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Instruments, Procedures, Processing, and Analyses

Yuri Brugnara,* Julian Flückiger, and Stefan Brönnimann

Oeschger Centre for Climate Change Research and Institute of Geography, University of Bern, Switzerland

Abstract

Each paper in this volume provides the metadata for an early instrumental meteorological series from Switzerland. However, there are many commonalities. For instance, similar instruments were used at different stations, and practices and reporting were similar. Furthermore, the processing and analysis of the data was performed in the same way across all papers. Here we summarise information on early meteorological instruments and procedures and describe the common processing, quality control, and analysis. The paper also describes potential quality issues of the different instruments. It ends with a brief description of the format, which is recommended for station data in general as it allows the application of readily available Quality Control Software and the incorporation into the Copernicus Climate Change Service (C3S) Repository.

1. Introduction

Using early instrumental meteorological data for climate science requires understanding how and why measurements were made, what instruments were used and what potential sources of errors are. While the papers in this volume compile all relevant information for each series, some general aspects on early instrumental measurements are summarised in this paper.

The standardisation of meteorological networks was one of the big achievements of the emerging national weather services in mid 19th century. Early instrumental measurements, which precede these more systematic measurements, suffer from a lack of standard proce-

* Corresponding author: Yuri Brugnara, University of Bern, Institute of Geography, Hallerstr. 12, CH-3012 Bern, Switzerland. E-mail: yuri.brugnara@giub.unibe.ch.

dures and protocols. Although scientific networks such as the Royal Society (or in Switzerland the "Naturforschende Gesellschaft") also suggested procedures, there was no common standard across time and even across a small territory such as Switzerland. In Section 2 of this paper we describe the measurement principles, instruments and their errors. This Section is partly based on two Master theses (Breda, 2010; Flückiger, 2018). In order to make the data comparable to present-day data, numerous processing steps are required. Units need to be converted and pressure needs to be reduced. This is described in Section 3. Then the data undergo Quality Control (QC) procedures and a set of standard analyses are performed. This sequence, presented in Section 4, was undertaken for all of the series mentioned in this book. To avoid duplication, we explain the methods here in more detail and only give a brief summary in the individual papers. Further descriptions are also found in Brugnara et al. (2019).

2. Instruments

2.1. Thermometers

2.1.1. Historical overview

In the 18th and 19th century, liquid-in-glass thermometers were mostly used. They required a thermometric substance that expanded with temperature in a linear manner as well as a stable glass. By the end of the 18th century, there was a strong consensus to use the freezing and boiling points of water to fix a calibration scale, though both remained under discussion with regard to the exact methods of calibration. In addition to several Réaumur scales, the scale of Micheli du Crest was also in use in Switzerland (*e.g.,* in Basel, Bern, and Zurich), which used the temperature in a cellar in Paris as zero point.

The thermometric substances also remained under discussion (for the following see Chang, 2004). Mercury and ethyl alcohol were the two main contenders. By mixing different shares of melting ice and boiling water, the Genevan Jean-André Deluc in 1772 was able to show that mercury expanded more linearly than any other liquid he had tested, including alcohol. Furthermore, the expansion of an alcohol-water emulsion depends on alcohol concentration, which was hard to measure precisely. Deluc's conviction that mercury was the best thermometric substance had gained wide acceptance around 1800. According to Middleton (1966) mercury and alcohol remained the standard thermometric substances in meteorology until well into the 20th century. Mercury was preferred due to Deluc's experiments, but Micheli du Crest, for instance, recommended alcohol as mercury, in his view, was more difficult to purify (Gisler, 1984).

Apart from the thermometric substance, which often remains unknown for a given measurement, location and exposure of the thermometer are further sources of errors. In the early 18th century thermometers were sometimes exposed to direct sunlight, or kept inside a building. From the 1760s onwards, the two prevailing schools were either to locate the instrument at some distance to any building or to fix the thermometer at a north-facing wall of a house (Middleton, 1966). However, not only direct sunlight affects the measurements, but also long-wave radiation from the surroundings, as was shown in 1817 by Jean Baptiste Joseph Fourier. During the first decades of the 19th century awareness increased that thermometers need to be

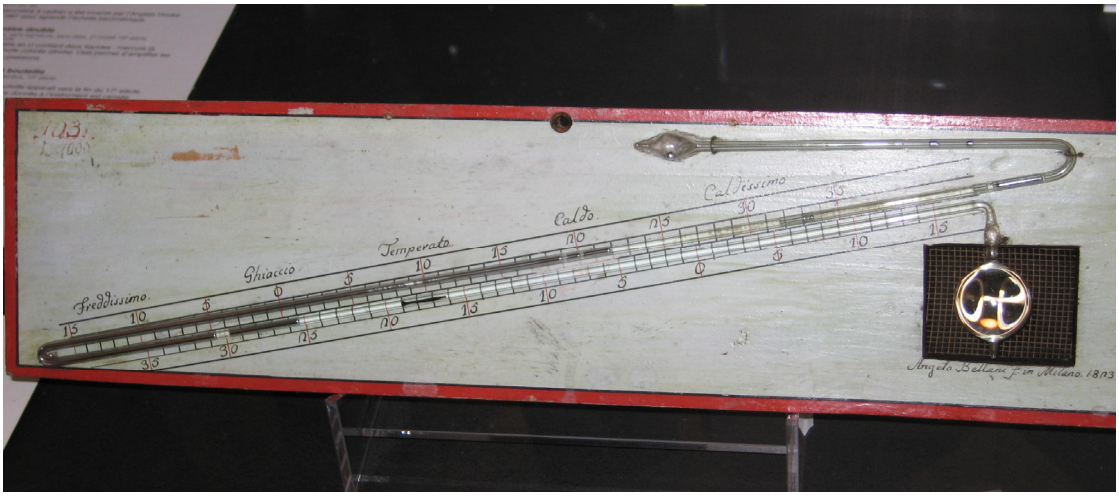

Figure 1. A maximum and minimum thermometer by Angelo Bellani, Milano, 1803 (Natural History Museum, Geneva, photo Renate Auchmann).

sheltered from radiation. The first protective constructions from the 1830s and 1840s mainly served to protect thermometers from direct sunlight and precipitation (Middleton, 1966). Wild (1860) listed further sources of inaccuracy such as the heat conductivity of the supporting structure, the circulation of the air around the thermometer and the construction of the thermometer itself.

Maximum and minimum thermometers were invented in the late 18th century by Six and Rutherford. An early combined maximum and minimum thermometer is shown in Figure 1.

2.1.2. Temperature: Current standards and errors sources of historical instruments

According to the World Meteorological Organisation (WMO), temperature should be measured 1.2 to 2 meters above the ground (WMO, 2008). The site should be exposed to sunshine and wind, not shielded by trees or buildings. The thermometer must be protected from radiation by a shield or a screen. The latter must also protect from precipitation while enabling a ventilation of the thermometer; otherwise the radiation from the heated shield walls may cause errors. The shield walls must be white and made of a high reflective and low heat absorptive material.

Historical temperature measurements with liquid-in-glass thermometers can be affected by a number of errors such as elastic errors of the glass, changes in the volume of the bulb, parallax or reading errors, capillarity, calibration errors caused by the emergent stem, unequal expansion of glass and scale, and errors in scale division and calibration.

Some errors depend on the observer. He or she must read the thermometer as quickly and precisely as possible to avoid parallax errors. Some errors depend on the instrument manufacturing. Capillarity errors can be avoided if the stem is large enough. The glass expansion with temperature is a non-linear effect, but it can be taken into account in the calibration.

The first two errors are due to glass stability. Some glasses contract during the first years. The consequent rising of the zero point is a known problem of old thermometers, first pointed out by Bellani (1808). The cause, namely the composition of the glass, was only found much later (Weber, 1888; Wiebe, 1891). Early thermometers used glass composed of a mixture of potassium and sodium oxides that tends to contract over several years. From this time until today thermometer glass is composed of either potassium oxide or sodium oxide and thus free of elastic effects. Old measurements, however, need to be corrected. Homogenising the long-term temperature series of Hohenpeissenberg, 1781–2006, Winkler (2009) suggested a procedure. He found the error to be 0.5 °R, corresponding to 0.63 °C and corrected temperature measurements by a ramp function that increased stepwise by 0.1 °C/year for the first 6 years following the manufacture of the thermometer and then remained constant (Winkler, 2009). The length of the ramp as well as the rate of change agree well with earlier findings (Despretz, 1837; Person, 1845; Recknagel, 1864). This correction was also applied to some of the series in this book. Note, however, that this comes with large uncertainties. For instance, Hankel (1860) notes that the thermometer of Geneva manufactured by Gourdon showed a drift 0.3 °C after 8 months and 0.9 °C after two years, thus larger than indicated by Winkler (2009). Also, the error is not a mere offset, but itself depends on temperature (Wiebe, 1885).

Not knowing the thermometric substance is another source of error due to non-linearities in its expansion. According to Deluc (1772), mercury thermometers tend to underestimate high temperatures by up to 1.75 °C at 50 °C. Conversely, they tend to overestimate low temperatures. He also found that, depending on the concentration, alcohol thermometers underestimated temperature even more, by up to 6.25 °C at 50 °C. More recent studies confirm different departures from linearity for mercury and alcohol in thermometers. Rivosecchi (1975) found that, combined with the irregular expansion of glass, mercury thermometers only underestimate temperature by 0.11 °C at 40 °C and overestimates it by 0.17 °C at -20 °C.

A third important error is the positioning of the thermometer north-facing wall, attached to a suspension device a few centimetres from a north-facing wall or standing on its own several meters away from the nearest building, protected from direct solar radiation and precipitation. Such historical settings were analysed by Böhm et al. (2010) for the Kremsmünster station. They performed observations in an unheated oriel with an automatic station located a few meters away in the garden of the building. According to these results, thermometers located at or close to north-northeast facing walls tend to overestimate real temperature in the morning, particularly between 6 AM and 8 AM during the months of April to September. Thermometers located at or close to north-northwest facing walls are affected the most during evening hours, with a peak at 4 PM to 6 PM during the same months. Thermometers located at or close to strictly north-facing walls show both deviation peaks – morning and evening – but less pronounced. This is consistent with results by Chenoweth (1993), who found exposition-related overestimations in summer of approximately +1.5 °C. For minimum temperatures, Chenoweth (1993) found an overestimation by unscreened thermometers attached directly to a north-facing wall up to ca. 1 °C, whereas unscreened thermometers attached to a suspension device on a north-facing wall showed only minor deviations. This is most likely the result of heat stored by the wall the thermometer is attached to. Unscreened thermometers attached to a north-facing wall located under an eave or a porch overestimate the minimum

temperature even more than others, perhaps because the eave or porch acts as a barrier for ascending warm air, warmed up by the wall (Chenoweth, 1993).

2.2. Barometers

2.2.1 Historical overview

In the 18th century, different types of mercury barometers were employed for stationary pressure observations. They can be divided into two main categories: fixed-cistern barometers, and siphon barometers. In the early 19th century a third category, the Fortin barometer, further increased the variety of instruments.

The fixed-cistern barometer is composed of a cistern filled with mercury, which is exposed to the air. A thin glass tube, closed at the upper end, where a vacuum is created, is vertically immersed into the mercury. This is equivalent to the setup conceived by Torricelli in the 17th century. Either on the glass tube itself or fixed externally to it, there is a scale, from which – in some cases with the help of a vernier (see Fig. 2) – the pressure can be read off. Because of the hydrostatic equilibrium between the mercury and the air, a change of pressure in the air causes a change of the level of the mercury in the tube and therefore a smaller change in the cistern as well. The dimension of the change in the cistern is dependent on the ratio between the diameter of the cistern and the tube. Therefore, a correction needs to be applied to readings made on the tube to take this level-change into account (Brugnara et al., 2015).

In the case of the Fortin barometer, this correction is not applied to the readings, but to the level of the mercury in the cistern itself. The mercury is set to zero (indicated by an ivory pin above the surface of the mercury) by a screw which pushes against a leather bag containing the mercury. This type of barometer was invented by Nicolas Fortin around the year 1800. It was a portable and precise barometer and its design endured with almost no changes for the following 150 years (Turner, 1983; Middleton, 1964).

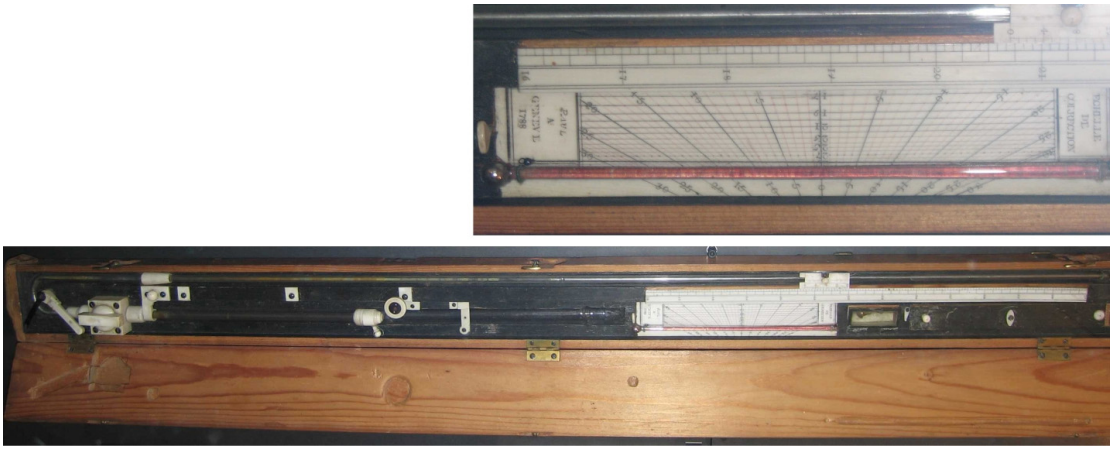

Figure 2. Deluc-type barometer manufactured by Paul, Geneva, 1788 and modified by Marc-Auguste Pictet. Modifications include the vernier (close-up) that was attached to the barometer tube (Natural History Museum, Geneva, photo: Renate Auchmann).

Rather than having a cistern, siphon barometers are u-shaped glass tubes with the closed vacuum-containing end on one side. On the other end, a shorter and open leg exposes the mercury to the air. The level of mercury in both ends is needed to obtain the pressure value. Owing to its rather impractical use, the siphon barometer was often criticised by contemporaries (Middleton, 1964).

Different corrections to the readings of the barometer are necessary due to thermal expansion of mercury and the change in gravity with latitude. Furthermore, for today's use, the measurement units need to be identified and converted into hPa. For some applications, the pressure values need to be reduced to mean sea level pressure.

2.2.2. Current standards and error sources of historical measurements

From all liquid-in-glass barometers, the mercury barometer is the most accurate and stable one. The WMO (2008) recommends the following characteristics for a mercury barometer:

1. Its accuracy should not vary over long periods;
2. The barometer should enable a quick and easy observation;
3. It should not loose accuracy when it is transported;
4. The bore of the tube should be at least 7 mm large, but preferably 9 mm large;
5. In the manufacture the tube should be prepared and filled under vacuum. The mercury should be double-distilled, degreased, repeatedly washed and filtered, as its purity is of significant importance;
6. The scale should preferably be calibrated at 0 °C;
7. The meniscus should not be flat, except if the bore of the tube is larger than 20 mm;
8. The instrument should have marks of 0.1 hPa;

Pressure measurements are affected by wind, temperature, shocks and vibrations. The barometer location must therefore be carefully chosen. Ideally the barometer should be in an environment with uniform temperature (no stratification), good light, and no strong wind variations. It should not be exposed to direct radiation or be close to a heating object. Barometers were mostly fixed on a wall. We can therefore expect that they were not subject to vibrations. Instruments mounted on a window frame might be affected by solar radiation. In general, mercury barometers can suffer from a number of errors such as uncertainties in the instrument temperature (no attached thermometer, or one that is not representative of the barometer temperature), defective vacuum space, the capillary depression of the mercury surfaces (the convexity of the meniscus changes depending on the ageing of the glass tube, pressure tendency and the position of the mercury in the tube), and lack of verticality, reading errors (the vernier should appear to be touching the top of the meniscus).

The effect of temperature is further discussed in Section 3. In the following we give further details to capillarity. The surface of mercury within the pipe is convex and lower than the surface around the pipe. This can be described with the following formula:

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

where h denotes the difference in height between the surfaces within (read at the top of the meniscus) and around the pipe, σ is the surface tension of the relevant fluid, Θ the contact angle of the fluid within the pipe with the pipe, r the inner radius of the pipe, ρ the density of the relevant fluid and g the local gravity (Eichler et al., 2016).

At the beginning of the 19th century the problem of capillarity was known (Cavendish, 1776) and tables for capillarity correction were published (Laplace, 1812), although assuming that the shape of the meniscus and therefore the angle of contact are the same in vacuum as in air, which is problematic for thin tubes. Capillarity correction for mercury barometers thus remained a problem. Another critical factor was discovered by John Frederic Daniell, who experimented with boiled and unboiled glass tubes and found out that the capillarity depression for mercury was smaller if the tube was boiled before it was filled with mercury. Progress was also made in the measurement of the angle of contact, but the surface tension of mercury was not measurable within a barometer and could not be supposed invariable even within the same barometer (Middleton, 1964).

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

2.3. Precipitation

Rain gauges in the 18th and 19th century consisted of a collector and a container. Precipitation measurements were measurements of the water depth in the container with known surface area. Straight-sided, conical or pyramidal shapes of collectors were in use (see Fig. 3 for an example, from the network of the Bernese Economic Society), and the volumes and mounting above or at ground varied. The most important error sources were wetting losses, splash into or out of the collector, and wind, the latter acting to reduce the measured precipitation amount (Strangeways, 2004). Further error sources are evaporation losses and measuring errors. Snow was measured in height of newly fallen snow, which then needs to be converted to equivalent water by assuming a density of snow (often assumed 100 kg/m^3).

Current WMO requirements for a precipitation gauge are the following:

1. The rim should have sharp edge and fall vertically on the inside;
2. The orifice area should be known to the nearest 0.5%;
3. The gauge should prevent rain from splashing in and out: the slope inside the gauge should be steep enough, at least 45%;
4. The wetting errors should be as small as possible;
5. The orifice should be narrow enough to minimise evaporation loss;

6. The measuring cylinder under the collector should be made of glass or plastic, material that has a little thermal expansion;

7. The measuring cylinder diameter should be less than 33% of the collector diameter;

8. The reading precision should be 0.1 mm;

9. The gauge should be above the maximum expected height of snow cover and high enough to avoid splashing from the ground. It is often between 0.5 m and 1.5 m;

To not significantly perturb the wind field, the obstacles should be at least twice their height distant from the gauge. The size of the gauge orifice is not very critical but it should be at least 200 cm^2 to measure solid precipitation. Even today, measuring precipitation is subject to errors. Wind field deformation can account for 2-10% underestimation, which can exceed 50% for solid precipitation (Goodison et al., 1998). Wetting loss in the collector walls and in the measuring cylinder when it is emptied account for 2-15 % in summer and 1-8% in winter. Evaporation from the container adds another 0-4 %, in- and out-splashing is between 1-2 %. In the early instrumental period, experience on precipitation measurements was still limited and errors were arguably larger.

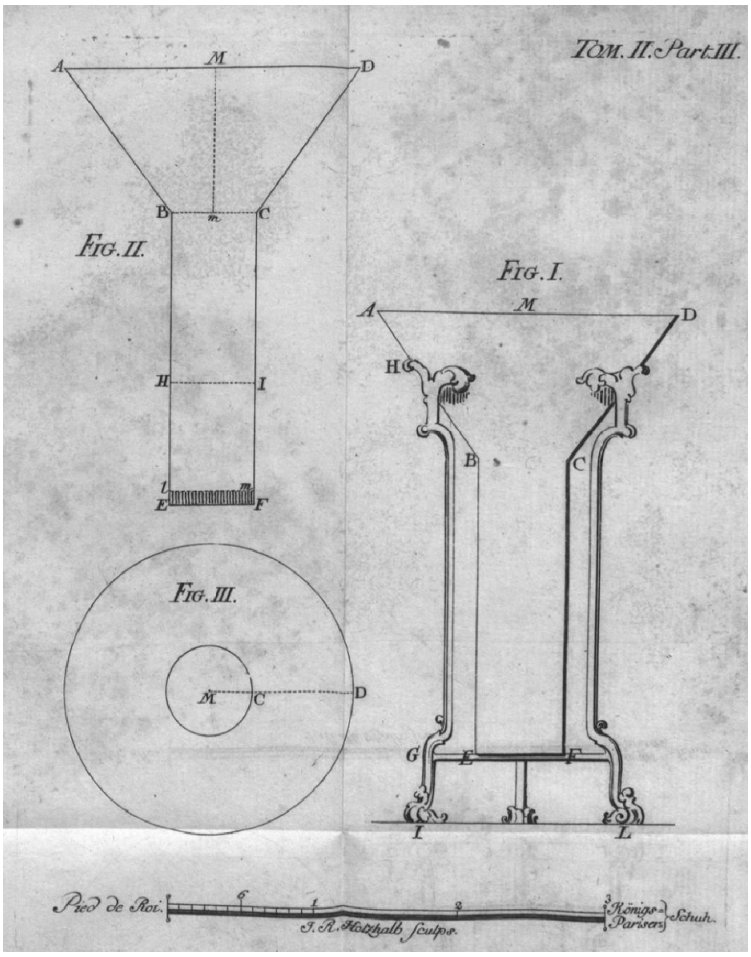

Figure 3. Design of the rain gauge used in the network of the Bernese Economic Society (Abhandlungen der Berner Ökonomischen Gesellschaft, 1761).

3. Processing

3.1. Length units

Although one result of the French Revolution was the adoption of the metric system, for a good part of the 19th century, the foot persisted as a unit of length. Unfortunately, the length of the foot differed from country to country. The Paris foot, the most commonly used in continental Europe and in Switzerland, was divided into twelve inches (1 inch = 27.07 mm), which in turn were divided into twelve lines. The British inch (= 25.4 mm), on the other hand, is usually divided into tenths or hundredths (see Brugnara et al., 2015, for an overview).

3.2. Time conversion and aggregation

For the series considered here, the Gregorian calendar had already been adopted, but times of day were measured in local solar time and therefore need to be converted to UTC using longitude (λ):

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

Sunrise and sunset observations are converted using the R package *suncalc*.To facilitate comparisons and analysis, we need daily and monthly means of the observations. To calculate them, we must take into account the climatological diurnal cycle. This is not only the case for temperature, but also for pressure; the magnitude of the diurnal cycle of this variable is approximately 1.2 hPa at the latitude of Bern. For temperature, the amplitude of the diurnal cycle is larger (in the order of 10 °C) and the simple arithmetic average of the observations usually gives a positively biased daily mean because observations are more representative of the daytime than the nighttime. We adjusted the diurnal cycle by using hourly data from the reanalysis ERA5 Land (Copernicus Climate Change Service, 2019). A different diurnal cycle is considered for each month.

For many records the exact time of the observations is not given. Only the part of the day when the observations are made is known (*e.g.,* “morning”, “afternoon”). Our approach for calculating daily mean temperatures for these records is summarised in Table 1. For mixed cases (*i.e.,* time is known for some of the observations in a day), the diurnal cycle correction is applied only if at least two times in a day are known; in this case, observations with unknown time are not used in the calculation of the daily mean.

For pressure, when one or more times are unknown no correction for the diurnal cycle is applied. The daily mean is calculated as simple arithmetic average of the observations. Note that the number of observations in a day can vary from one day to another, so different formulas can be used within the same record.

Monthly means are calculated as the average of daily means. Following the guidelines of the World Meteorological Organization (WMO, 2017), monthly means are calculated only if there are less than 11 observations missing and less than 5 of them are in consecutive days.

For precipitation, daily and monthly sums are calculated. Monthly sums are calculated only if no daily sums are missing.

Table 1. Calculation of daily mean temperature for unknown observation times

Condition	Formula
3 observations and the 3rd is in the evening	$(obs_1 + obs_2 + 2\ obs_3) / 4$
3 observations and the 3rd is in the afternoon	$(2\ obs_1 + obs_2 + obs_3) / 4$
2 observations (morning and evening)	$(obs_1 + 2\ obs_2) / 3$
2 observations (morning and afternoon)	$(obs_1 + obs_2) / 2$
daily maximum and minimum temperatures are measured	$(T_{max} + T_{min}) / 2$
only 1 observation	daily averages are not calculated

3.3. Thermometer scales

In the first liquid-in-glass thermometer, the so-called Florentine thermometer (Camuffo and Bertolin, 2012), the scale was simply defined by dividing the tube in equal parts, and the comparability of thermometers relied on the fact that all thermometers had to be made exactly identical. This worked relatively well as long as all instruments were made by the same person, but for the thermometer to become a truly scientific instrument there was a need for better reproducibility. One way to do that was to define a scale after one or more fixed points, that is by exposing the thermometer to conditions known to be at a constant temperature, such as the melting point of ice, and graduating the tube according to the level of the liquid at the fixed points. The 18th century saw the rise and fall of dozens of different temperature scales based on various fixed points (many of these scales are described by Middleton, 1966). The most relevant in the area of today's Switzerland are those by Réaumur, Fahrenheit, Micheli du Crest, and the "centigrade" scale (later attributed to Celsius).

The Réaumur scale was the most widespread in continental Europe for about one century, between ca. 1730 and 1830. Already in the 1740s, however, scholars had realised the inadequacy of this scale for a use in meteorology: its definition was ambiguous and the techniques to construct and calibrate the thermometers changed among different makers (see Gauvin, 2012). Initially, Réaumur thermometers were filled with spirit, but soon mercury versions were created. It is difficult to use measurements made with this scale, at least until 1770-1780, because there were hardly two Réaumur thermometers that would measure the same temperature in the same conditions. Things improved rapidly after Deluc's "Recherches sur les modifications de l'atmosphère" was published in 1772. Deluc defined a new Réaumur scale with two clear fixed points (melting point of ice and boiling point of water at a constant pressure) to be used for mercury thermometers. Measurements made with Deluc's thermometer can be transformed to the Celsius scale by simply multiplying by a constant factor.

The Fahrenheit scale went also through some evolution after it was proposed in 1724, but by the 1750s it had already reached the modern definition, which is equivalent to that of Deluc's. In Switzerland this scale was not common; the only relevant use was by Frédéric Moula in Neuchâtel (see also Brugnara et al., 2019), who already used the modern version of the scale.

The scale proposed by Micheli du Crest in 1741 was intended to define a "universal thermometer" that would overcome the comparability problems of Réaumur thermometers. Micheli du Crest was not only a brilliant scientist, but also a skilled instrument-maker. His ther-

mometers were in many ways better than Réaumur's, to the point that the main assistant of Réaumur, the Abbé Jean Antoine Nollet, immediately adopted some of the methods described by Micheli du Crest (see also Talas, 2002). The thermometer of Micheli du Crest never obtained international recognition in part because of the high reputation of Réaumur in the French scientific community, in part because of his choice of using spirit of wine as thermometric liquid. The Bavarian instrument-maker Georg Friedrich Brander was one of the few who tried to create a market for Micheli du Crest's thermometer (Talas, 2002), and was partially successful in doing so in his region (so that this type of thermometer was sometimes called Brander thermometer, see Brugnara et al., 2019), but its use gradually subsided at the end of the 18th century. The conversion of the Micheli du Crest scale to °C requires a quadratic function (Table 2) because of the non-linear expansion of the spirit. The fixed points chosen by Micheli du Crest were the same that were later adopted by Deluc, although his scale went from -10.4 to 100, so that the zero would indicate a "normal" temperature in a temperate climate, defined as the temperature in the cellar of the Royal Observatory in Paris.

Some thermometers require specific corrections based on information gathered on the instrument. It is the case, for example, for Réaumur thermometers before the 1770s or for instruments with a known shift of the zero. These corrections, when applied, are described in the single papers dedicated to each record.

Table 2. Thermometer scales in the early instrumental period and their conversion to °C

Name	Use	Formulae	Reference
Réaumur (after Deluc)	after ca. 1772	°C = Re × 1.25	
Fahrenheit		°C = (°F – 32) × 5/9	
Micheli du Crest		°C = 11.95 + 1.10 × °MdC – 0.0026 × (°MdC)^2	Brugnara et al., 2019

3.4. Reduction of pressure

Mercury expands with temperature, and therefore pressure readings must be reduced to a standard temperature of 0 °C for comparison (WMO, 2008). In fixed cistern barometers, the mercury rises in the cistern when it falls in the tube and vice versa, so there are two ways to properly reduce the pressure to a standard temperature. In one case, a standard-scale is used and afterwards, the correction is calculated. In that case, the point on the scale at which the barometer has initially been adjusted must be known. In the other case, an appropriately contracted scale is fit to the barometer. In both cases, the ratio between the cross section of the tube and the cistern must be known; however, the correction to a standard temperature for fixed-cistern barometers with contracted scales was not solved properly until 1914 (Middleton, 1964) and hence our historical measurements need to be corrected.

Historical pressure series can be divided into three categories, each with its own problems. In the first case, the correction for temperature is known to have been performed by the contemporary user of the barometer himself. Since the metadata rarely reveal the formulas and tables employed, the amount of the bias often remains uncertain.

In the second case, the contemporary user of the barometer wrote down the pressure values without stating whether the values were reduced to 0 °C or not. For series in the 19th century, in most cases one can assume that the values were reduced to a standard temperature. However, there is still uncertainty about the choice of temperature to which barometer readings were reduced.

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

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

where L_0 is the observation reduced to 0 °C (WMO, 2008), γ is the thermal expansion coefficient of mercury at 0 °C (1.82×10^{-4} K^{-1}), T is the temperature of the barometer in °C and L_{mm} is the original observation in mm of mercury. Obviously, errors in the thermometer readings translate into pressure errors. Additionally, there is an uncertainty for fixed-cistern barometers that increases with temperature. Correction requires the ratio between the cross sections of the tube and cistern or the neutral point, which is often unknown.

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

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

where P_0 is the absolute pressure in hPa, $\rho = 1.35951 \times 10^4$ kg m^{-3} is the density of mercury at 0 °C, $g_n = 9.80665$ m s^{-2} is the standard gravity acceleration and L_0 is the barometric reading in mmHg. Since gravity acceleration varies with latitude and altitude based on the geographical coordinates of the barometer, further correction for local gravity is needed:

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

where P_n is the pressure corrected for local gravity, g_0 is the standard gravity acceleration and P_0 is pressure reduced to 0 °C. Assuming flat terrain around the station, the local gravity $g_{\phi,h}$ can be estimated with the formula

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

where ϕ stands for the latitude and h is the altitude of the station in meters above sea level. For comparability purposes, pressure values from different altitudes can be reduced to the altitude of the mean sea level. This is not done for the data delivered within the project (Brugnara et al., 2019), but it is performed for some of the analyses using the formula:

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

where SLP stands for sea level pressure, P_n is the station pressure with all the corrections applied from above, $g_{\phi,h}$ is local gravity, $R = 287.05$ J kg^{-1} K^{-1} is the gas constant for dry air,

$a = 6.5 \times 10^{-3}$ K m^{-1} is the standard lapse rate of the fictitious air column below the station, T_s is the outside temperature at the station in Kelvin and h is the altitude in meters above mean sea level.

4. Quality Control and analysis

4.1. Format

In order to preserve original data and provide processed data (which requires expert knowledge) plus metadata, we use the SEF (Station Exchange Format), which was agreed upon within the Copernicus Climate Change Service (C3S) Project 311a. Quality Control routines programmed and published within this service read this format, and the data can be integrated into the global surface data repository of C3S in this format. For a description see Brunet et al. (2020).

Since only temperature, pressure, and precipitation data were processed, other variable are not provided in SEF. Instead, they were published as an R data frame. All data are available on the repository PANGAEA: https://doi.pangaea.de/10.1594/PANGAEA.909141 (Brugnara, 2019).

4.2. Quality Control (QC)

The Quality Control procedure applied to the series in these papers has different elements. First, a QC of the metadata is performed that checks for possible errors in coordinates, station altitude or similar. Then the actual data are quality controlled. The sequence of steps applied here encompasses range checks, physical plausibility checks, etc. In particular, we applied the tests implemented in the R package *dataresqc* v1.0.0. Suspicious values were checked in the original documents and in many cases corrected. The rest was flagged in the SEF files.

As an additional quality control, we flagged all temperature and pressure observations whose difference from the previous or following observation deviated more than 4 standard deviations from the mean difference between morning and afternoon observations or between afternoon and evening observations, depending on the case. This was necessary because some tests in the package *dataresqc* cannot handle missing observation times.

4.3. Analyses

After having applied the QC, the last step is to visualise the data. A set of standard plots was generated for each series. Additional comparisons and analyses were then performed for individual series. The standard plots per station or series include the following:

- Box plots of each variable and observation time per calendar month (not always shown),
- scatter plots of morning against afternoon (noon, evening) measurements for temperature and pressure,

- plots of the diurnal temperature cycle in January and July from the nearest location in the current MeteoSwiss network (typically data from 1981 to 2010, reduced by 1 °C to approximately account for global warming) and of averages of the historical temperature data plotted at the time of day of the measurement, and
- monthly time series plots of each variable (not always shown)

Additional analyses include:

- Scatter plot (per variable and observation time) of overlapping segments of two series at the same location and
- monthly time series plots of differences of overlapping segments of two series at the same location

Together, these standard analyses help to better assess the data at hand, the quality of the data, the signal-to-noise ratio to be expected for climatological analyses as well as usefulness for analysing weather events.

5. Conclusions

Early instrumental meteorological data are challenging to use in climate science. A thorough understanding is required of how and why measurements were made, what instruments were used and what the potential sources of errors are. This paper covers general aspects on early instrumental measurements. Typical instruments types and associated errors are described and related to present-day standards. The paper also describes the procedure which each individual paper in this collection followed. This encompasses the treatment of time, conversion of units, reduction of pressure as well as the formatting of the data. Finally, the paper describes the quality control performed and some standard analyses which were done for all of the series.

The inventory of all series has been published (Pfister et al., 2019) and the imaged data sheets of all series can be downloaded from https://zenodo.org/record/3066836#.XVv-fGRS8-U. The data are described in Brugnara et al. (2019) and can be downloaded from https://doi.pangaea.de/10.1594/PANGAEA.909141. They will be delivered to additional repositories, including MeteoSwiss, the Copernicus Climate Change Service (C3S) Repository, and EURO-CLIMHIST (Pfister et al., 2017).

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