Providing Data Provision for a Sensitivity Analysis of Snow Time Series

Final Project Report

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Summary

The project “Providing data provision for a sensitivity analysis of snow time series”, funded by the Swiss Global Climate Observing System (GCOS) office, accompanied the Swiss National Science Foundation (SNSF) funded project Hom4Snow by digitizing data, providing metadata and carrying out quality control measures to already available and newly digitized data. The Hom4Snow project tries to develop and test suitable methods for homogenizing manual snow measurements. For this purpose, it wants to make use of a unique set of parallel stations operated by Federal Office of Meteorology and Climatology (MeteoSwiss) and the WSL Institute for Snow and Avalanche Research SLF (SLF) that measured snow independently from each other in close distance for sensitivity testing of different snow climate indicators and to develop suitable methods for break detection.

The main goal of this GCOS funded project was to build up said data set of independent parallel snow measurements. The data set should be digitally available, quality controlled and associated with sufficient metadata to test the independence of two parallel series and to verify potential breaks. As a first step, independent parallel station pairs had to be identified. In case the snow data was not digitally available this was done with metadata which partly had to be first gathered by extracting relevant information from the station history records of the MeteoSwiss stations and by extracting information from the SLF annual winter reports. While compiling the relevant metadata we found incorrect location entries for some stations in collaboration with MeteoSwiss. Unfortunately, location histories for manual snow measurements have often not been documented properly in the last four decades and are attributed with high uncertainties. The gathered and corrected snow metadata has already been transferred to the MeteoSwiss data warehouse.

After identifying the independent station pairs, we digitized not yet available station records for 23 stations. Thereby, the parallel station data set could be extended by 100%, because often the time period between 1986 and 2011 was missing. Afterwards, all stations in the independent parallel station data set have been quality controlled and gap filled. For this purpose we applied a set of quality control algorithms and developed some new ones for manual daily snow data mainly based on the consistency between depth of snowfall and snow depth. The quality control worked well and many data values were corrected or temporally shifted. A final visual check of all data completed the quality checks. Short gaps in the data have been filled by manually fitting the evolution derived from the best correlated neighboring station. We found 30 station pairs which measured snow independently from each other for at least 30 years. The average length of independent measurements for these 30 station pairs is 50 years. The longest parallel station pair has independent measurements for 78 consecutive winters. This new data set is already in use by the Hom4Snow community for sensitivity and break detection analysis.

The thorough metadata inspection and digitization confronted us extensively with historic observer sheets, annals or instructions. We used this as an opportunity to collect information on the history of snow measurement practices in Switzerland and other countries. We were able to find interesting insights regarding the first steps of manual snow measurements in the measurement networks of different meteorological services worldwide .

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1. Introduction

Snow can have large impacts on society in alpine countries. Absence of snow means loss of touristic value for regions that depend on winter sports tourism and too much snow imposes high risks for human infrastructure for example due to avalanches or high snow load on buildings. Therefore, it is important to monitor the status of the snow cover and potential changes due to changing climate conditions. The only long-term data for snow with sufficient spatial coverage comes from daily manual HN and HS measurements. As most climate variables, these records often experience breaks due to station relocations and observer or instrumentation changes, which add uncertainty to a sound climatological analysis.

This kind of data inhomogeneity and its correction i.e. homogenization has been studied for many climate variables such as temperature, air pressure and precipitation (e.g. Acquaotta, Fratianni, Aguilar, & Fortin, 2019; Begert, Schlegel, & Kirchhofer, 2005; Guenzi, Acquaotta, Garzena, Baronetti, & Fratianni, 2020). However, only little research has yet been done on homogenization methods for snow data (Marcolini, Bellin, & Chiogna, 2017). The Hom4Snow project at the SLF tries to fill those research gaps in collaboration with the MeteoSwiss, the Central Institution for Meteorology and Geodynamics (ZAMG) and the University of Graz. The Swiss part of the project, funded by the SNSF, makes use of a unique data set of “parallel” stations which measured snow independently in close vicinity. These parallel stations are used for testing the sensitivity of snow variables to local changes and for finding suitable methods for break detection, which is an important step in the homogenization procedure. The parallel stations exist due to the fact, that the two institutions SLF and MeteoSwiss (before 1979: Schweizerische Meteorologische Zentralanstalt (MZA), between 1979 and 2000: Schweizerische Meterologische Anstalt (SMA)) measure snow on the ground independently from each other in Switzerland.

The project “Providing data provision for a sensitivity analysis of snow time series”, kindly funded by MeteoSwiss in the framework of GCOS Switzerland, accompanies the Hom4Snow project by digitizing data, providing metadata for the parallel stations, and carrying out quality control measures to the already available and the newly digitized data. It thus supports the Strategic Pillar 1: Enhance and strengthen the Swiss climate observing system of the strategy for GCOS Switzerland for the period 2017-2026 with the strategic priority 1.4 "Extend time series in the past through promoting data rescue, incl. development of QA/QC tools" (MeteoSwiss, 2017).

2. Metadata

For snow measurement stations in Switzerland, operated either by MeteoSwiss or by the SLF, metadata is an important part of the station record. In this case, metadata comprises information on the location of measurement, the observer, the observation methodology, used instrumentation and any incident relevant for the observations. However, for manual snow measurements not all metadata is digitally available and the metadata records of meteorological stations usually focus more on the parameters temperature, precipitation, air pressure and wind. However, snow related metadata sometimes can be found in the correspondence between the observers and the weather- or hydrographic service. A decent set of metadata for each station is crucial e.g. to verify the independence of two parallel snow series. Additionally, breaks in the time series that can be detected by statistical methods, need to be verified by metadata before any homogenization is done on the data. Lastly, metadata can also be useful for assessing the data quality of a measurement series.

As there was no synoptic dataset of manual snow measurement metadata for the stations operated by MeteoSwiss, our aim was to compile such a dataset. For this purpose, we scanned the station histories (STAGEs) of potential parallel stations for specific keywords related to snow measurements, snow measurement instruments, observer changes, location specifications and location changes. Afterwards, we aggregated the snow related entries in a database. This snow metadata database has proven to be very useful for the later compilation of independent parallel station pairs (Section 3) and the reconstruction and correction of existing station location history records (Section 2.1).

2.1 Location histories

Snow measurement locations in the past are often poorly documented and it is difficult to obtain a location history that is reliable. For example, different sources of metadata can contain contradictory information and it is difficult to find out which data point is correct. Problems arise for different reasons. Before the era of modern maps in the late 1950's, coordinates were most likely often rough estimates and much less accurate than nowadays. The exact position of a station was not of relevance as it is today with e.g. operational numerical modeling of snow covers and often only the town or village name was exact enough. A report on the SLF station network from 1992 for example lists snow measurement coordinates only with a precision of kilometers (Martinec & Gliot, 1992). These inaccuracies could lead to small coordinate corrections in the metadata record, which do not represent an actual change in measurement position. With the automation of the standard meteorological measurements from the 1980's onward, the location of the manual snow measurements often became spatially separate from the other (automatic) measurements during the last few decades. Consequently, station coordinates are often those from the automatic measurements, which are not representative for the snow measurements and sometimes no additional coordinates for the manual snow measurements exist. However, for the present station network, MeteoSwiss made efforts to document coordinates of all measurement variables correctly but coordinates before ca. 2010 can have these problems.

In order to get a correct station history for manual snow measurement location at the MeteoSwiss stations, we compared coordinates from the STAGE with coordinates obtained from the MeteoSwiss data warehouse. We identified several inconsistencies between the two datasets. Some of these inconsistencies were easily identified as errors in the MeteoSwiss database given the official station history as valid information. These errors were for example overseen relocations, obviously wrong coordinates in the database (e.g. on a road intersection) or wrong dates for relocations. There were also many examples, where coordinates in the STAGE were incorrect or not complete (e.g. coordinates were sometimes documented on station site plans and not in the STAGE, the coordinates from the site plan on the other hand had been transferred to the MeteoSwiss data warehouse). For other inconsistencies, background knowledge was required. This could be the case if e.g. the STAGE did not document whether the coordinate is attributed to the manual or the automatic snow measurement. We sent these cases to MeteoSwiss where the instrument maintenance group checked each case. The corrections were sent back to us and will also be updated in the MeteoSwiss metadata stack and on OSCAR Surface[1].

For location histories of the SLF stations, we used coordinates from the SLF-internal database. We are aware that the problems described in the introduction of this section are present for the SLF stations but did not have a means to correct or verify the location histories and took the data from the database for granted.

[1] Contact for measurement observations at MeteoSwiss was Christian Allemann

2.2 Observer histories

Changes regarding the observer(s) of a station might influence the data quality and could potentially cause inhomogeneities (for an example of observer behavior see Section 4.2.5). Therefore, we tried to collect as much information as possible on who carried out the measurements. This is not always as easy as it seems to be. If a station is operated by public or private institutions such as schools, sanatoriums, train stations or municipal administrations, it is often not clear who carries out the actual measurements because the person in charge of correspondence with MeteoSwiss or SLF is not necessarily the observer. For the MeteoSwiss stations, we used the observer information that was gathered in the course of scanning the STAGEs as mentioned above. For MeteoSwiss we only have observer names when the observer changed or when an inspector from MeteoSwiss was visiting the station and made a note in the station history. As there was no synoptic digital observer history available for the SLF stations, we compiled such a database from different historic sources such as the "Winterbericht" published annually by SLF from 1947 onward. For every SLF station, we have an observer name for each winter in which snow measurements were carried out.

2.3 Data quality assessment from metadata

The metadata reveals interesting insights into the quality of the measured snow data. These are for example bad habits regarding new snow measurement practice, inappropriate locations of the measurement sites or accumulated and interpolated measurements if the measurements are only carried out at business days. The following are two examples of such insightful metadata entries:

> *«[Neuschnee-Brett] Eigenbau. Misst [Neuschnee] jedoch meistens auf dem Holzbalkongeländer laut Bemerkungen. Auch ein neues Brett würde daran kaum etwas ändern.»*
>
> *«Statt der bei der letzten Insp. gelieferten Schneemesseinrichtung werden nach wie vor mit vergammeltem Holzpfosten und -Brett Schneehöhen gemessen.»*

This type of information is an invaluable asset when the data quality seems to be spurious and one tries to find out whether measured data in the period of interest is trustworthy or not (see Section 4.2).

3. Independent parallel station pairs

The first goal in the Hom4Snow project was to carry out a sensitivity analysis of several snow climate indices (such as average snow depth, sum of depth of snowfall, days with snow cover, etc.) based on parallel station pairs. Snow data measured independently within close distance is used to get an idea about local scale variation of these snow climate indices and how they are possibly affected by whatever changes to a station. In Switzerland, MeteoSwiss and SLF have measured snow at close locations (i.e. in the same village) independently in the past and still do so at some locations. However, sometimes the stations or institutions copied data from each other or were run by the same observer which means the two times series are not independent from each other. Therefore, the aim of this work was to detect independent station pairs. Independence is determined based on metadata and based on the actually measured data. The resulting set of independent parallel station pairs has been used in a sensitivity analysis for detecting the robustness of different snow climate indicators (**?**).

3.1 Detecting independence conflicts

3.1.1 Independence conflicts based on measurement data

In order to detect independent parallel station pairs based on measurement data, we calculated correlations of both measured HS and HN from the two parallel stations for each winter season. Abrupt changes in the correlation coefficients from one individual winter seasons to another can indicate a shift from independent to dependent stations or vice versa. Very high correlation coefficients of the HS series and/or HN series above 0.99 are showing that we are dealing with the same data. Usually, data of those two stations then cannot be treated as independent time series. However, station pairs with very little amount of snow and few days of snow can have high correlation coefficients although they are independent. This makes a closer look to the data and an additional evaluation of the metadata inevitable.

3.1.2 Independence conflicts based on metadata

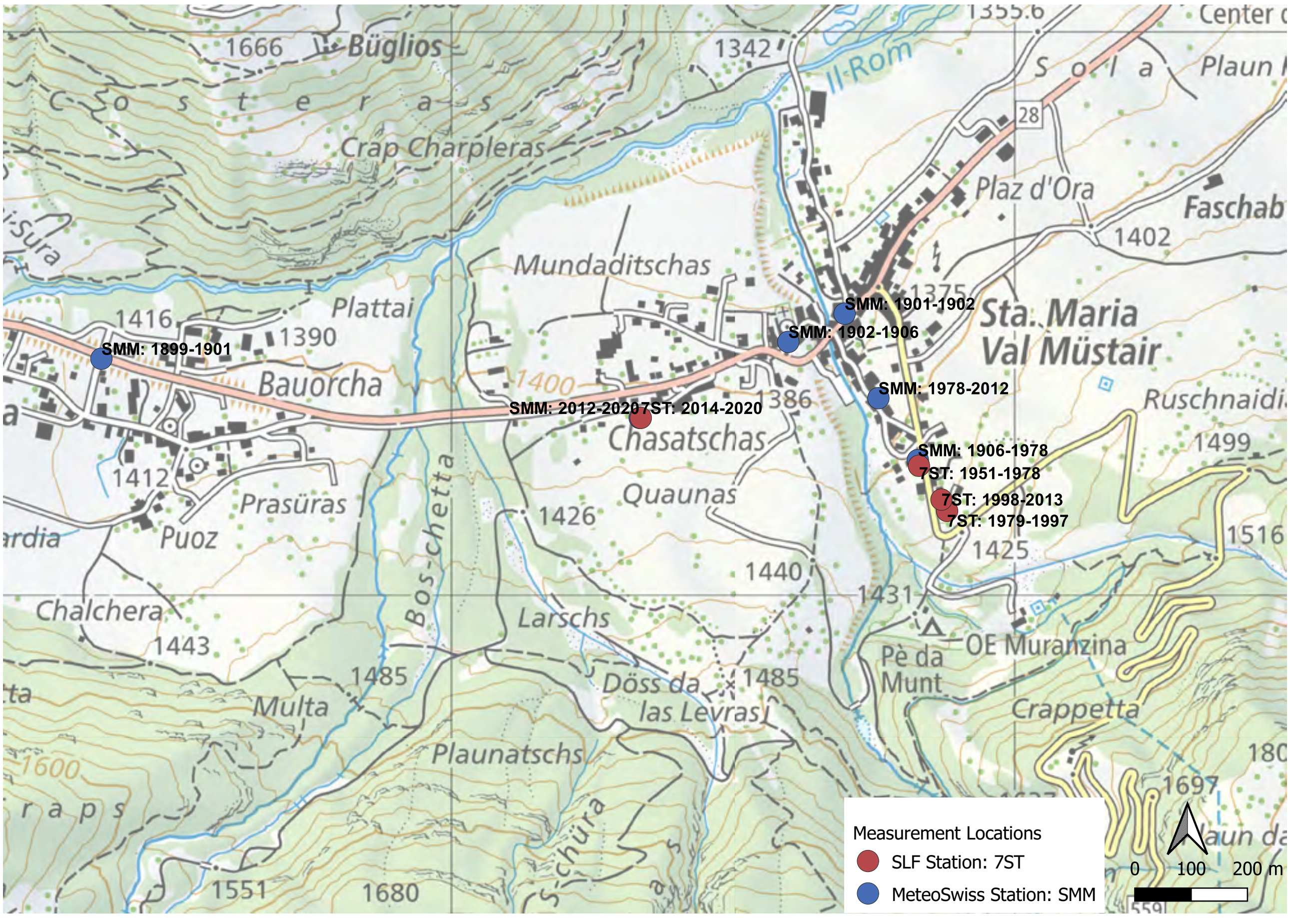


Figure 1: *Example of snow measurement locations over time from the MeteoSwiss station SMM (blue) and the SLF station 7ST (blue) in Sta. Maria Val Müstair. According to the metadata, the two stations were situated at the same location in the periods 1950-1978 and 2014-present.*

Additionally, we used metadata in order to detect independence conflicts of parallel measurement series. The most important metadata in this regard is a) the location of measurement and b) the person/institution that carried out the observations. By plotting the locations from different times of the two stations on a map, we were able to identify periods in which the measurements were carried out at the same location or very close to each other (Figure 1). In the case of the shown example of Sta. Maria, a comparison of the data demonstrated that the two series were virtually identical between 1968 and 1978 although the location was already the same from 1950 onward. Whenever the correlation coefficient in a single year was high for a station pair or when the measurement locations were close together, we additionally compared the names of observers.

3.2 List of independent parallel station pairs

The above described work resulted in Table 4 (see Appendix A) which provides an overview on the data availability, and independence of all potential parallel station pairs in Switzerland. Potential parallel station pairs are stations, that measured snow within 4 km horizontal and 100 m vertical distance. We found 30 station pairs which measured snow independently from each other for at least 30 years. The average length of independent measurements for these 30 station pairs is 50 years. The longest parallel station pair has independent measurements for 78 consecutive winters.

4. Digitalization, quality control and gap filling

4.1 Digitalization and data assemblage

In order to get complete digital records of snow measurements (HS and HN), we aggregated data of already digitized series or digitized the data by ourselves. Digitization was done manually based on scans of the original observer sheets. The sources of already digitized data are the MeteoSwiss data warehouse (accessed via the MeteoSwiss interfaces Climap and IDAWEB) and the original Swiss Federal Institute of Technology (ETH) snow database compiled by Moesch (2002) from where we took data that was digitized by Witmer, Filliger, Kunz, and Küng (1986). When data of a MeteoSwiss station was already in the SLF database, we still used the data from the MeteoSwiss data warehouse or from the database by Moesch (2002) and compiled it again. We then fed the newly compiled time series of measured snow data to a database on which we are able to track corrections and changes to the data during data quality control and gap filling.

Overall, available data of 23 MeteoSwiss stations has been digitized in the course of this project (Table 1). 21 of those stations are now part of the parallel station data set described in Chapter 3. Two stations have been digitized although they are not in the parallel station set because they now provide long data series and might be useful reference series for later homogenization of the snow data. For the station in Stans (SNS) we now have a complete digital record from 1948 to present and in Leysin (LYN) we have a complete HN record from 1931 to present. Most of the digitized series were also quality controlled and gap filled in order to have continuous data in the winter months November to April. For some stations we did not perform quality control and gap filling because it turned out that the station was not (or not long enough) independently operated from the respective parallel station (see Section 3.1.1). In this case, we use the data from the parallel station (usually operated by SLF) which is already quality controlled and gap filled.

A special case is the station in Egg/Sihlsee (SSE) as it is nowadays neither operated by the SLF nor by the MeteoSwiss. The station was established as part of a snow water equivalent (SWE) measurement network that has been built up since the winter 1943/44 by E. Hoeck from the Department of Hydrology at the ETH Zurich in cooperation with the electric power industry (Rohrer, 1991). In 2020, the station is still in operation and we received scans of original observer sheets as well as already digitized data from

METEODAT GmbH[2]. Additionally, Witmer et al. (1986) already digitized 20 years of the station (1961-1980) in which it was part of the MeteoSwiss precipitation station network. The station pair EIN/SSE is the longest parallel station pair with independent measurements for 78 consecutive winters (see Table 4). In the region of Einsiedeln, we now have snow measurements in close vicinity from three parallel stations (GSS, EIN and SSE) in the period 1973-2020. There exists a fourth station (Euthal) in the same area which has not been digitized due to limited resources. The station setting of the Einsiedeln region paves the way for further in-depth analysis of local scale snow depth variability.

Even though we quality controlled the digitized data, our experience of the last months shows that we still find erroneous values in the course of the Hom4Snow project. As the data quality still might improve, we decided to deliver the digitized data set to GCOS and MeteoSwiss as soon as the Hom4Snow project is finished in order to avoid different versions.

Table 1: *MeteoSwiss stations that have been digitized and quality controlled in the course of this project.*

Station Abbreviation	Location	in Parallel Station Set	Quality Controlled
BIV	Bivio	✓	✓
BRW	Braunwald	✓	✗
CAV	Cavaglia	✓	✓
GAD	Gadmen	✓	✓
GSS	Gross	✓	✓
KUB	Küblis	✓	✓
LAN	Landquart	✓	✓
LTB	Lauterbrunnen	✓	✓
LYN	Leysin	✗	✓
MUE	Mürren	✓	✓
PAV	Payerne	✓	✓
RIE	Ried	✓	✓
SDO	Splügen	✓	✓
SED	Sedrun	✓	✓
SIM	Simplon Dorf	✓	✗
SMZ	St. Moritz	✓	✗
SNS	Stans	✗	✓
SSE	Sihlsee	✓	✓
THS	Thusis	✓	✓
TIC	Tiefencastel	✓	✗
VLS	Vals	✓	✗
ZER	Zermatt	✓	✓
ZNZ	Zernez	✓	✓

4.2 Data quality assessment

In order to verify that the digitized snow series are physically plausible, continuous and attributed to their correct date, several quality control tests were performed on the data. The manual snow measurement record consists of two variables (measured each morning), the snow depth (HS) and the depth of snowfall (HN) that has been accumulated during the last 24 hours. In the course of quality and plausibility control, several criteria are checked. These criteria are either testing for single events (e.g. implausible values) or for the frequency of a certain event (e.g. how often is HS constant if there is HN). Data for all stations in the parallel station dataset (Section 3.2) which have measured data independently from each other for at least 30 years has been quality checked. While doing the quality control, we also found cases, where data points

[2]https://www.meteodat.ch/

from the MeteoSwiss data warehouse did not equal the original observer sheets but did not hold any data alteration identifier in the database.

4.2.1 Missing data, gaps filling

The historical snow measurement time series in Switzerland are often not complete regarding their temporal coverage. There are data gaps of months or even years for some stations. Additionally, most of the stations lack measurements over the summer months (usually from May to October). Snow measurements at SLF stations usually take place from November until April and the summer months do not hold any data, which is the reason why the analysis of the parallel data set in **?** is focused on the winter months between November and April. However, even in the case of the MeteoSwiss where the instructions states to measure year-round, data is often only sparsely available during summer months or it is not clear whether there was zero snow measured or if there was no measurement and the data was filled with zeros later on e.g. during digitization.

Missing values of less than a week in length were interpolated based on the data from neigboring stations and expert knowledge. Missing values of more than a week but less than a year in length were interpolated by manually fitting the evolution derived from the best correlated neighboring station using the ratio between the median values (separated in 5 percentiles) of the candidate series with the best correlated reference series of the last three to five years preferably before or else after the gap. The occurrence of gaps longer a week were rare, as we beforehand applied a 80% cut-off data availability which meant that only almost complete series were used.

4.2.2 HN date shifts

Unfortunately, SLF and MeteoSwiss/MZA have different conventions regarding the date to which depth of snowfall (HN) is attributed. SLF attributes both the snow depth (HS) and HN to the date at which the measurement takes place. Measurements are usually carried out in the morning. For the SLF, HN is the sum of fallen new snow from the morning the day before until the morning of the measurement. In contrast to SLF, MeteoSwiss attributes HN to the day before the measurement (because the longer period is covered by the preceding day). This definition has changed over time on the observer sheet templates of MeteoSwiss, for example, HS was also attributed to the following day in the period 1974-1978 (see Figure 2). In some periods, there is no clear instruction on to what date a measurement should be assigned. Although logical, this change in conventions of MeteoSwiss/MZA snow measurements introduces several uncertainties to the data. The following error sources are possible:

1. Observers fill in the observer sheets intuitively (especially if sheet layout is ambiguous, see Figure 2) and do not follow the official date convention that is valid in that time period.
2. Persons that digitize data may or may not interpret the observer behavior.
3. When fed to the MeteoSwiss data warehouse, the data may or may not be corrected or shifted.

With the parallel station data from SLF and MeteoSwiss, it is possible to detect potential date shifts by cross-correlation of the two parallel HS and HN time-series respectively (assuming that above-mentioned date uncertainties are not occurring for SLF stations). The detected potential date-shifts are then verified by visual inspection of the two parallel series and looking at the original observer sheets. It turns out, that many combinations of shifted dates either in the observer sheets and/or in the digital Climap/IDAWEB data are indeed occurring at various MeteoSwiss stations for HN and HS respectively. With help of the parallel station, we corrected date shifts in the HN series in order to comply the definition of the SLF where a HN reading is attributed to the date of measurement for all parallel stations of MeteoSwiss.

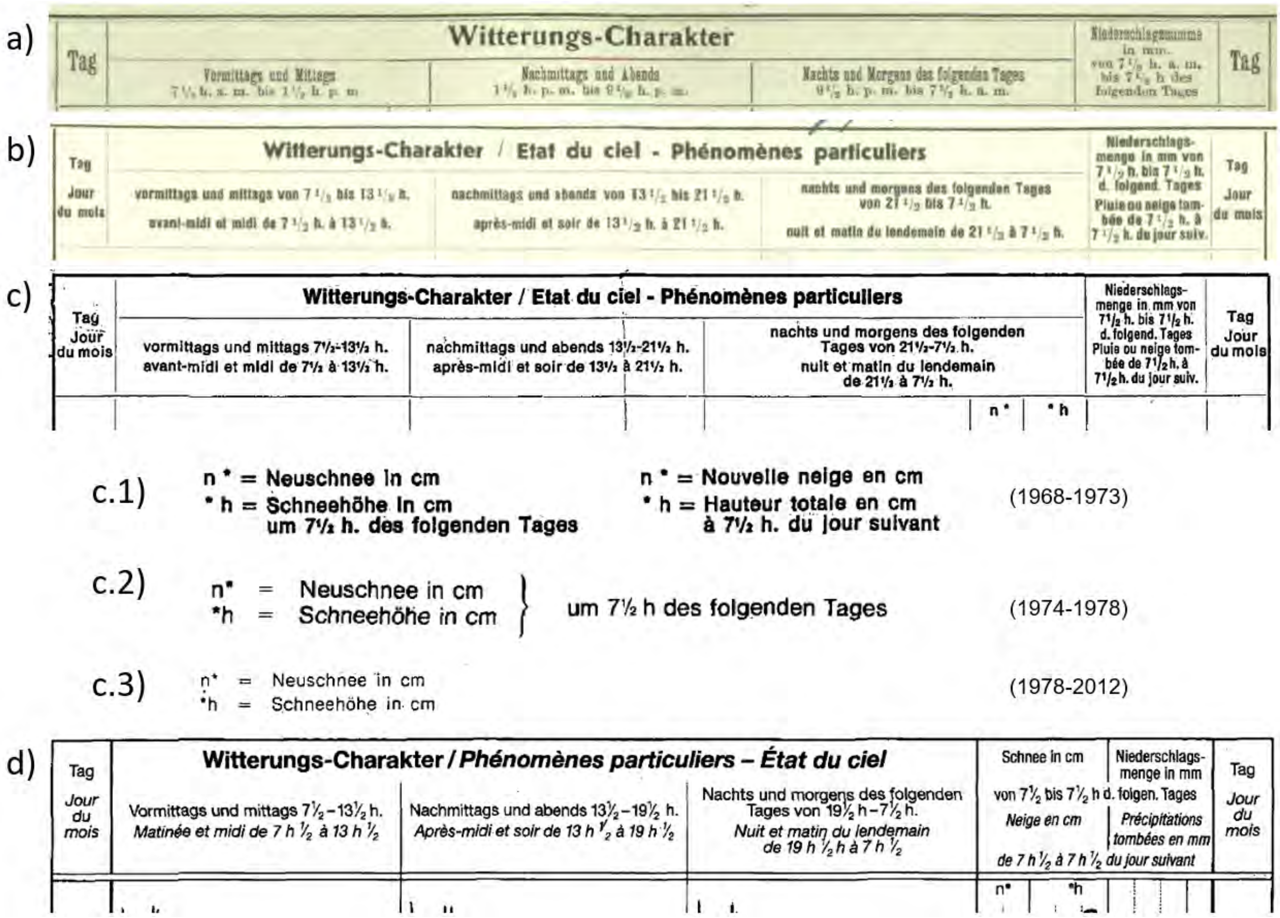


Figure 2: *Observer sheet headers and footnotes and their change over time for the MeteoSwiss Station Bernina. a) 1917-1958: no columns for snow in the header b) 1959-1967: no columns for snow in the header c) 1968-2001: dedicated columns for HN and HS in the header c1)- c3) different definitions of n* (HN) and *h (HS) in the footnote of the observer sheets e) 2002-2012: snow treated as precipitation in the header.*

4.2.3 Critical tests

After correcting the date shifts in the HN series, we conducted tests on the combined HS and HN time series. These tests search for events that are rather unlikely and have to be checked manually:

- *HS temporal inconsistency*
  Detect temporal breaks in the HS series. Check if a jump larger than 50 cm up or down is followed by subsequent jump larger than 50 cm in the other direction.

$$abs(HS[t] - HS[t-1]) > 50\,cm\ AND$$
$$abs(HS[t+1] - HS[t]) > 50\,cm\ AND$$
$$sign(HS[t] - HS[t-1]) \neq sign(HS[t+1] - HS[t])$$

- *HS increase-decrease*
  Detect breaks in the HS series by testing for unlikely high settlement after a snow fall event.

$$HS[t] - HS[t-1] > 30\,cm\ AND$$
$$HS[t+1] < (HS[t-1] + 10\,cm)$$

- *HS increase @ no HN*
  Test for cases where snow depth is increasing without any snow fall.

  $$HS[t] - HS[t-1] > 1\,cm\ AND\ HN[t] = 0$$

- *Zero HS @ HN*
  Test for cases where no snow depth was measured although new snow was recorded.

  $$HS[t] = 0\ AND\ HN[t] > 1\,cm$$

- *Strong HS decrease*
  Test for unlikely large melting events.

  $$HS[t] - HS[t-1] < -40\,cm$$

- *HS increase much larger HN*
  Test if the change in HS is much larger than the recorded amount of new snow.

  $$HN[t] > 0\ AND$$
  $$HS[t] - HS[t-1] > HN[t] + 30\,cm$$

- *HS change much lower HN*
  Test if the change in HS is much lower than the recorded amount of new snow.

  $$HN[t] > 0\ AND$$
  $$HS[t] - HS[t-1] < HN[t] - 30\,cm$$

- *Implausible HS*
  Test for implausible values of snow depth. These are defined as negative values and values larger than 700 cm.

  $$HS[t] < 0\ OR$$
  $$HS[t] > 700\,cm$$

- *Implausible HN*
  Test for implausible values of depth of snowfall. These are defined as negative values and values larger than 200cm.

  $$HN[t] < 0\ OR$$
  $$HN[t] > 200\,cm$$

We calculated these tests for all parallel stations and plotted occurrences of positive tests along with the data from the respective parallel station. From all positive tests we made a preselection, where we excluded cases where a test was positive but the data is still possible. This preselection was done based on the parallel station data and on data from other stations in the vicinity of the station in question. After the preselection, we looked in detail at the remaining cases and with help of neighboring stations corrected false data entries analogously to the method for filling short gaps of missing data (see Section 4.2.1).

4.2.4 HN inferred from HS

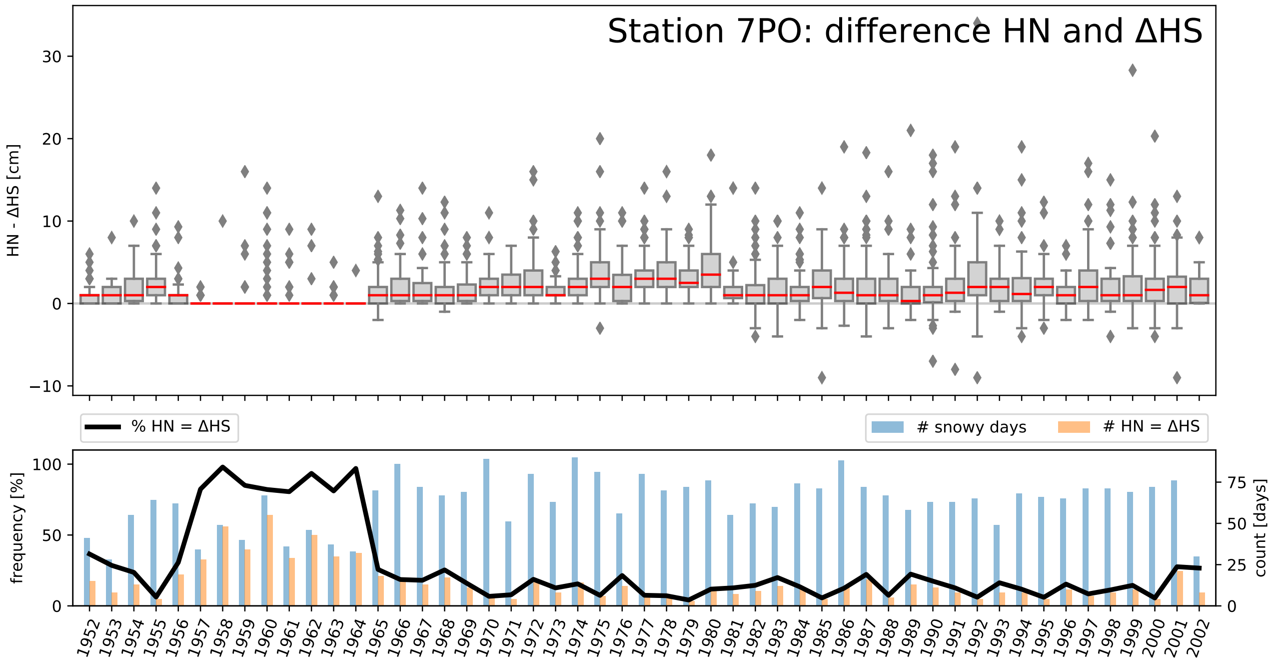


Figure 3: *Example investigation plot for determining whether a station has measured HN directly or calculated HN form HS measurements. In the top panel, the differences of HN and difference of HS and HS form the preceding day (ΔHS) at snowy days (HN > 0) are displayed as boxplots for each year. We can see a clear departure from "normal" observer behavior in the years 1957-1964. In this period, likely only HS was measured most of the time and HN is mostly calculated from the HS measurements.*

Table 2: *Stations and periods with low HN data quality. With the exception of stations 1LB, 7SC, GOS all others were operated by Rhaetian Railway (RhB).*

Station	Period(s) of low HN data quality
1LB	1955-1975, 1981-2000
5KU	1984-2010
5LQ	1966-2003
7BP	2007-2020
7BR	1952-1974
7CA	1952-1977, 1995-2020
7DI	1952-1971
7PO/PON	1957-1963
7PV	1952-1968
7SC	1996-1997, 2002
GOS	1962-1965
THS	1983- 1998

Due to metadata records, we know that the stations operated by the RhB at certain times only measured HS directly. There, HN data was "reconstructed" already by the observer by calculating the ΔHS. This behavior potentially has consequences on snow climate indices such as the sum of new snow over a winter. In order to verify that other stations did not do the same type of HN reconstruction from HS measurements, we made some benchmark tests. For each station, we plotted the difference of HN and ΔHS as one boxplot per year, where we only considered days where new snow was recorded. Additionally, we plotted the number of snowy days (HN > 0) and the number of snowy days where HN equals ∆HS for each year and calculated the ratio (see Figure 3 for an example). This gives a good overview on how frequently ∆HS = HN is typically occurring for stations that measure HN directly and that infer HN from ∆HS. Stations where ∆HS = HN is occurring in over 70% of the snowy days are likely to have calculated HN from HS measurements and required additional investigation. Accordingly, the stations and times that are suspicious regarding the quality of HN data are listed in Table 2.

4.2.5 Measurement rounding

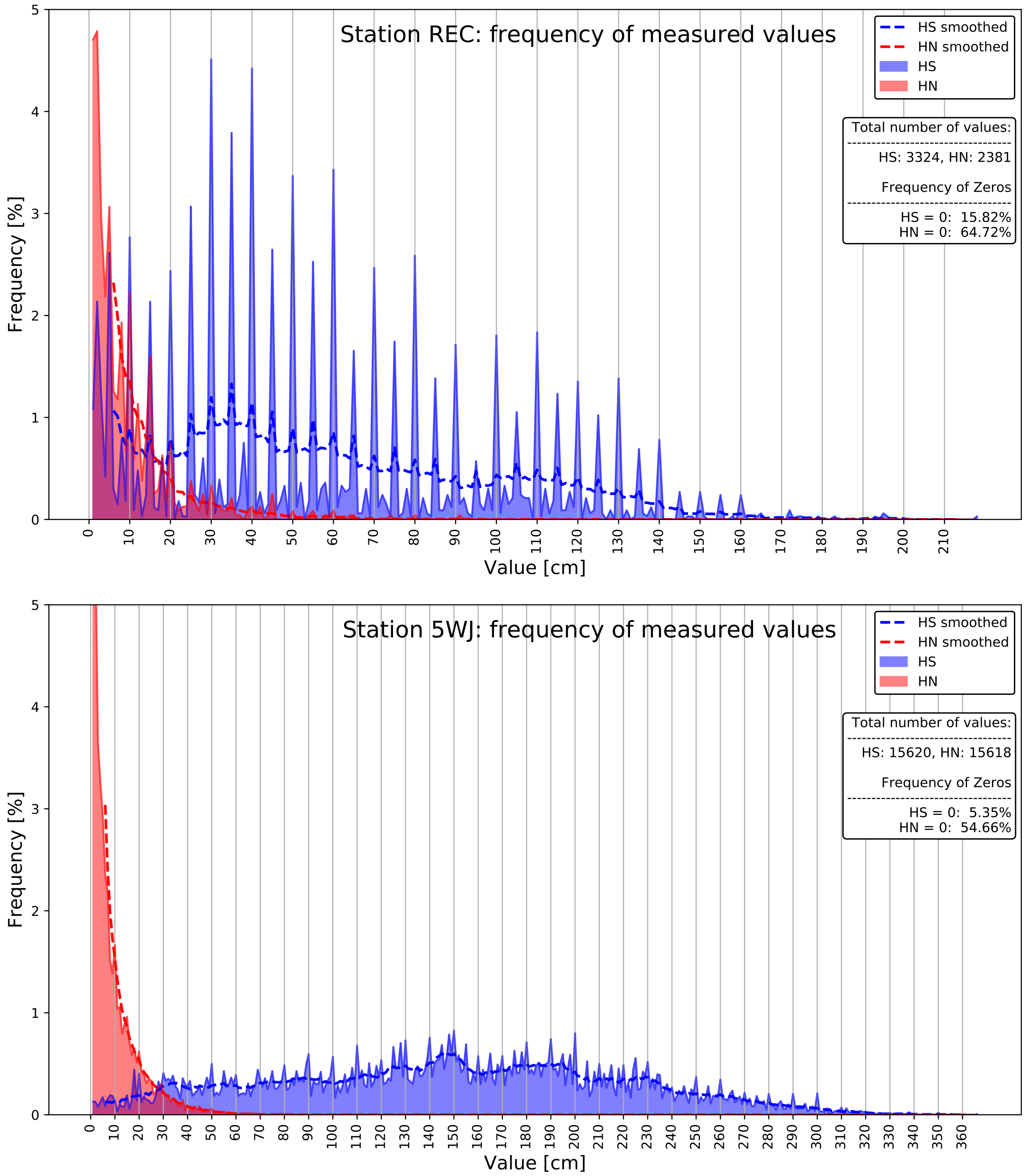


Figure 4: *Relative frequency of HS and HN measurement values (solid lines) in the winter months Nov-Apr for station REC at 1325 m a.s.l. (top) and station 5WJ at 2536 m a.s.l. (bottom). For comparison with a theoretical smooth distribution, dashed lines show unweighted moving averages with a window size of 10 for HS and HN. The station REC shows peaks in frequency for multiples of 5 and 10 in the HN and HS record. The station 5WJ also shows minor peaks for multiplies of 5 and 10 but not as pronounced as in station REC.*

When looking at distributions of measurement values for single stations, we can see spikes in the distribution for multiples of 5 and 10 for some stations (Figure 4). Obviously, human observers tend to round their measurements. In order to detect stations where measurement rounding is happening we calculate an even-odd-ratio where we average the ratios of the frequencies of multiples with the mean frequency of the neighboring odd values of the respective frequencies.

$$\text{even-odd-ratio} = \text{mean}(\text{freq}(\text{multiples of x})/\text{mean}(\text{freq}(\text{neighboring odds}))) \tag{4.1}$$

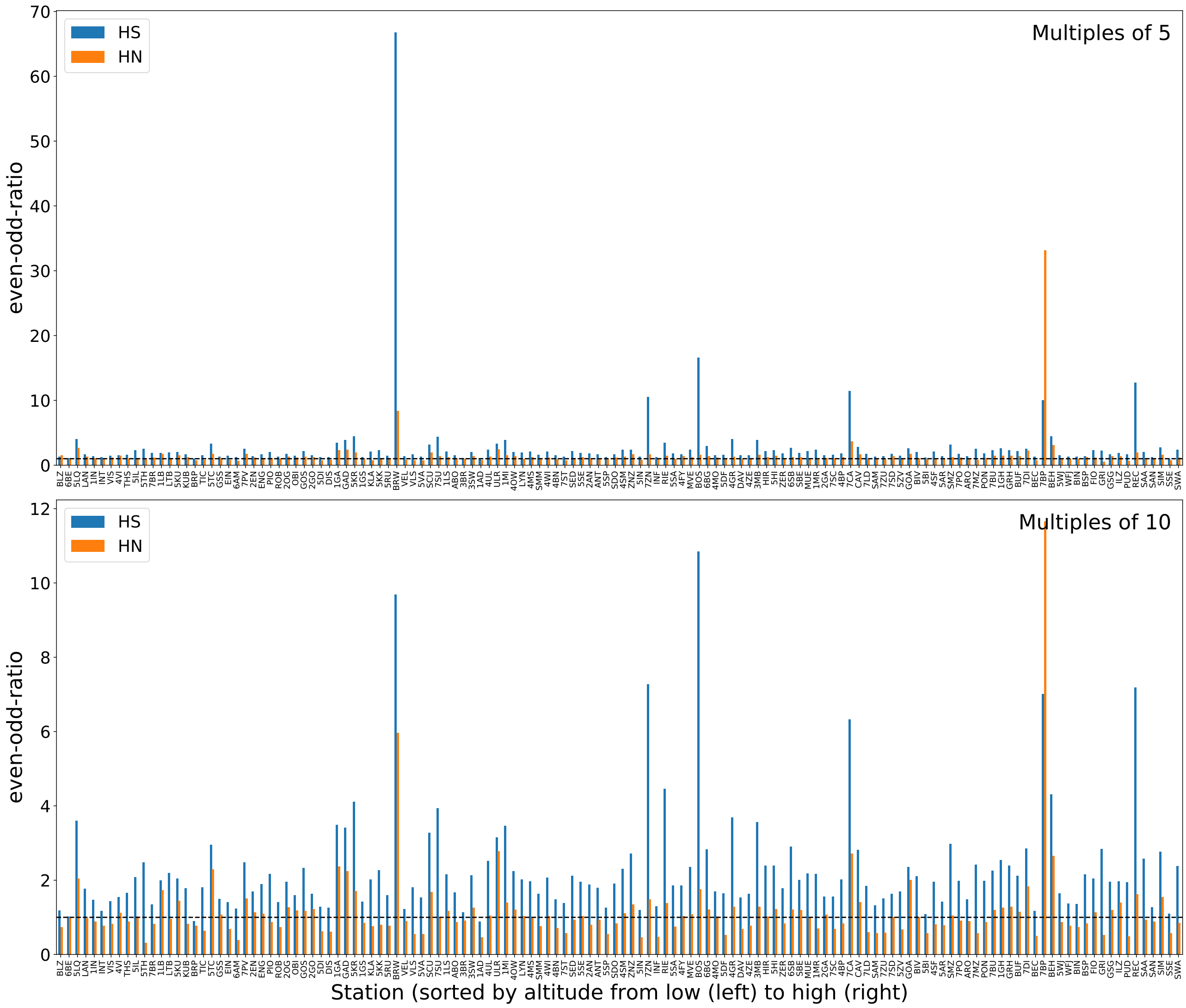


Figure 5: *Ratios of multiples of 5 (top) and multiples of 10 (bottom) frequency versus average neighboring non-multiples frequency for the different parallel stations.*

The result of the measurement rounding test shows that there is a high bias in the data towards multiples of 10 for some stations (e.g. stations BRW, BOS, 7BP, see Figure 5). Although the effect is more pronounced for the HS data, rounding is occurring both for HS and HN data. Rounding is possibly originating from the scale printed on the measurement stakes or due to a psychological effect. It is not easily possible to correct this behavior subsequently (especially for HN as HN series are not continuous time-series). For analyzing yearly or monthly climate indices (such as days with snow or maximum snow depth), there will most likely not be a large impact. However, when looking at the sum of new snow or the mean snow depth, there can be an effect due to rounded measurements (see Figure 6). Due to the highly skewed distribution of measured HN values, rounding up to the next "even" value will be more likely than rounding to the next lower value. The effect is probably also considerable when measures such as the number days with HS > 5cm per winter are used as snow climate indices. We are aware of measurement rounding in the parallel station dataset but we did not see a way to get rid of this rounding effect in the data.

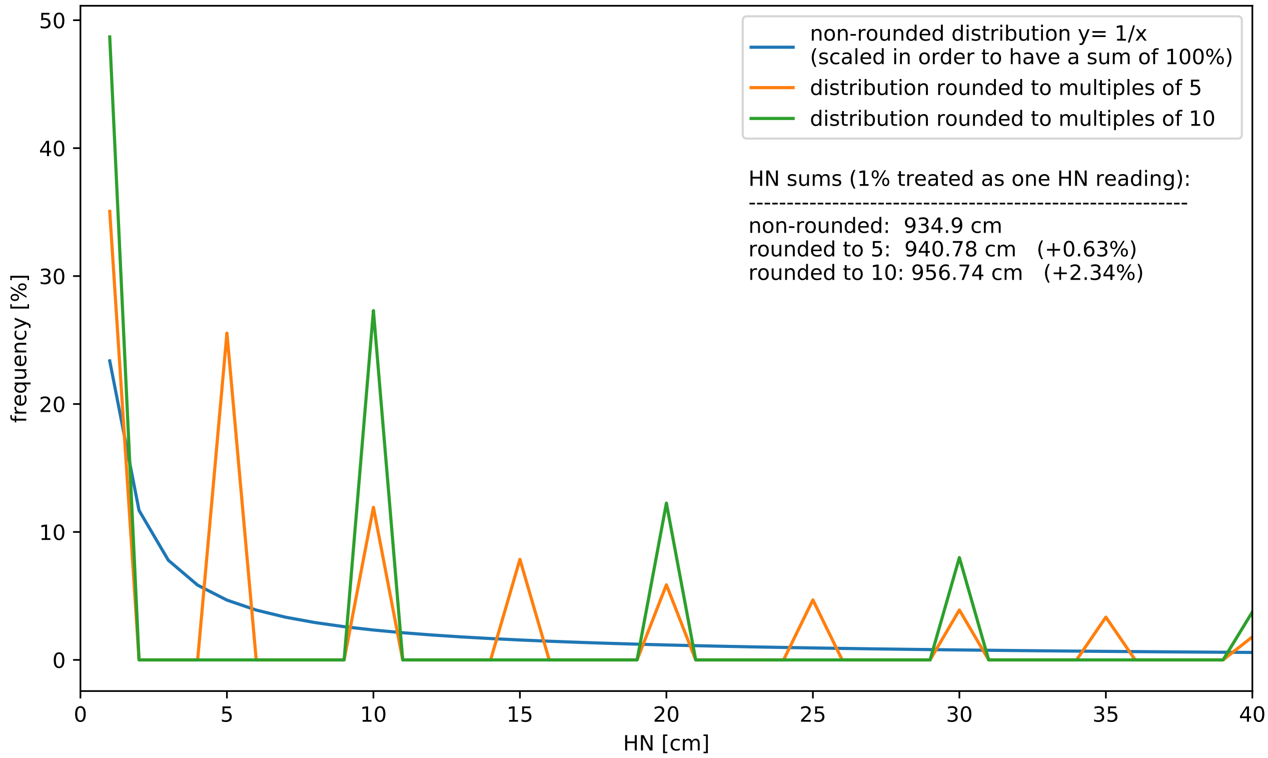


Figure 6: *Effect of measurement rounding on the sum of new snow based on a synthetic measurement distribution. We used a synthetic HN distribution of y=1/x for $x \in \mathbb{N}$, $1 \leq x \leq 40$ and scaled it in order to have a sum of 100% for all values between 1 cm and 40 cm (blue line). We then rounded the synthetic distribution to multiples of 5 (orange line) and 10 (green line). Values which would usually be rounded to zero have been rounded to 1. Finally, we calculated the "sum of new snow" by treating 1% in the distributions as one HN measurement for all three synthetic distributions.*

4.2.6 Consecutive HS values

Closely related to measurement rounding are consecutive runs of the same HS value. One would expect that if an observer was recording the exact same value for more than 10 days, something unlikely has happened to the snow cover. We therefore measure the lengths of windows with consecutive values, while ignoring zeros and nans and then count how frequently long consecutive windows occur (Figure 7). The found cases of long consecutive values were manually checked but in most cases not corrected.

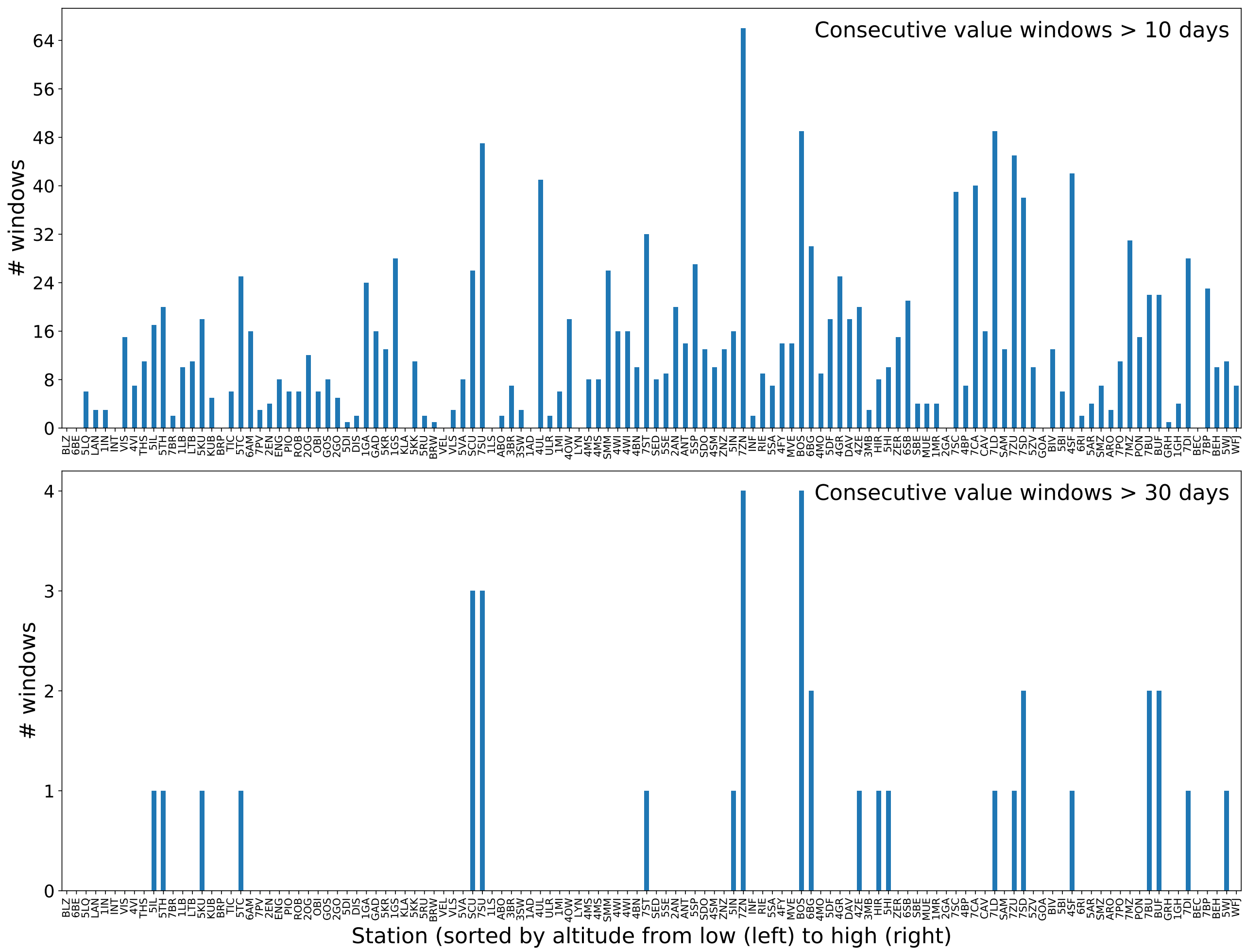
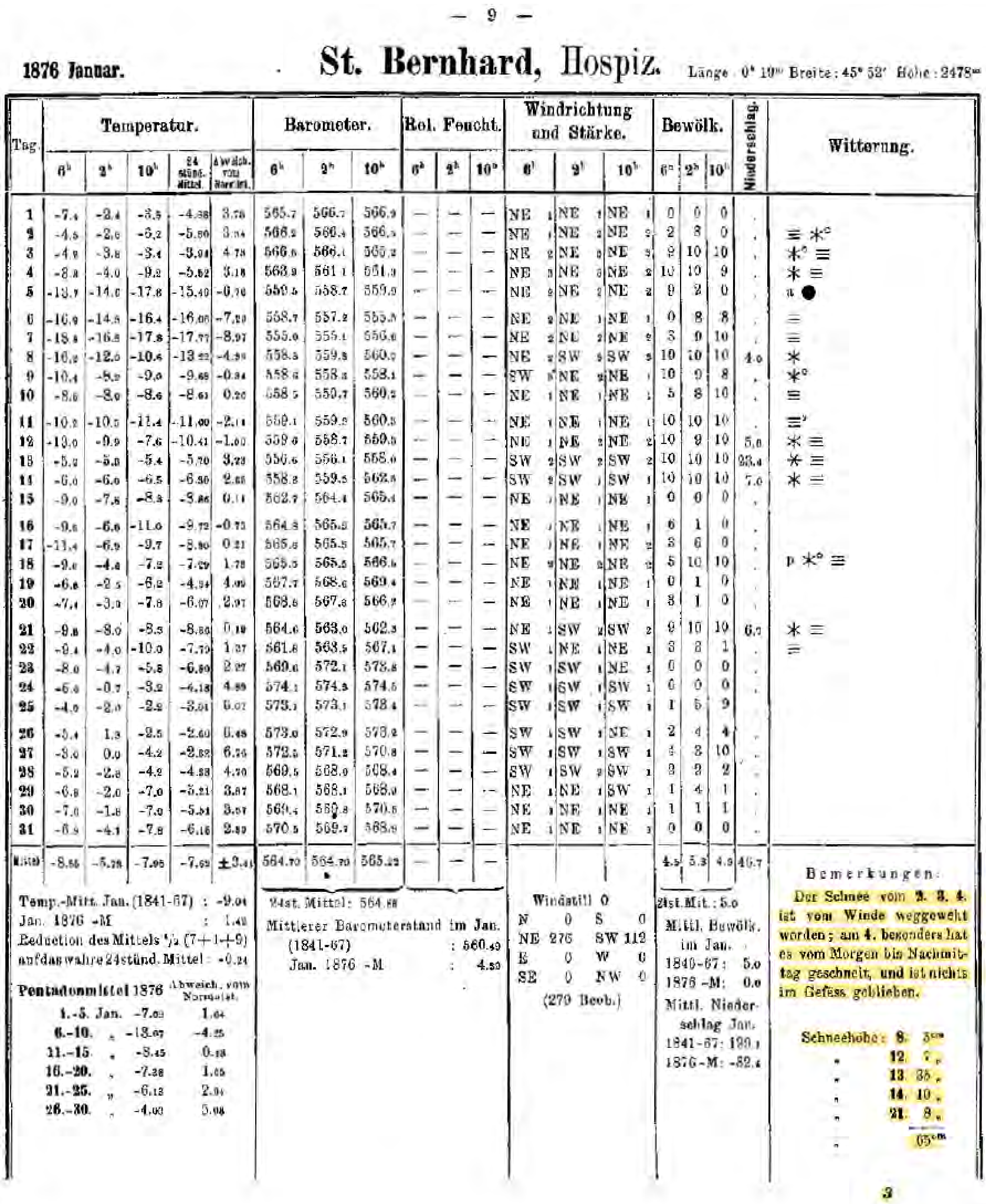


Figure 7: *Number of consecutive value windows longer than 10 days (top) and 30 days (bottom) for the different stations in the parallel station dataset.*

5. Short history of snow measurements

When working with historic environmental data such as depth of snowfall or snow depth, there is always the uncertainty of how trustworthy the recorded data is since historic measurements often lack sufficient metadata. Let us look at the example of depth of snowfall: as most meteorological services were at first hand interested in regular weather observations such as temperature, air pressure and precipitation, the focus was most likely rather on the water equivalent of the precipitated new snow than on its depth. However, we do not know if the observers directly recorded the depth of snowfall or the water equivalent of snowfall collected in the rain gauge. Snowfall amount given with a precision in tenth of centimeter in the early decades of snow measurements may indicate the latter.



— 9 —

1876 Januar. **St. Bernhard, Hospiz.** Länge 0° 19'' Breite: 45° 52' Höhe: 2478m

Tag	Temperatur. 6h	2h	10h	24 stünd. Mittel	Abweich. vom Normal.	Barometer. 6h	2h	10h	Rel. Feucht. 6h	2h	10h	Windrichtung und Stärke. 6h	2h	10h	Bewölk. 6h	2h	10h	Niederschlag.	Witterung.
1	-7.4	-2.4	-3.5	-4.38	3.78	565.7	566.7	566.9	—	—	—	NE 1	NE 1	NE 1	0	0	0	.	
2	-4.5	-2.6	-5.2	-5.80	3.34	566.2	566.4	566.5	—	—	—	NE 1	NE 2	NE 2	2	3	0	.	≡ ✱°
3	-4.9	-3.8	-3.4	-3.94	4.78	566.6	566.1	565.2	—	—	—	NE 2	NE 3	NE 3	9	10	10	.	✱° ≡
4	-8.3	-4.0	-9.2	-5.62	3.18	563.9	561.1	561.3	—	—	—	NE 3	NE 3	NE 2	10	10	9	.	✱ ≡
5	-13.7	-14.6	-17.8	-15.40	-0.76	559.5	558.7	559.9	—	—	—	NE 2	NE 2	NE 2	9	2	0	.	n ●
6	-16.9	-14.5	-16.4	-16.06	-7.20	558.7	557.2	555.5	—	—	—	NE 2	NE 1	NE 1	0	8	8	.	≡
7	-18.8	-16.8	-17.8	-17.77	-8.97	555.0	555.1	556.6	—	—	—	NE 2	NE 2	NE 2	3	9	10	,	≡
8	-16.2	-12.5	-10.6	-13.22	-4.30	558.3	559.8	560.0	—	—	—	NE 2	SW 3	SW 3	10	10	10	4.0	✱
9	-10.4	-8.2	-9.0	-9.65	-0.34	558.6	558.3	558.1	—	—	—	SW 1	NE 2	NE 1	10	9	8	.	✱°
10	-8.6	-8.0	-8.6	-8.61	0.26	558.5	559.7	560.2	—	—	—	NE 1	NE 1	NE 1	5	8	10	.	≡
11	-10.2	-10.5	-11.4	-11.00	-2.11	559.1	559.2	560.3	—	—	—	NE 1	NE 1	NE 1	10	10	10	.	≡'
12	-13.0	-9.9	-7.6	-10.41	-1.60	559.6	558.7	559.5	—	—	—	NE 1	NE 2	NE 2	10	9	10	5.0	✱ ≡
13	-5.2	-5.3	-5.4	-5.70	3.23	556.6	556.1	558.0	—	—	—	SW 2	SW 2	SW 2	10	10	10	23.4	✱ ≡
14	-6.0	-6.0	-6.5	-6.30	2.66	558.2	559.5	562.8	—	—	—	SW 2	SW 1	SW 1	10	10	10	7.0	✱ ≡
15	-9.0	-7.8	-8.3	-8.86	0.11	562.7	564.4	565.4	—	—	—	NE 1	NE 1	NE 1	0	0	0	.	
16	-9.6	-6.6	-11.0	-9.72	-0.73	564.8	565.5	565.7	—	—	—	NE 1	NE 1	NE 1	6	1	0	.	
17	-11.4	-6.9	-9.7	-8.90	0.21	565.6	565.5	565.7	—	—	—	NE 1	NE 1	NE 2	3	6	0	.	
18	-9.0	-4.8	-7.2	-7.29	1.78	565.5	565.5	566.6	—	—	—	NE 2	NE 2	NE 2	5	10	10	.	p ✱° ≡
19	-6.8	-2.5	-6.2	-4.94	4.09	567.7	568.6	569.4	—	—	—	NE 1	NE 1	NE 1	0	1	0	.	
20	-7.4	-3.0	-7.8	-6.07	2.97	568.6	567.8	566.9	—	—	—	NE 1	NE 1	NE 1	3	1	0	.	
21	-9.8	-8.0	-8.5	-8.80	0.19	564.6	563.0	562.3	—	—	—	NE 1	SW 2	SW 2	9	10	10	6.7	✱ ≡
22	-9.4	-4.0	-10.0	-7.70	1.37	561.8	563.5	567.1	—	—	—	SW 1	NE 1	NE 1	3	8	1	.	≡
23	-8.0	-4.7	-5.8	-6.80	2.27	569.6	572.1	573.8	—	—	—	SW 1	SW 1	NE 1	0	0	0	.	
24	-6.0	-0.7	-3.2	-4.18	4.89	574.1	574.3	574.5	—	—	—	SW 1	SW 1	SW 1	0	0	0	.	
25	-4.0	-2.0	-2.2	-3.01	6.07	573.1	573.1	573.4	—	—	—	SW 1	SW 1	SW 1	1	5	9		
26	-5.4	1.3	-2.5	-2.60	6.48	573.0	572.9	573.2	—	—	—	SW 1	SW 1	NE 1	2	4	4	.	
27	-3.0	0.0	-4.2	-2.82	6.76	572.5	571.2	570.8	—	—	—	SW 1	SW 1	SW 1	4	3	10	.	
28	-5.2	-2.8	-4.2	-4.33	4.70	569.5	568.9	568.4	—	—	—	SW 1	SW 2	SW 1	3	2	2	.	
29	-6.8	-2.0	-7.0	-5.21	3.87	568.1	568.1	568.0	—	—	—	NE 1	NE 1	SW 1	1	4	1	.	
30	-7.0	-1.8	-7.0	-5.51	3.57	569.4	569.8	570.5	—	—	—	NE 1	NE 1	NE 1	1	1	1		
31	-6.9	-4.1	-7.8	-6.16	2.49	570.5	569.7	568.9	—	—	—	NE 1	NE 1	NE 1	0	0	0	..	
Mittel	-8.55	-5.28	-7.05	-7.62	±3.41	564.70	564.70	565.22	—	—	—				4.5	5.3	4.9	46.7	

Temp.-Mitt. Jan. (1841-67) : -9.04
Jan. 1876 -M : 1.42
Reduction des Mittels ⅓ (7+1+9) auf das wahre 24stünd. Mittel : -0.24

Pentadenmittel 1876 — Abweich. vom Normalst.

1.-5. Jan.	-7.03	1.04
6.-10. „	-13.67	-4.25
11.-15. „	-8.45	0.18
16.-20. „	-7.38	1.05
21.-25. „	-6.13	2.04
26.-30. „	-4.03	5.08

24st. Mittel: 564.88
Mittlerer Barometerstand im Jan. (1841-67) : 560.49
Jan. 1876 -M : 4.30

Windstill 0
N 0 S 0
NE 276 SW 112
E 0 W 0
SE 0 NW 0
(279 Beob.)

24st. Mit.: 5.0
Mittl. Bewölk. im Jan.
1840-67: 5.0
1876 -M: 0.0
Mittl. Niederschlag Jan.
1841-67: 199.1
1876-M: -82.4

Bemerkungen:
Der Schnee vom 2. 3. 4. ist vom Winde weggeweht worden; am 4. besonders hat es vom Morgen bis Nachmittag geschneit, und ist nichts im Gefäss geblieben.

Schneehöhe: 8. 3cm
„ 12. 7 „
„ 13. 35 „
„ 14. 10 „
„ 21. 8 „
„ 65cm

3

Figure 8: *Odd information regarding occurrence of snowfall and snow measurement. The comment and temperature implies that there was a lot of snowfall on the 4th January 1876. However, they did not measure any new snow, because wind hindered snow from coming into the rain gauge. This leads to our interpretation, that new snow values were measured inside the rain gauge at least at this station.*

To solve these uncertainties, it is important to know how the measurements were organized and carried out and what focus the meteorological organizations had when they recorded snow parameters. For this purpose, the following chapter tries to reconstruct the history of snow measurements in Switzerland and compares the measurement practices to other countries. When trying to get insights into how people started to measure HN and HS systematically in Switzerland, the most informative source are the “Meterologische[n] Beobachtungen” or later “Annalen” which were annually published by the Swiss meteorological agency from 1864 until 2010 and instruction manuals for observers published in irregular intervals by the Swiss meteorological agency. In the following, we chronologically list information regarding snow measurement practices and their documentation in Switzerland and other countries:

1863 A manual for Observers at Swiss weather stations is published by the MZA in 1863 (Mousson, 1863). Snow that is collected in the rain gauge should be melted and the water content be measured. Additionally, the observers are asked to make notes on the first and last appearance of snow in the winter and to record the “depth of the snow in centimeters” in the comments section of the station.

1864 In line with Mousson (1863), the first “Annalen” issue of the MZA treats snow related information as side notes and there is no systematic measurement of neither depth of snowfall nor snow depth (Wolf, 1864). In the monthly overview tables for each station that are published in the annals, a column next to the precipitation column states the nature of the precipitation (i.e. “Schnee”, “neige”). Below the monthly tables, snow depthis occasionally documented within miscellaneous notes. However, it is often uncertain whether depth of snowfall or snow depth is recorded.

1867 Inside the annals of 1867, an article on red snow in Switzerland is published (Killias, 1867). The author formulates the hypothesis that the red snow is originating from Sahara dust. Besides this special attention on snow in the mentioned article, the monthly overview tables are identical to 1864 regarding snow measurements.

1873 The International Congress in Vienna introduces symbols for weather phenomena that should be documented at every station. A star symbol shall be written next to the precipitation record in case the precipitation is solid (Hellmann, 1907). In the preceding years, the MZA has already recorded the phase of precipitation in their annals with written notes on the nature of precipitation.

1876 The symbols for weather phenomena introduced at the International Meteorological Congress in Vienna get implemented in the annals of the MZA in in 1876 (Wolf, 1876). It is still unclear, how new snow measurements are carried out. Whether measurements are carried on a board on the ground or on the snow surface as done today or in some kind of vessel or with a completely different methodology remains unclear. A comment below a monthly table in the annals can be interpreted in the sense, that snow was measured in a vessel (Annalen 1876, page 9, see Figure 11). However, the mentioned “Gefäss” could also be used to measure liquid precipitation and was not necessarily used for snow measurements.

1889 First notes on the snow depth ("mittlere Höhe der Schneedecke") below some monthly station overview tables. Additionally, remarks on the snowfall limit elevation are reported by the observers.

1891 Snow measurements are in detail discussed at the International Meteorological Conference which took in Munich in 1981. The summary protocol by Scott (1892) summarizes the outcome as follows:

> *Snow.*— Special attention was directed to the subject of snow lying on the ground, and it was decided to employ a symbol ⧆ to indicate that more than half of the country surrounding a station was covered with snow.
>
> It is resolved to collect and print information as to the practices of snow collection and measurement at present in force.

Regarding new snow measurements, the difficulties of the exact snow measurements have been discussed but no resolution was passed in Munich (Hellmann, 1907). Subsequent to the conference, all meteorological institutions which attended the conference were asked to report their practices on snow measurements. The responses to this letter of inquiry were then collected in the attachments to the comprehensive protocol (Erk, 1891). Overall, 20 weather services replied, the measurement practices are summarized in Table 3.

Almost all of the weather services (19) measure water equivalent of snowfall (HNW). Most of them do so by collecting the snow in the rain gauge and melting it. However, the meteorological offices are beginning to become aware of the fact that rain gauge collections are associated with substantial undercatch rates. Several weather services started to collect snow in different apparatuses and study the effect of different windshields on the undercatch (e.g. St. Petersburg or Elssass-Lothringen). Some weather services measure HNW by cutting snow from the ground with a cylinder and then measuring it, which is close to the methodology applied nowadays. No single weather service is measuring the depth of snowfall systematically. Only the MZA states that HN measurements are desirable, but not how they should be carried out. Some countries (e.g. Canada, USA) use depth of snowfall measurements to estimate the HNW at windy conditions when they think undercatch was obviously too high. In 1891, the focus was clearly on the fallen amount of water rather than on the deposition. This is probably due to the fact, that the weather services wanted to have continuous time series for the amount of precipitation. About two thirds (13) of the weather services measure in some way the snow depth of the accumulated snow on the ground. However, various different methodologies are used and often HS is recorded at irregular intervals and not systematically. Only two weather services (Königl. Preuss. Meteorologisches Institut, Berlin & Königl. bayerische Meteorologische Centralstation, München) measure SWE of the total snow cover systematically.

1893 An update of the manual for observers increases the level of detail regarding observations of snow in Switzerland (Schweizerische Meteorologische Centralanstalt, 1893). For the first time, a board for measuring the depth of snowfall is mentioned (p. 22). We did not find any reference worldwide, that mentions new snow measurements with a board prior to this publication. In contrast, some states in Germany explicitly forbid to use a board for measuring new snow due to concerns of heat flux alterations (see Table 3). However, the instruction of 1893 stays unclear if the new snow board should be placed on top of an existing snow cover as done today or if it should be placed on the ground.

> *«[. . .]; daher ist es unerlässlich, dass neben der Messung des erhaltenen Schmelzwassers auch die Höhe des gefallenen Schnees in Centimetern notiert wird. Zu diesem Zwecke lege man an einem vor Verwehungen möglichst geschützten Ort ein Brett horizontal aus und messe vormittags 7 h mittelst Masstab direkt die Höhe des frisch gefallenen Schnees, der dann immer wieder weggewischt werden muss. Ausserdem soll von Zeit zu Zeit, jedenfalls nach jedem bedeutenderen Schneefall und ebenso bei rascher Abnahme der Schneedecke (womöglich täglich) die totale Höhe der Schneelage ermittelt und unter dem betreffenden Datum notiert werden.»*

1895 In 1895, the MZA implements the order from the Conference in Munich in their annals. From now on, the monthly tables are accompanied with a sign for more than 50% snow covered ground (star in a square). However, still no snow depth and depth of snowfall measurements are documented systematically. If an observer recorded these variables, the data is presented below the monthly station tables. Most of the stations report values for snow depth and snow depth, but only in irregular intervals. The exact methodology for the depth of snowfall measurements is still unknown.

1901 The German weather service publishes snow depth in a dedicated column in their annals (International Meteorological Committee 1903). The annals of the MZA change their format: supplementary notes on weather conditions, where the occasionally measured snow data is included, are bundled for all stations in a separate section after the data tables.

1903 The meteorological Conference in Southport discusses the matter of snow measurements again (International Meteorological Committee, 1903). Gustav Hellmann from the German weather service proposes to make snow depth a mandatory measurement variable at every station. After discussion, the participants decide to stick with the order from the Conference in Munich (1891) to record only the presence of snow but considers actual depth measurements “desirable”.

1942 The WSL Institute for Snow and Avalanche Research SLF is founded at Weissfluhjoch in Davos. In the following years, the SLF starts to build up a separate network of snow measurement stations besides the already existing network of MeteoSwiss. The majority of the SLF stations are operated during the winter months from October until end of April.

From 1958/1959 In 1958/1959, the MZA measures snow continuously at 50% of their stations in the station network due to more easy data processing with punched cards (Schlüepp et al. 1980). Additionally, snow becomes increasingly important for winter tourism industry. Consequently, snow depth is displayed in the annals of the MZA in a dedicated column as of 1960.

1966 The MZA is equipped for punched card data processing at the whole station network. All observer stations of the MZA record the depth of snowfall and the snow depth (Schlüepp et al. 1980).

Despite the alpine topography, snow did not get as much attention in Switzerland as in other countries in the late 19th century. However, the snow depth and the depth of snowfall were measured in irregular intervals at many stations. This irregular data could be used for extending snow time series further back into the past by interpolation techniques. However, there will be high uncertainties in the reconstructed, interpolated series due to several reasons which are i) at stations with only little snow, it is often unclear whether the depth of snowfall or the snow depth is measured, ii) we do not know the measurement technique for the depth of snowfall and iii) often the measurements were carried out at snow fall events, but it is not guaranteed that every snow fall event was captured. From 1895, the Boolean series of snow present vs. no snow present is continuously available for Swiss stations. This information can possibly be used to extract climatic variables such as the first and last day of snow in a winter and the number of snow days. However, the definition of "snow present" has very likely changed over time or is probably not treated consistently over all stations. No exact observation time of the "snow day" is documented in the observer manuals. Observations could happen anytime in the day and are thus not comparable with the morning observations of today. Additionally, the observer manual from 1893 instructs the observers to document snow days if more than 50% of the surrounding of a station is covered with snow. Therefore it can happen, that one observer looks at the surrounding of a station in kilometer scale and another observer in meter scale.

6. Conclusion and limitations

All foreseen tasks could be fulfilled. These tasks are the following:

- identification of the independent parallel data series
- digitization of missing snow data from original observer sheets
- interpolation of short gaps (less than one winter) in the time series was accomplished
- the application of numerous quality control algorithms worked well
- the collection of and compilation of snow related metadata per station is completed
- the compilation of information about the history of snow measurements was successful

The only exception is the original goal to perform a consistency check between the snow data and already quality checked precipitation data from MeteoSwiss. This goal had to be given up for three reasons: First, due to illogical and changing measurement forms, the actual day of the of the new snow measurement is often one day off during several years. Secondly, different procedures to digitize this data and to fill it in the database during the last few decades caused this day shift either to disappear, to remain or in the worst case to double. Occasionally, even the daily snow depth values were affected by these procedures. Thirdly, as we learned from MeteoSwiss during the investigation, the daily precipitation data can also be affected by this issue for the same reasons. This issue is so far not affecting our main analysis as we focus on seasonal or monthly values.

Even though we quality controlled the digitized data, our experience of the last months shows that we still find erroneous values in the course of the Hom4Snow project. As the data quality still might improve, we decided to deliver the digitized data set to GCOS Switzerland and MeteoSwiss as soon as the Hom4Snow project will be finished (2024) in order to avoid different versions.

We had to learn that the exact location of the former snow measurements has a much higher uncertainty than the location of main meteorological elements like temperature or precipitation, because they were often (especially after automation) measured in separate locations, whose coordinates were not recorded. The first Paper of the Hom4Snow project (Buchmann, Begert, Brönnimann, & Marty, 2020), using the first part of the compiled data, demonstrated that the collected data provides a unique data set of parallel snow measurements for the investigation of the sensitivity of different snow climate indicators on changes in the measurement environment.

7. Outreach

We contributed to the EGU general assembly in May 2020, which covered our work regarding the interpolation of long data gaps in snow depth time series:

> Aschauer J., Bavay M., Begert M. & Marty C. (2020): Comparing methods for gap filling in historical snow depth time series. In EGU General Assembly Conference Abstracts (p. 17211).

We contributed to the 10th Seminar for Homogenization and Quality Control and 5th Conference on Spatial Interpolation Techniques in Climatology and Meteorology in October 2020, organized by the Hungarian Meteorological Service.

> Buchmann M., Aschauer J., Broennimann S., Begert M. & Marty C. (2020): Evaluating the robustness of snow climate indicators using a unique set of parallel snow measurement series.

8. Outlook

There some stations (not only those part of the parallel data set), which have a high quality of available snow data, a long history going back to the beginning of the 20_{th} century, a complete data availability with the exception that 1-10 years are missing for a certain time period. We therefore already made some limited preliminary investigation about the performance of different methods to fill these g aps. We would like to include simple spatial interpolation methods and regression based spatial interpolation methods as well as temperature index-based model approaches. A further investigation would include a comparison of the above-mentioned temperature index models with the SNOWGRID model (Olefs et al., 2013) of the Austrian Meteorological Service ZAMG. Another question that should be answered is whether it is better to first interpolate meteorological variables (temperature and precipitation) and then model snow depth with a temperature index approach or whether direct spatial interpolation of snow depth should be preferred in case there is no meteorological data at a station. The former approach would benefit from the fact, that especially in early times temperature and precipitation are measured in a much denser network than snow depth. We hope to be able to write a paper about the performance of these different approaches to fill gaps in time series with missing data.

Depending on available resources such methods and the digitization of more time series (see Section 4.1) would provide more long-term time series. Such data series, especially in the first half of the last century, are an inevitable base for the so far limited number of available reference series during this time period. These reference series are necessary for any future homogenization efforts.

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List of Abbreviations

EGU	European Geosciences Union
ETH	Swiss Federal Institute of Technology
GCOS	Global Climate Observing System
GIDS	gradient-plus-inverse-distance-squared
HN	depth of snowfall
HNW	water equivalent of snowfall
HS	snow depth
△HS	difference of HS and HS form the preceding day
IDS	inverse distance squared
LASSO	least absolute shrinkage and selection operator
MAAPE	mean arctangent absolute percentage error
MeteoSwiss	Federal Office of Meteorology and Climatology
MZA	Schweizerische Meteorologische Zentralanstalt
PCA	principal component analysis
RhB	Rhaetian Railway
RMSE	root-mean-squared error
SLF	WSL Institute for Snow and Avalanche Research SLF
SMA	Schweizerische Meterologische Anstalt
SNSF	Swiss National Science Foundation
STAGE	station history
SWE	snow water equivalent
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research
ZAMG	Central Institution for Meteorology and Geodynamics

A. Additional tables

Table 3: *Snow measurement practices in the different meteorological measurement networks in 1891.*

Measurement Network	snow cover observations	solid precipitation observations	Miscellaneous	HS	SWE	HN	HNW
Deutsche Seewarte, Hamburg	Total snow depth (HS) measurements at various locations where snow is distributed evenly. The average of the measurements is recorded. No snow rod.	No HN measurements. For HNW, new snow is captured in pluviometer, melted and measured.	-	✓	✗	✗	✓
Königl. Preuss. Meteorologisches Institut, Berlin	HS measured with snow rod at the end of the week. SWE and density of the total snow cover are measured every 5th day by sinking a cylinder of known area in the snow, melting and measuring water content.	No HN measurements. SWE of new snow is measured by sinking a cylinder of known area in the snow at a site that is kept clear from snow. An underlying board is explicitly not allowed due to concerns regarding heat flux alterations.	-	✓	✓	✗	✓
Königl. bayerische Meteorologische Centralstation, München	Daily HS measurements with snow rod. SWE of total snow cover is measured every 6th day analogously to the approach used in Preussen.	No HN measurements. SWE of new snow is measured by sinking a cylinder of known area in the snow at a site that is kept clear from snow. An underlying board is explicitly not allowed due to concerns regarding heat flux alterations.	HS measured since 1986/1987, SWE/Density measured since 1891/1892 analogously to the approach used in Preussen	✓	✓	✗	✓
Centralbureau für Meteorologie und Hydrographie im Grossherzogthum Baden, Karlsruhe	HS measurements with snow rod.	No HN measurements. New snow is captured in pluviometer, melted and measured.	-	✓	✗	✗	✓
Königlich Württembergisches statistisches Landesamt, Meteorologische Centralstation, Stuttgart	No information regarding HS measurements.	No HN measurements. New snow is captured in a "collecting vessel", melted and measured. Collecting vessel is probably the pluviometer.	-	✗	✗	✗	✓

Measurement Network	snow cover observations	solid precipitation observations	Miscellaneous	HS	SWE	HN	HNW
Meteorologischer Landesdienst Elsass-Lothringen, Strassburg	HS measurement with 2 snow rods at locations with different slope aspect.	No HN measurements. New snow is captured in two different collecting vessel", melted and measured. The collecting vessel are a Hellmann pluviometer with windshield construction and a wooden box (opening of 1 m^2, "deep enough that snow is not blown out")	only one station is measuring snow (Gebweiler Belchen, 1425m)	✓	✗	✗	✓
Königl. säcHS. meteorologisches Institut, Chemnitz	The presence of a snow cover is recorded (with three grades of thickness). Actual HS measurements with snow rod only at few stations.	No HN measurements. No information on SWE measurements.	-	✓	✗	✗	✗
Schweizerische Meteorologische Centralanstalt	Occasional HS measurements at "suitable site". No information on methodology.	HN measurements are "desired" but neither mandatory nor systematic. Snow is melted and measured in collecting vessels. Vessels at high altitude stations have double height (70cm) compared to the ones normally used.	Observers are instructed as follows "auch direct die Höhe sowohl des frisch gefallenen Schnees, als auch von Zeit zu Zeit der totalen Höhe der Schneedecke an einem hiezu geeigneten Ort zu ermitteln und in der Tabelle unter dem betreffenden Datum zu notiren."	✗	✗	✗	✓
K. K. Centralanstalt für Meteorologie und Erdmagnetismus, Wien	No information regarding HS measurements.	No HN measurements. New snow is captured in pluviometer, melted and measured.		✗	✗	✗	✓
Physikalisches Centralobservatorium St. Petersburg	Since Fall 1889 "Beobachtungen über die Schneedecke". Since Fall 1890 HS measurements with snow rod at 1200 stations.	No HN measurements. New snow is captured in pluviometer, melted and measured.	St. Petersburg sends in a detailed report on the effect of different kinds of rain gauges (with different wind shield constructions) on the measured new snow water equivalent values.	✓	✗	✗	✓

Measurement Network	snow cover observations	solid precipitation observations	Miscellaneous	HS	SWE	HN	HNW
Privater Beobachtungsdienst für Niederschlagsmessung in Livland, Dorpat	No HS measurements.	No HN measurements. New snow is captured in pluviometer, melted and measured.		✗	✗	✗	✓
Meteorologiska Centralanstalten, Stockholm	Observers make a note on the presence of a snow cover and measure snow depth in irregular intervals.	No HN measurements. New snow is captured in pluviometer, melted and measured.	-	✓	✗	✗	✓
Norwegisches Meteorologisches Institut, Christiania	No information regarding HS measurements.	No HN measurements. New snow is captured in pluviometer, melted and measured.	-	✗	✗	✗	✓
Dänisches Meteorologisches Institut, Kopenhagen	No HS measurements.	No HN measurements. New snow is captured, melted and liquid water content is measured.		✗	✗	✗	✓
Royal Meteorological Society, London	"It is also desirable to measure with a foot rule the depth of snow in several places where it has not drifted."	No HN measurements. New snow is captured in pluviometer, melted and measured.		✓	✗	✗	✓
Observatoire Royal de Belgique	Observers are instructed to note the presence and the height of snow. No information on methodology of the latter.	No HN measurements. New snow is captured in pluviometer, melted and measured.		✓	✗	✗	✓
Kgl. Niederländisches Meteorolog. Institut, Utrecht.	On some occasions when a heavy snow fall is observed, the real thickness of the snow cover is computed by piercing a stick in the snow and observing how many centimeters this can be gone on several spots before touching the frozen soil.	No HN measurements. New snow is captured in pluviometer, melted and measured.		✓	✗	✗	✓

Measurement Network	snow cover observations	solid precipitation observations	Miscellaneous	HS	SWE	HN	HNW
Societa meteorol. Italiana, Moncalieri	Some kind of snow depth measurement is carried out, but no information on methodology: "Dans nos Stations de montagne on mesure d'abord l'hauteur de la neige sur lo sol"	No HN measurements. New snow is captured in pluviometer, melted and measured.	The correspondence from Italy admits that the observers are not trained in measuring snow.	✓	✗	✗	✓
U. S. Weather Bureau, Washington	"actual depth of snow is measured in inches", no information on measurement instrumentation.	No HN measurements. New snow is captured in a collecting vessel, melted and measured. If there was a lot of wind, the (new) snow height is measured and SWE is estimated as 1/10 of the snow height. No information on how they measure new snow height.		✓	✗	✗	✓
Meteorological Service of Canada, Toronto	No information regarding HS measurements. But obviously there has to be some kind of HS measurement (see notes on SWE measurements).	No HN measurements. SWE is estimated as 1/10 of the (new) snow height. No information on how they measure new snow height. In some instances, SWE is measured by "sinking a cylinder of the same area as a rain-gauge into the snow and then melting and measuring the quantity in the usual manner with a graduated rain measure."	The director Charles Carpmael answers as following: "In reply I would say that by a series of experiments made at Toronto some years ago it was found from a number of observations, that an average of ten inches of snow was equivalent to one inch of rain, accordingly this measurement was adopted throughout Canada. In a few instances our Observers adopt the plan of sinking a cylinder of the same area as a rain-gauge into the snow and then melting and measuring the quantity in the usual manner with a graduated rain measure."	✗	✗	✗	✓

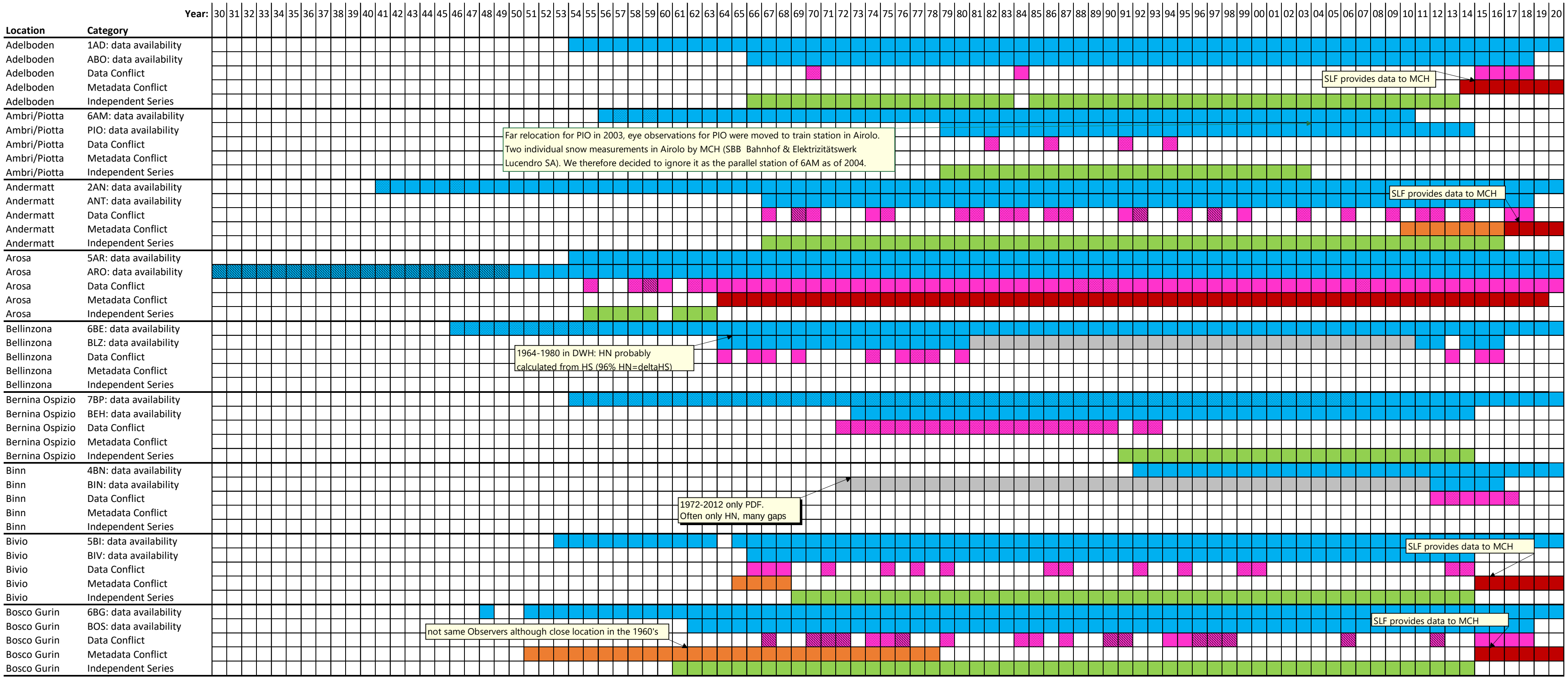
Table 4: *Overview table for the parallel snow measurement station pairs in Switzerland. One station pair refers to five rows, each column refers to one hydrological year. For each station pair, there are two rows indicating data availability in station A and station B (blue colors), one row indicating a data conflict i.e. high correlation (r>0.99) between the time series of the two parallel stations (pink color), one row showing metadata conflicts (same observer and/or close location, orange/red colors) and one line which marks independent measurements in a certain hydrological year (green).*

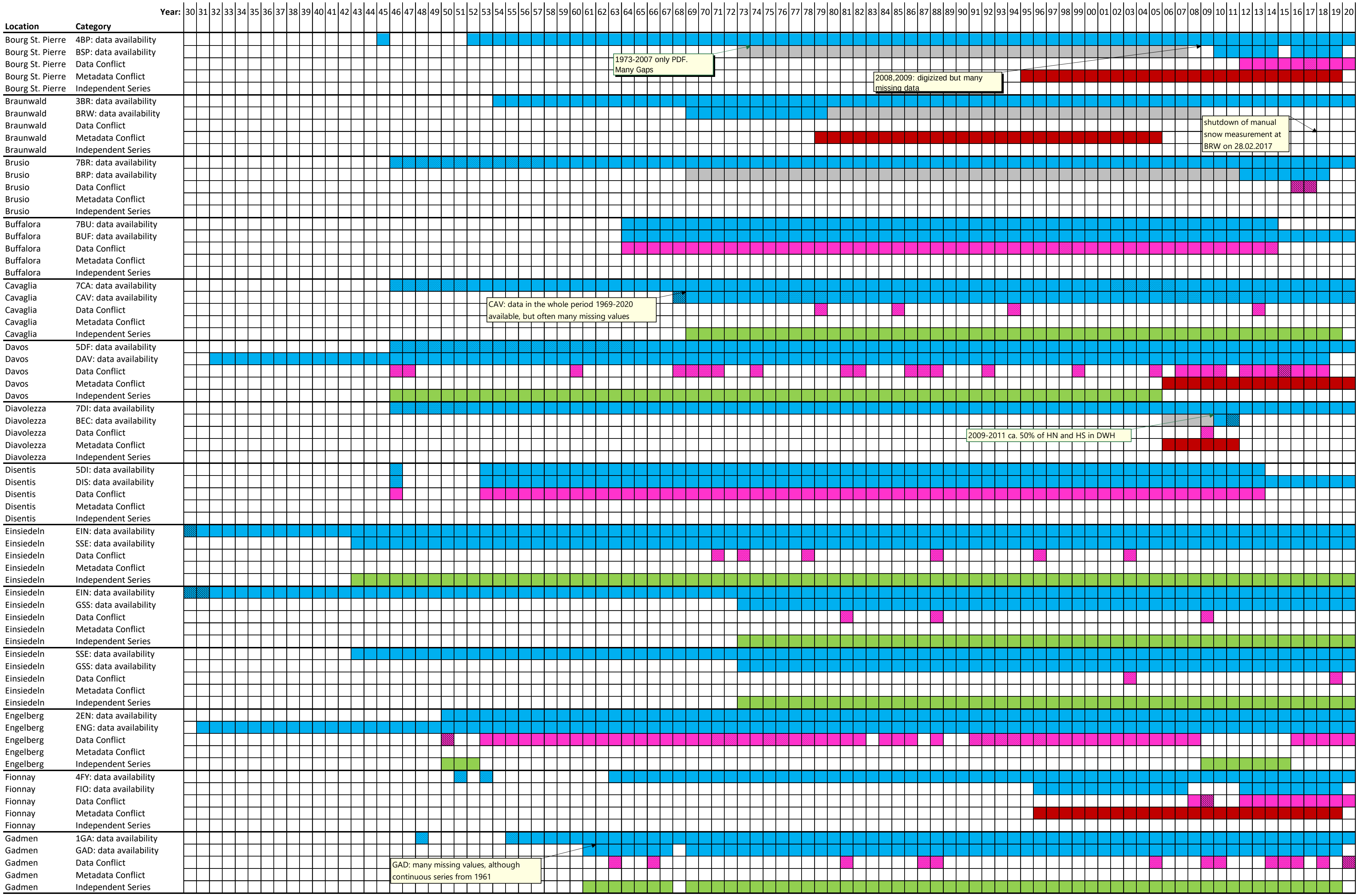
Legend

Legend	
HN and HS available *	(1)
only HS available *	(2)
only HN available *	(3)
same Observer	(4)
close/same Location	(5)
same Observer, close Location	(6)
independent Series	(7)
likely identical HS and HN **	(8)
likely identical HS **	(9)
likely identical HN **	(10)
data available only on PDF	(11)

* (1), (2), (3): at least 50% of the data available in digital form in one winter season (Nov-Apr)

** (8), (9), (10): very high correlation coefficients (r>0.99) in the respective winter

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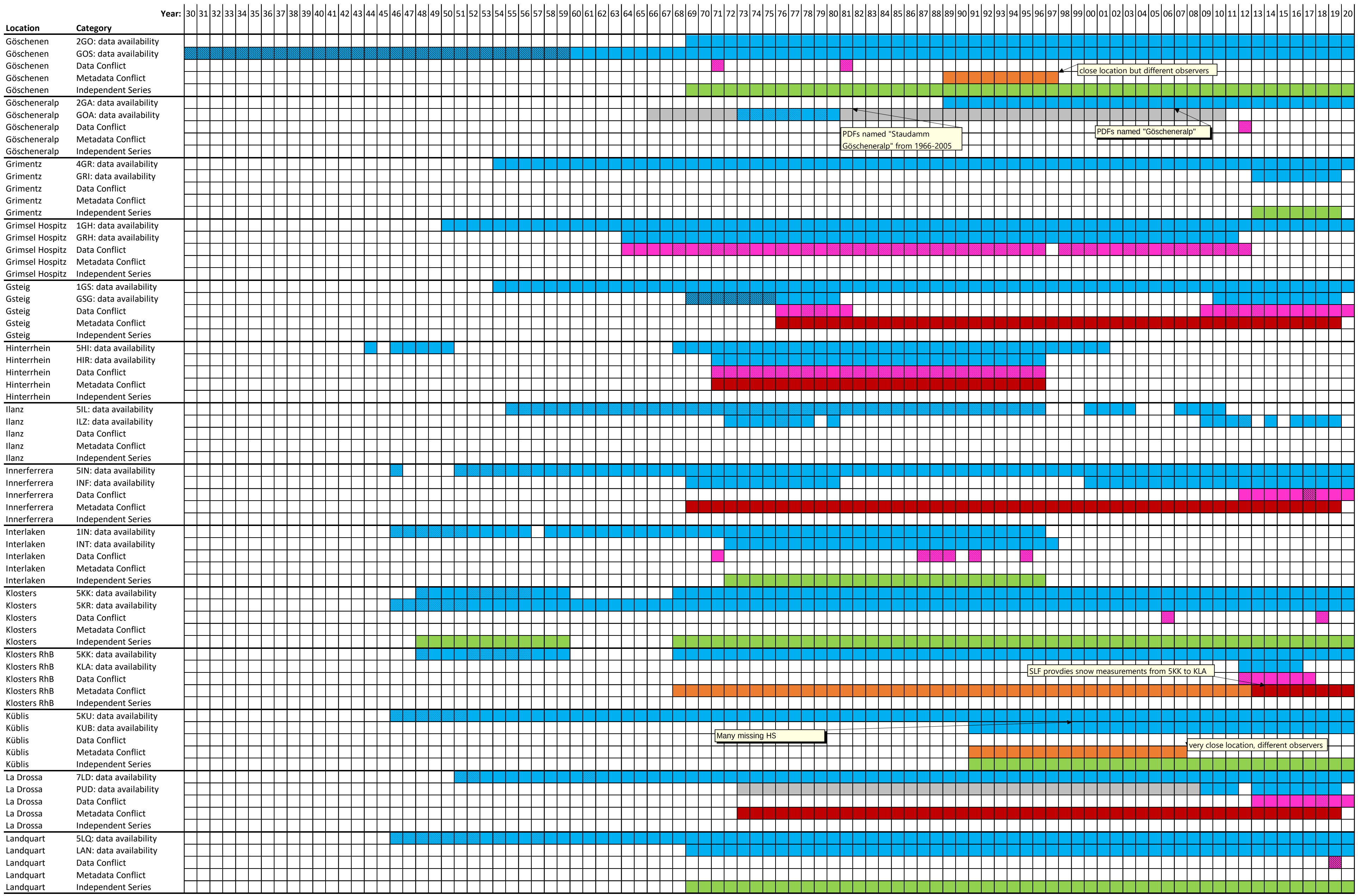
Location
Category
Bourg St. Pierre 4BP: data availability
Bourg St. Pierre BSP: data availability
Bourg St. Pierre Data Conflict
Bourg St. Pierre Metadata Conflict
Bourg St. Pierre Independent Series
1973-2007 only PDF. Many Gaps
2008,2009: digizized but many missing data
Braunwald 3BR: data availability
Braunwald BRW: data availability
Braunwald Data Conflict
Braunwald Metadata Conflict
Braunwald Independent Series
shutdown of manual snow measurement at BRW on 28.02.2017
Brusio 7BR: data availability
Brusio BRP: data availability
Brusio Data Conflict
Brusio Metadata Conflict
Brusio Independent Series
Buffalora 7BU: data availability
Buffalora BUF: data availability
Buffalora Data Conflict
Buffalora Metadata Conflict
Buffalora Independent Series
Cavaglia 7CA: data availability
Cavaglia CAV: data availability
Cavaglia Data Conflict
Cavaglia Metadata Conflict
Cavaglia Independent Series
CAV: data in the whole period 1969-2020 available, but often many missing values
Davos 5DF: data availability
Davos DAV: data availability
Davos Data Conflict
Davos Metadata Conflict
Davos Independent Series
Diavolezza 7DI: data availability
Diavolezza BEC: data availability
Diavolezza Data Conflict
Diavolezza Metadata Conflict
Diavolezza Independent Series
2009-2011 ca. 50% of HN and HS in DWH
Disentis 5DI: data availability
Disentis DIS: data availability
Disentis Data Conflict
Disentis Metadata Conflict
Disentis Independent Series
Einsiedeln EIN: data availability
Einsiedeln SSE: data availability
Einsiedeln Data Conflict
Einsiedeln Metadata Conflict
Einsiedeln Independent Series
Einsiedeln EIN: data availability
Einsiedeln GSS: data availability
Einsiedeln Data Conflict
Einsiedeln Metadata Conflict
Einsiedeln Independent Series
Einsiedeln SSE: data availability
Einsiedeln GSS: data availability
Einsiedeln Data Conflict
Einsiedeln Metadata Conflict
Einsiedeln Independent Series
Engelberg 2EN: data availability
Engelberg ENG: data availability
Engelberg Data Conflict
Engelberg Metadata Conflict
Engelberg Independent Series
Fionnay 4FY: data availability
Fionnay FIO: data availability
Fionnay Data Conflict
Fionnay Metadata Conflict
Fionnay Independent Series
Gadmen 1GA: data availability
Gadmen GAD: data availability
Gadmen Data Conflict
Gadmen Metadata Conflict
Gadmen Independent Series
GAD: many missing values, although continuous series from 1961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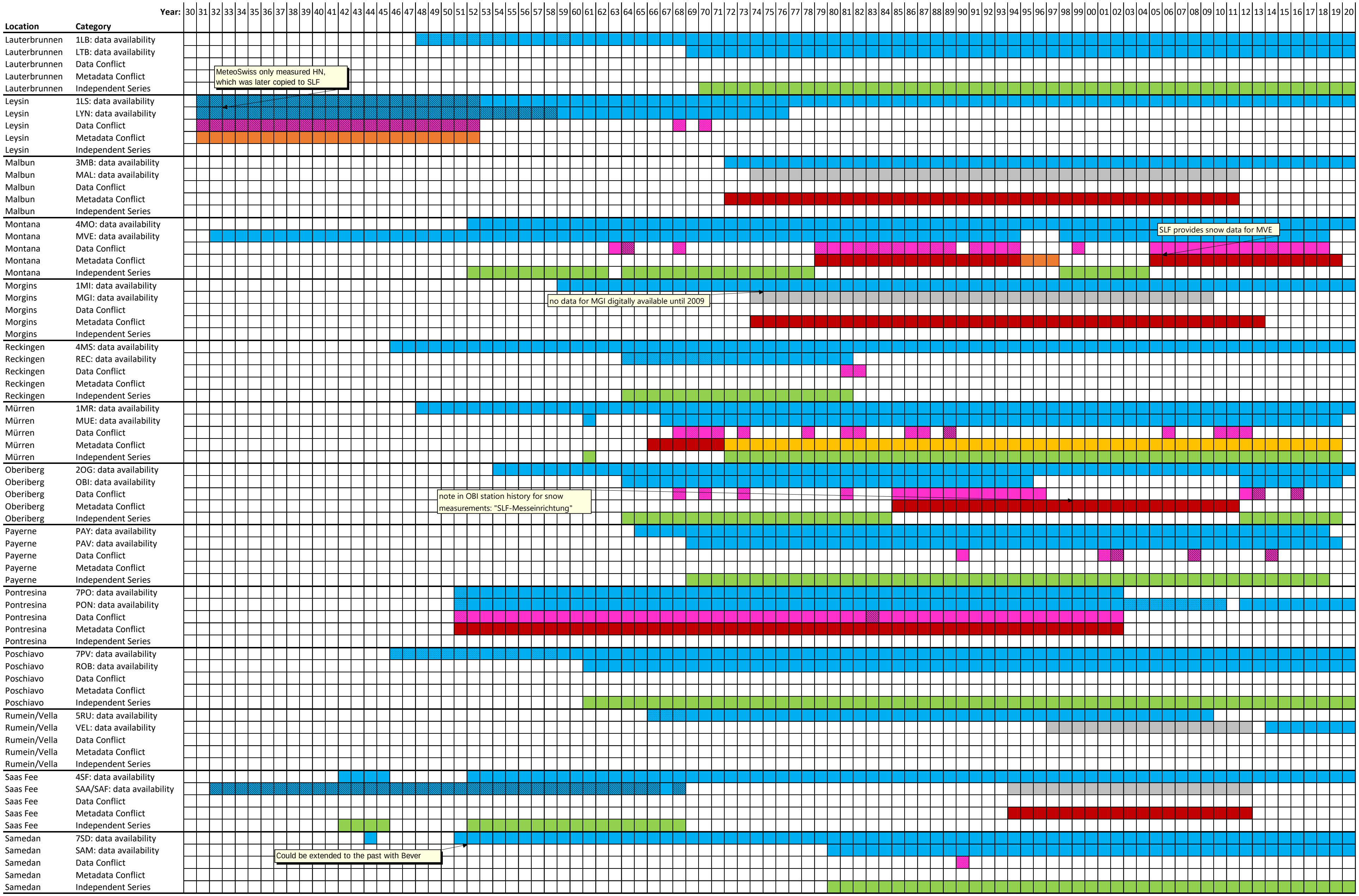
Location
Category
Göschenen 2GO: data availability
Göschenen GOS: data availability
Göschenen Data Conflict
Göschenen Metadata Conflict
Göschenen Independent Series
Göscheneralp 2GA: data availability
Göscheneralp GOA: data availability
Göscheneralp Data Conflict
Göscheneralp Metadata Conflict
Göscheneralp Independent Series
Grimentz 4GR: data availability
Grimentz GRI: data availability
Grimentz Data Conflict
Grimentz Metadata Conflict
Grimentz Independent Series
Grimsel Hospitz 1GH: data availability
Grimsel Hospitz GRH: data availability
Grimsel Hospitz Data Conflict
Grimsel Hospitz Metadata Conflict
Grimsel Hospitz Independent Series
Gsteig 1GS: data availability
Gsteig GSG: data availability
Gsteig Data Conflict
Gsteig Metadata Conflict
Gsteig Independent Series
Hinterrhein 5HI: data availability
Hinterrhein HIR: data availability
Hinterrhein Data Conflict
Hinterrhein Metadata Conflict
Hinterrhein Independent Series
Ilanz 5IL: data availability
Ilanz ILZ: data availability
Ilanz Data Conflict
Ilanz Metadata Conflict
Ilanz Independent Series
Innerferrera 5IN: data availability
Innerferrera INF: data availability
Innerferrera Data Conflict
Innerferrera Metadata Conflict
Innerferrera Independent Series
Interlaken 1IN: data availability
Interlaken INT: data availability
Interlaken Data Conflict
Interlaken Metadata Conflict
Interlaken Independent Series
Klosters 5KK: data availability
Klosters 5KR: data availability
Klosters Data Conflict
Klosters Metadata Conflict
Klosters Independent Series
Klosters RhB 5KK: data availability
Klosters RhB KLA: data availability
Klosters RhB Data Conflict
Klosters RhB Metadata Conflict
Klosters RhB Independent Series
Küblis 5KU: data availability
Küblis KUB: data availability
Küblis Data Conflict
Küblis Metadata Conflict
Küblis Independent Series
La Drossa 7LD: data availability
La Drossa PUD: data availability
La Drossa Data Conflict
La Drossa Metadata Conflict
La Drossa Independent Series
Landquart 5LQ: data availability
Landquart LAN: data availability
Landquart Data Conflict
Landquart Metadata Conflict
Landquart Independent Series
close location but different observers
PDFs named "Staudamm Göscheneralp" from 1966-2005
PDFs named "Göscheneralp"
SLF provdies snow measurements from 5KK to KLA
Many missing HS
very close location, different observers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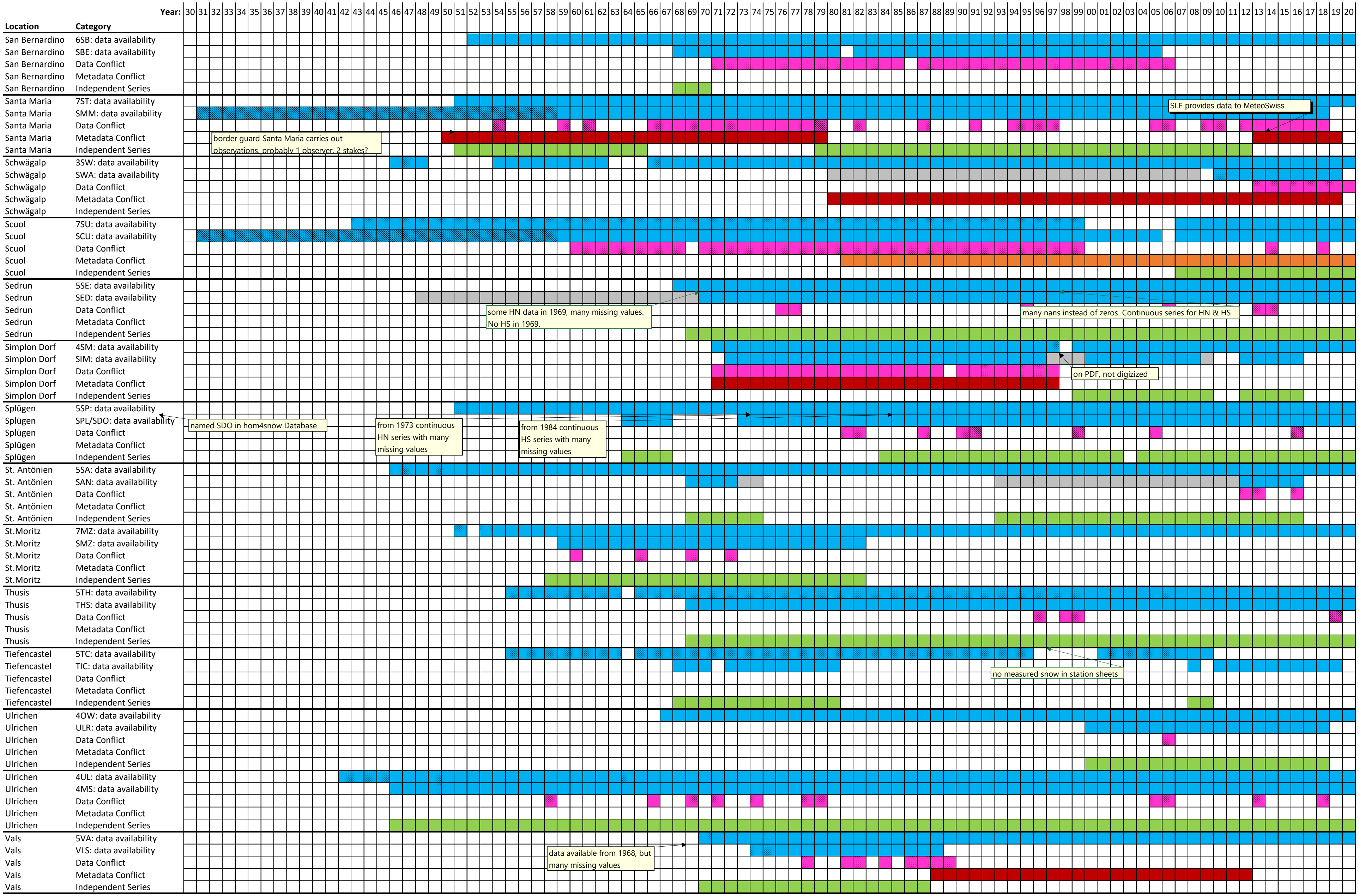
Location
Category
Lauterbrunnen 1LB: data availability
Lauterbrunnen LTB: data availability
Lauterbrunnen Data Conflict
Lauterbrunnen Metadata Conflict
Lauterbrunnen Independent Series
Leysin 1LS: data availability
Leysin LYN: data availability
Leysin Data Conflict
Leysin Metadata Conflict
Leysin Independent Series
Malbun 3MB: data availability
Malbun MAL: data availability
Malbun Data Conflict
Malbun Metadata Conflict
Malbun Independent Series
Montana 4MO: data availability
Montana MVE: data availability
Montana Data Conflict
Montana Metadata Conflict
Montana Independent Series
Morgins 1MI: data availability
Morgins MGI: data availability
Morgins Data Conflict
Morgins Metadata Conflict
Morgins Independent Series
Reckingen 4MS: data availability
Reckingen REC: data availability
Reckingen Data Conflict
Reckingen Metadata Conflict
Reckingen Independent Series
Mürren 1MR: data availability
Mürren MUE: data availability
Mürren Data Conflict
Mürren Metadata Conflict
Mürren Independent Series
Oberiberg 2OG: data availability
Oberiberg OBI: data availability
Oberiberg Data Conflict
Oberiberg Metadata Conflict
Oberiberg Independent Series
Payerne PAY: data availability
Payerne PAV: data availability
Payerne Data Conflict
Payerne Metadata Conflict
Payerne Independent Series
Pontresina 7PO: data availability
Pontresina PON: data availability
Pontresina Data Conflict
Pontresina Metadata Conflict
Pontresina Independent Series
Poschiavo 7PV: data availability
Poschiavo ROB: data availability
Poschiavo Data Conflict
Poschiavo Metadata Conflict
Poschiavo Independent Series
Rumein/Vella 5RU: data availability
Rumein/Vella VEL: data availability
Rumein/Vella Data Conflict
Rumein/Vella Metadata Conflict
Rumein/Vella Independent Series
Saas Fee 4SF: data availability
Saas Fee SAA/SAF: data availability
Saas Fee Data Conflict
Saas Fee Metadata Conflict
Saas Fee Independent Series
Samedan 7SD: data availability
Samedan SAM: data availability
Samedan Data Conflict
Samedan Metadata Conflict
Samedan Independent Series
MeteoSwiss only measured HN, which was later copied to SLF
SLF provides snow data for MVE
no data for MGI digitally available until 2009
note in OBI station history for snow measurements: "SLF-Messeinrichtung"
Could be extended to the past with Bever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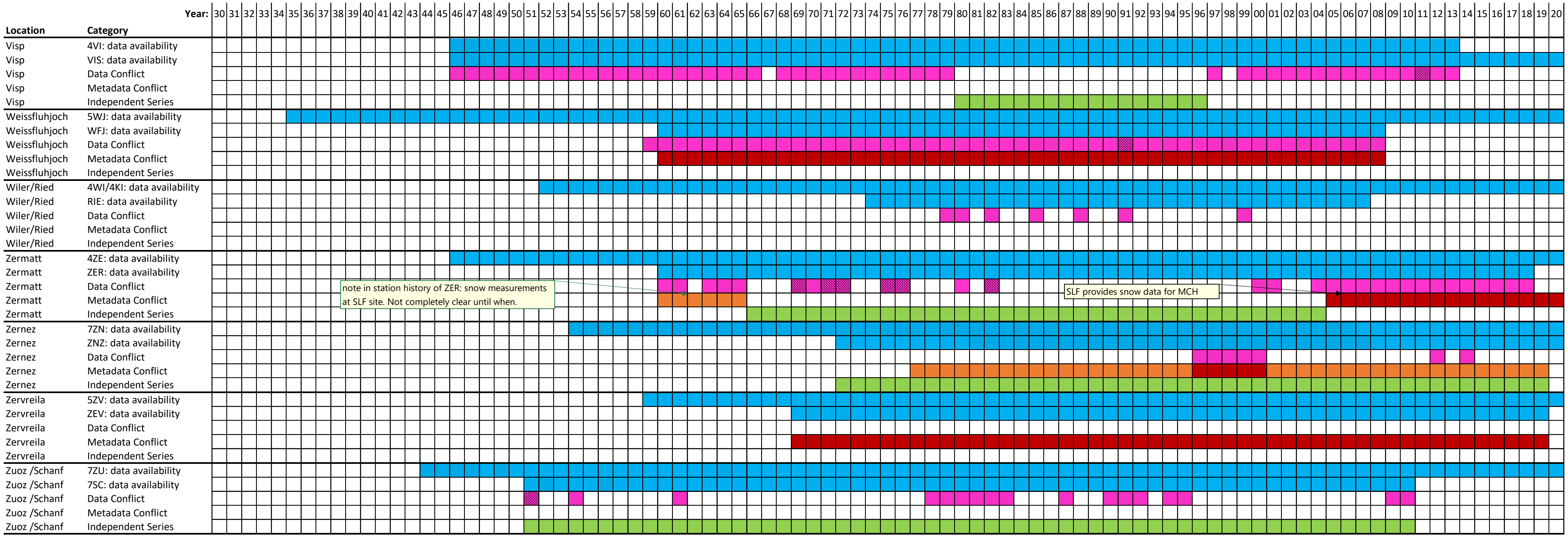
Location
Category
San Bernardino 6SB: data availability
San Bernardino SBE: data availability
San Bernardino Data Conflict
San Bernardino Metadata Conflict
San Bernardino Independent Series
Santa Maria 7ST: data availability
Santa Maria SMM: data availability
Santa Maria Data Conflict
Santa Maria Metadata Conflict
Santa Maria Independent Series
Schwägalp 3SW: data availability
Schwägalp SWA: data availability
Schwägalp Data Conflict
Schwägalp Metadata Conflict
Schwägalp Independent Series
Scuol 7SU: data availability
Scuol SCU: data availability
Scuol Data Conflict
Scuol Metadata Conflict
Scuol Independent Series
Sedrun 5SE: data availability
Sedrun SED: data availability
Sedrun Data Conflict
Sedrun Metadata Conflict
Sedrun Independent Series
Simplon Dorf 4SM: data availability
Simplon Dorf SIM: data availability
Simplon Dorf Data Conflict
Simplon Dorf Metadata Conflict
Simplon Dorf Independent Series
Splügen 5SP: data availability
Splügen SPL/SDO: data availability
Splügen Data Conflict
Splügen Metadata Conflict
Splügen Independent Series
St. Antönien 5SA: data availability
St. Antönien SAN: data availability
St. Antönien Data Conflict
St. Antönien Metadata Conflict
St. Antönien Independent Series
St.Moritz 7MZ: data availability
St.Moritz SMZ: data availability
St.Moritz Data Conflict
St.Moritz Metadata Conflict
St.Moritz Independent Series
Thusis 5TH: data availability
Thusis THS: data availability
Thusis Data Conflict
Thusis Metadata Conflict
Thusis Independent Series
Tiefencastel 5TC: data availability
Tiefencastel TIC: data availability
Tiefencastel Data Conflict
Tiefencastel Metadata Conflict
Tiefencastel Independent Series
Ulrichen 4OW: data availability
Ulrichen ULR: data availability
Ulrichen Data Conflict
Ulrichen Metadata Conflict
Ulrichen Independent Series
Ulrichen 4UL: data availability
Ulrichen 4MS: data availability
Ulrichen Data Conflict
Ulrichen Metadata Conflict
Ulrichen Independent Series
Vals 5VA: data availability
Vals VLS: data availability
Vals Data Conflict
Vals Metadata Conflict
Vals Independent Series
SLF provides data to MeteoSwiss
border guard Santa Maria carries out observations, probably 1 observer, 2 stakes?
some HN data in 1969, many missing values. No HS in 1969.
many nans instead of zeros. Continuous series for HN & HS
on PDF, not digizized
named SDO in hom4snow Database
from 1973 continuous HN series with many missing values
from 1984 continuous HS series with many missing values
no measured snow in station sheets
data available from 1968, but many missing values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Location
Category
Visp 4VI: data availability
Visp VIS: data availability
Visp Data Conflict
Visp Metadata Conflict
Visp Independent Series
Weissfluhjoch 5WJ: data availability
Weissfluhjoch WFJ: data availability
Weissfluhjoch Data Conflict
Weissfluhjoch Metadata Conflict
Weissfluhjoch Independent Series
Wiler/Ried 4WI/4KI: data availability
Wiler/Ried RIE: data availability
Wiler/Ried Data Conflict
Wiler/Ried Metadata Conflict
Wiler/Ried Independent Series
Zermatt 4ZE: data availability
Zermatt ZER: data availability
Zermatt Data Conflict
Zermatt Metadata Conflict
Zermatt Independent Series
Zernez 7ZN: data availability
Zernez ZNZ: data availability
Zernez Data Conflict
Zernez Metadata Conflict
Zernez Independent Series
Zervreila 5ZV: data availability
Zervreila ZEV: data availability
Zervreila Data Conflict
Zervreila Metadata Conflict
Zervreila Independent Series
Zuoz /Schanf 7ZU: data availability
Zuoz /Schanf 7SC: data availability
Zuoz /Schanf Data Conflict
Zuoz /Schanf Metadata Conflict
Zuoz /Schanf Independent Series
note in station history of ZER: snow measurements at SLF site. Not completely clear until when.
SLF provides snow data for MCH