting the weather and knowing the nature of a season in advance has always preoccupied people involved with agriculture, as it directly influences their food and income situation. Studer himself was an enthusiastic nature devotee and had a great interest in exploring and describing nature. On his numerous trips to the Bernese Oberland and Valais, he and his brother would try to explain the topography and contribute to the standardization of the names of the mountains. He started recording meteorological measurements and observations in December 1779 but had to stop his work in 1827 due to bad eyesight.

The overarching aim of this study was to evaluate the meteorological observations by Studer for the period of 1807-1818. Its potential as well as limitations were highlighted by using a homogeneity assessment, mainly following the WMO guidelines. The first part of this analysis was a metadata analysis regarding information about the instruments. There were many sources of error identified concerning the location, position, and fixation of the instruments. In addition, Studer provided little information about the instruments. For the thermometers, the direction they faced is known. Comparison of the primary, east-facing thermometer and the secondary, west-facing thermometer resulted in the exclusion of the primary thermometer for this study. The barometers used by Studer were mercury barometers. The first was the actual barometer and the secondary barometer was only the control barometer. This study only used with the primary barometer. The barometers were placed in an unheated, poorly ventilated room. Fortunately, Studer also measured the temperature in this room. Even though little information on the measurements and observations could be found in the metadata analysis, it was still a very valuable step for the study. It highlighted on the one hand what one needs to be aware of when dealing with early instrumental measurement series, and on the other hand, showed how valuable even limited information (e.g., about instruments) could be.

The quality control of the temperature measurements revealed many errors that occurred in the digitization process. Therefore, a thorough check of the digitization was necessary to correct erroneous data and to eliminate missing values that were indeed neither missing nor biased. The quality control for the pressure measurements resulted in fewer erroneous values. The digitization had, however, already been corrected beforehand. Several reference series were used for the breakpoint detection of both the temperature and the air pressure measurements. There was a rather limited choice of reference series. The breakpoint detection of the air pressure measurements could only be performed with three references series, as Pearson correlation coefficients < 0.6 were not accepted. Another difficulty was again the lack of available metadata on the series. Even though Studer noted some replacements of instruments, he did not clearly indicate, for example, which thermometer was replaced. In addition, breakpoints were found that could not be explained by the metadata. It is important to point out that the metadata on the instruments was only available for the period evaluated in this thesis (1807-1818). A revision of the entire meteorological observations starting in 1779 yielded no additional metadata for the unevaluated period. Thus, a homogeneity assessment for all meteorological observations by Samuel Studer would be extremely difficult, especially given that it is known that he lived and thus measured and observed in Büren an der Aare for seven years. Nothing is known about where the instruments were located or how they were positioned at that time.

A further step forward from the preliminary study was to include the precipitation observation. The sub-daily descriptive notes were transformed into daily, binary (0 or 1), quantitative information. The size of the precipitation event was not considered. Under some restrictions, the number of days with precipitation per month was gathered and compared with the study conducted by Gimmi et al. and the Studer data that had already been implemented into the Euro-Climhist database. The evaluation of the number of precipitation days per month, however, was not very convincing, because the results were extremely biased by missing values. Therefore, the absolute values were transformed into relative values. The number of precipitation days was expressed as the percentage of precipitation days per month.

Following the homogeneity assessment of temperature and air pressure, as well as the evaluation and refurbishment of the precipitation data, the case study was conducted. As in the preliminary study, the Unknown Eruption and the Mount Tambora eruption were the focus of this case study. The research question was whether the climatic consequences of these two volcanic eruptions could be detected in the Studer data. For this purpose, hypothesis testing was applied to check for the significance of the results. The investigated period of 1807-1818 was divided into a reference period and into the investigated years. Specifically, the two years following each eruption—1808-1809 and 1815-1816—were considered as the years perturbed by the volcanic eruptions and were tested against the reference period, which therefore entailed the following years: 1807-1808, 1811-1815, and 1818. The case study was conducted to determine whether the temperature and air pressure anomalies were significantly lower and the precipitation anomalies significantly higher in the two years following the eruptions. Additionally, the question was posed, whether these hypotheses were also true when investigating the periods March-August and September-February in the two years following the eruptions. The case study results revealed that indeed the climatic consequences of the Mount Tambora eruption could be detected in the summer months of the Studer data in the year following the eruption. Specifically, the temperature and air pressure means were significantly lower in 1816 compared with the reference period. The same result was found for the temperature and air pressure measurements for the period of March-August 1816. The precipitation anomalies were expected to be higher in the perturbed years. There were significant results for the summer and March-August of 1816. Thus, the climatic consequences of the volcanic eruptions were determined in the Studer data. The climatological consequences of the Unknown Eruption could be detected as significantly lower temperature in the period from September 1809 to February 1810. The summer after the Unknown Eruption was not significantly colder than the reference series. In addition, there were no significant results for either variable for the second year following each eruption.

A major limitation of this study is the missing values. Studer was often traveling in the summer months, and especially for the month of August, many measurements and observations are missing. The study was mainly based on monthly values that were only calculated if the criteria set by the WMO were met. Throughout the study, the missing values had to be noted, and the

August data needs to be considered with great care. Moreover, for the case study, the missing values, especially in the summer months, are a shortcoming, particularly for the missing percentage of precipitation days for August 1816. If further studies are conducted based on the Studer series, the best option would be to interpolate the missing values. Otherwise, the data density of the summer months just seems to be critically low. The same issue usually occurred for the month of October. The limitation is especially grave for the case study, as the investigated years were not complete. Regarding the homogeneity assessment, the breakpoint detection was not performed ideally due to the lack of suitable reference series. For future studies, it would be worth constructing a reference series with more suitable, already homogenized series if the data is available. In addition, the lack of extensive metadata makes a further extension of the study period extremely difficult. The metadata available for the period investigated in this study must therefore be highly appreciated.

The Studer series has been critically reviewed in this study. Early instrumental measurement series contain valuable information for further climate research. Even though the Studer series has limitations, it still has great potential. If the mentioned limitations can be handled, the series is especially valuable due to its time span and resolution. A 48-year long time series with three sub-daily measurements and observations, covering a vast number of variables, is rare. A lot of information can be found in the Studer series. It is also of great value because Studer himself worked, measured, and observed with great care. His endurance and preciseness over such a long period must be appreciated. Through its length and resolution, the study is also very suitable as a comparison series and could in the future be embedded into the evaluation of other similar series. The Studer series could be used together with other series from Bern, to receive an even longer time period, extending over up to several centuries. For this purpose, a thorough evaluation of the entire Studer series would be worthwhile, even though it will certainly pose many challenges.

7. Registers

7.1. List of Abbreviations

CHIMES	Swiss Early Instrumental Measurements for Studying Decadal Climate Variability
GHCN	Global Historical Climatology Network
IMPROVE	Improved understanding of past climatic variability from early daily European instrumental sources.
HISTALP	Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region
JJA	June, July, August
NA	Not announced
PD	Precipitation days
VEI	Volcanic Explosivity Index
WMO	World Meteorological Organization

7.2. List of Figures

All figures are own representations, which were created specifically for this work.

7.3. List of Tables

7.4. List of Images

8. Bibliography

8.1. Sources

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A. Annex

A.1. Precipitation Days and Resulting Percentages[319]

	JAN			FEB			MAR			APR			MAY			JUN		
	NA	PD	%	NA	PD	%	NA	PD	%	NA	PD	%	NA	PD	%	NA	PD	%
1807	0	11	35	0	17	59	0	8	26	0	14	47	5	11	42	1	12	41
1808	0	13	42	0	13	46	0	8	26	0	9	30	1	12	40	1	16	55
1809	0	17	55	0	9	31	0	9	29	0	18	60	0	13	42	0	13	43
1810	0	3	10	1	10	36	0	14	45	0	9	30	0	24	77	0	8	27
1811	1	7	23	0	12	41	0	1	3	0	12	40	0	12	39	0	14	47
1812	0	11	35	0	12	43	0	14	45	0	10	33	0	18	58	0	18	60
1813	0	10	32	0	10	34	0	11	35	0	12	40	0	19	61	0	19	63
1814	0	22	71	0	8	28	0	6	19	0	8	27	0	10	32	0	20	67
1815	0	10	32	0	7	24	0	14	45	0	8	27	0	12	39	0	18	60
1816	0	16	52	0	11	38	0	12	39	0	13	43	0	19	61	0	17	57
1817	0	13	42	0	13	45	0	14	45	0	12	40	0	18	58	0	9	30
1818	0	9	29	0	12	41	1	17	57	0	7	23	0	16	52	0	10	33

[319] NA= not announced, PD=days with precipitation

	JUL			AUG			SEP			OCT			NOV			DEC		
	NA	PD	%	NA	PD	%	NA	PD	%	NA	PD	%	NA	PD	%	NA	PD	%
1807	7	7	NA	10	5	NA	0	16	53	15	5	NA	0	17	57	0	6	19
1808	6	14	NA	8	11	NA	1	18	62	0	18	58	0	13	43	0	17	55
1809	1	15	50	0	15	48	0	19	63	0	4	13	2	13	46	1	13	43
1810	0	20	65	0	10	32	0	9	30	9	7	NA	1	16	55	0	20	65
1811	0	11	35	8	7	NA	0	9	30	1	12	40	0	12	40	0	11	35
1812	0	17	55	4	10	37	0	11	37	8	13	NA	1	9	31	1	9	30
1813	4	15	56	5	8	NA	1	12	41	5	15	58	0	15	50	0	5	16
1814	9	12	NA	7	11	NA	5	5	20	2	6	21	0	14	47	0	19	61
1815	0	17	55	1	13	43	0	7	23	0	13	42	0	11	37	0	14	45
1816	5	19	NA	1	16	53	0	15	50	1	10	33	0	17	57	0	12	39
1817	1	16	53	0	15	48	0	8	27	7	10	NA	0	4	13	0	15	48
1818	7	6	NA	12	4	NA	1	11	38	1	7	23	0	7	23	3	1	4

A.2. Case Study P-Values[320]

Temperature

Months	Period	P-Value
JJA	1809	0.9304
JJA	1810	0.482
JJA	1816	1.05e-05
JJA	1817	0.3858
September-February	1809/1810	0.0106
September-February	1810/1811	0.8902
September-February	1816/1817	0.8472
September-February	1817/1818	0.993
March-August	1809	0.5824
March-August	1810	0.9079
March-August	1816	0.0081
March-August	1817	0.1276

Pressure

Months	Period	P-Value
JJA	1809	0.0805
JJA	1810	0.3707
JJA	1816	0.0564
JJA	1817	0.2044
September-February	1809/1810	0.6601
September-February	1810/1811	0.1184
September-February	1816/1817	0.7684
September-February	1817/1818	0.6196
March-August	1809	0.2486
March-August	1810	0.0629
March-August	1816	0.0026
March-August	1817	0.7001

[320] JJA=June, July, August

Precipitation

Months	Period	P-Value
JJA	1809	0.6106
JJA	1810	0.7163
JJA	1816	0.0071
JJA	1817	0.7014
September-February	1809/1810	0.6435
September-February	1810/1811	0.3193
September-February	1816/1817	0.0509
September-February	1817/1818	0.8293
March-August	1809	0.3963
March-August	1810	0.3964
March-August	1816	0.0005
March-August	1817	0.3593

Declaration of consent

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