Copernicus Climate Change Service

LAPrec - user guide and technical report

A gridded precipitation dataset for the Alpine region that extends back into the 19th century

Issued by: MeteoSwiss and ZAMG/ F. Isotta, C. Frei, B. Chimani and J. Hiebl

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Contributors

Meteoswiss
F. Isotta
C. Frei

ZAMG
B. Chimani
J. Hiebl

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Introduction

Spatial climate analyses that extend back over many decades are an important basis for monitoring climate variations and long-term change (e.g. van der Schrier et al., 2013). They also serve as input for modelling environmental systems (e.g. ecosystems and glaciers, Kittel et al., 2004), and for calibrating climate reconstructions with proxy data (tree rings, Frank & Esper, 2005).

A key challenge in the construction of such long-term gridded datasets is that the number of observations becomes more and more limited into the past. As a result, analyses for the 19th and the early 20th century are subject to larger uncertainty and they exhibit less effective resolution than those obtained with dense observations in the more recent past. Variation in observation density is a potential source of temporal inconsistency. It can manifest in spurious long-term trends in gridded climate datasets (e.g. Begueria et al., 2016; Frei, 2014). The situation is further complicated because long-term measurement series are often affected by changes in measurement conditions. This requires laborious homogenization before the data can be used (e.g. Venema et al. 2012).

The present report documents a new gridded precipitation dataset that extends back till 1871 and was specifically constructed to satisfy high standards in climate consistency. The dataset has monthly resolution and covers the mountain range of the European Alps with territory from eight countries. It will be updated in intervals of approximately two years. The dataset is denoted as LAPrec, for long-term Alpine precipitation reconstruction. Its technical specifications are summarized in Table 1.

Unlike traditional approaches in spatial climatology, LAPrec builds on a statistical reconstruction that integrates information from two data sources: The first, a set of high-quality station series, taken from the HISTALP station data archive (e.g. Auer et al. 2007), extends over the full period of interest, continuously without gaps. It informs about the temporal variation over the long term. The second, a high-resolution spatial analysis, the Alpine Precipitation Grid Dataset (Isotta et al. 2014), covers a few recent decades only but builds on data from thousands of rain-gauges. This component enriches the final result with spatial detail that is not resolved by the long-term stations alone. The approach explicitly avoids artefacts from variations in station density and it resolves major mesoscale patterns despite limited station coverage.

The dataset is developed in the framework of the Copernicus Climate Change Service (Project C3S_311a Lot4) in a collaboration between ZAMG (Zentralanstalt für Meteorologie und Geodynamik, Austria) and MeteoSwiss (Federal Office of Meteorology and Climatology, Switzerland). HISTALP is an initiative of Alpine weather services, led by ZAMG, to assemble and analyze high-quality climate series in the European Alps (Auer et al. 2007). Under the HISTALP umbrella, several grid datasets have been developed that extend over centennial and longer periods (Chimani et al., 2011, 2013; Efthymiadis et al., 2006). AGPD was developed at MeteoSwiss and has been used for previous long-term reconstructions for the Alps (Schmidli et al. 2002; Masson & Frei 2016). LAPrec is a cross-product that brings together the merits of the two initiatives in terms of long-term extent / consistency (HISTALP) and spatial resolution (APGD).

The present report describes the two data sources integrated into LAPrec (section 1), and it outlines the reconstruction methodology (section 2). The technicalities of production and data access are explained in section 3, and a selection of reconstruction results and analyses are presented in section 4. Section 5 discusses the limitations of the dataset and guides users in the professional application. The report closes with final remarks (section 6).

Table 1: Technical specifications of LAPrec

Parameter	monthly precipitation sum (mm)
Domain	Alpine region (approx. 43–49°N, 4–17°E, land area only)
Time period	two versions: 1871–2017 and 1901–2017, regularly updated
Time resolution	monthly
Coordinate system	ETRS89 / ETRS-LAEA (EPSG 3035)
Grid spacing	5 km
Input Data	HISTALP (Auer et al. 2007), APGD (Isotta et al. 2014)
Method	RSOI (Kaplan et al. 1997; Schiemann et al. 2010)

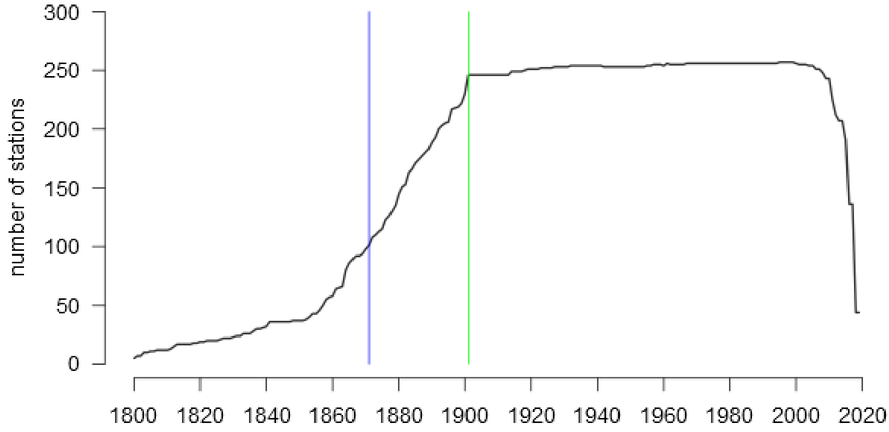
1. Data

The construction of LAPrec builds on two data components, namely a dataset of high-quality long-term station series that contributes information on long-term variations, and a dataset of high-resolution grid data that enhances information on spatial variability. The two data components are described in the following.

1.1 Long-term station dataset

HISTALP is an international data collection consisting of monthly homogenised climate records for the greater Alpine region (Auer et al., 2007). To meet the basic requirements of climate variability and change studies, it aims to provide instrumental data that extend far back in time, are dense in space, quality-improved, homogenized, multiple and user-friendly. The station series were subject to an intensive homogenization procedure. The homogenization method HOMER (Mestre et al. 2013) was used to check the homogeneity of the stations data. For the detection of breaks, the pairwise detection algorithm was applied. This algorithm is similar PRODIGE (Caussinus and Mestre 2004) and uses a maximum likelihood approach. A break signal was only considered a break if at least 50 % of the available reference stations detected it. For correction an ANOVA is used. Precipitation is a multiplicative parameter in regards to homogenization, meaning that the adjustment is a monthly factor that is multiplied to the original value. At least five reference stations have been needed, but all stations with a correlation of at least 0.7 have been used. Only in a small number of cases the five stations of such a high correlation have not been available. The homogenization of the stations has been done in groups of climatic zones in the HISTALP-GAR (Greater Alpine Region) area, to ensure the use of appropriate reference stations. As the case occurred that quite a number of stations had missing data within the same time period or didn't have any reference stations at the beginning of the time series, special networks where created for those stations in order to be able so find the best possible solution for them. As far as possible, found break points where shifted according to appropriate metadata information, but the small number of available metadata for some of the stations left quite a number of breaks unexplained.
The number of available monthly precipitation series rises continuously from 5 in 1800 to 40 in 1853 (Fig. 1). With the foundation of national meteorological institutes in the 1850s and 1860s the network quickly becomes denser and encompasses 246 stations by 1901. The high number of around 250 series is maintained until the most recent years when data collection and updating of data still are in progress.

Fig. 1: Temporal evolution of available HISTALP precipitation series. The vertical lines denote the starts of the two reconstruction periods of the LAPrec dataset, 1871 (blue) and 1901 (green).



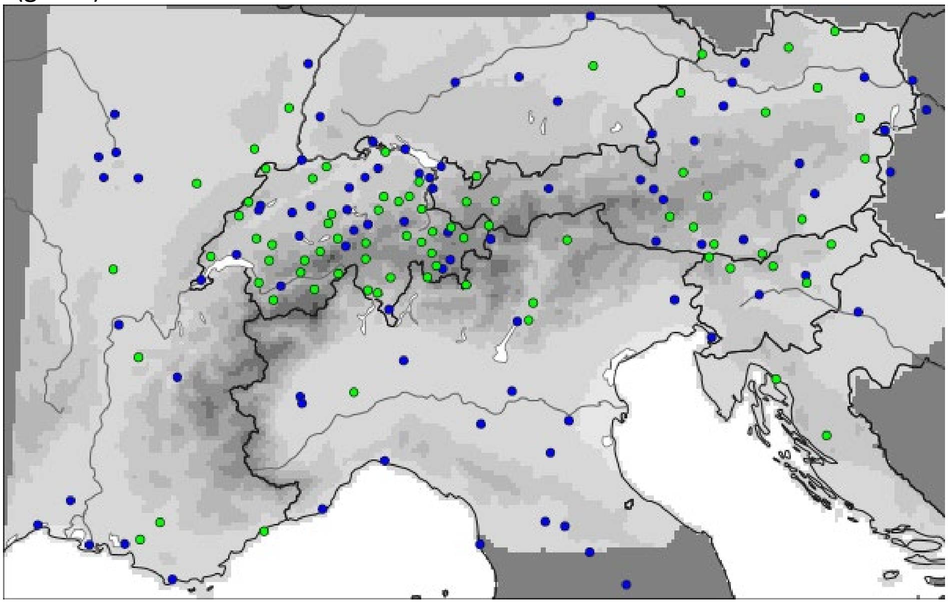
The rapid increase in precipitation series during the second half of the 19th century makes it hard to find a decent compromise between spatial network density and temporal extension of the study period. In the search for a proper starting year for the climate-consistent precipitation grid dataset, we decided to perform data preparation, apply the reconstruction methods and issue the LAPrec dataset twofoldly: the longer version starts in 1871 and uses 85 almost continuous series, the shorter version starts 1901 and uses 164 almost continuous series (Fig. 2). Clearly, a fraction of series had to be dismissed because of missing data. For the handling of data gaps, three criteria have been defined, in order to guarantee a sufficient temporal data coverage of the individual series:

(1) During the calibration period 1971-2008 (see chapter 2), missing data may affect a maximum of one year (12 not necessarily consecutive months). (2) Apart from that, not more than eight years (96 not necessarily consecutive months) might be missing during the entire period of reconstruction, irrespectively of the length of the period. (3) The most recent six calendar years of the study period (i.e., at present 2012-2017) are excluded from criterion 2, in order to minimize the effect of pending station data updates on station network density.

The remaining data gap are filled using the method by Schneider (2001). The filling is based on expectation maximization (prediction assuming the data is from a multivariate Gaussian). The problem is solved iteratively, since imputing changes the mean and covariance matrix and the mean/covariance matrix are used for imputing. One of the major advantages is that the expectation maximization delivers an unbiased estimate of the covariance matrix. This is different from the cross-product of the gap-filled data matrix, as it accounts for the uncertainty in imputation. (The imputed values are conditional expectations.)

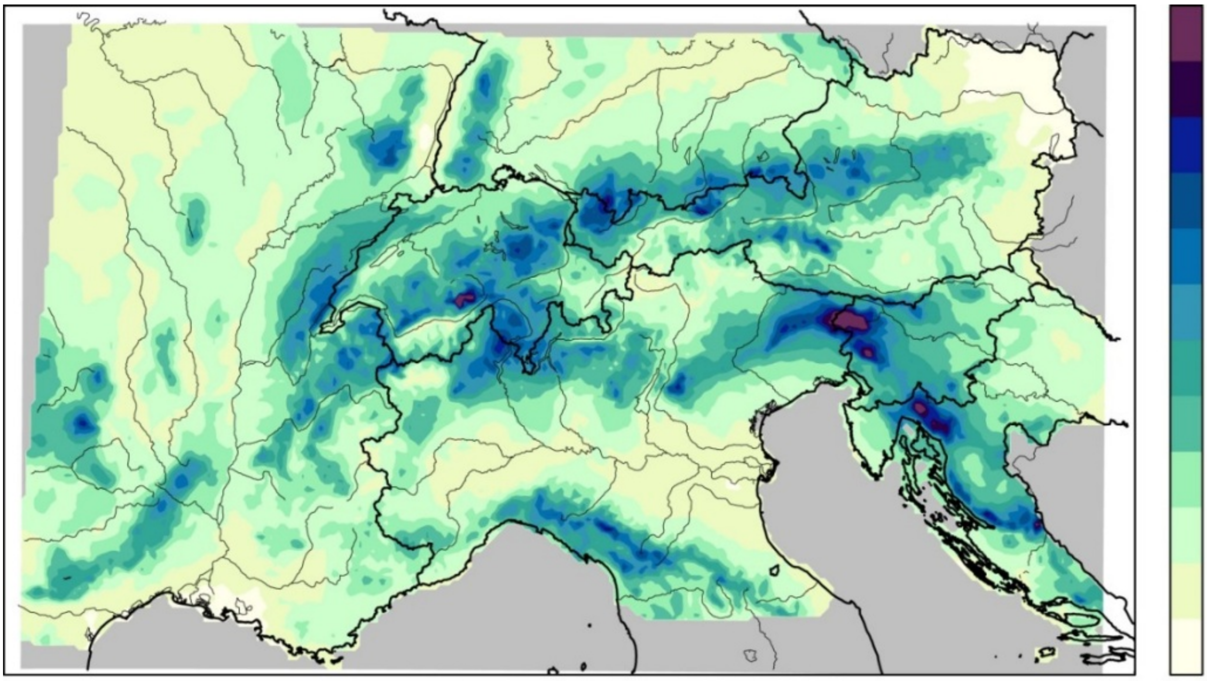
HISTALP partners contributing to the final station data collection are MeteoSwiss (Switzerland), ZAMG (Austria), numerous Italian authorities and institutes, Meteo France (France), ARSO (Slovenia), DHMZ (Croatia), DWD (Germany), OMSZ (Hungary) and FBIH (Bosnia and Herzegovina).

Fig. 2: Map showing the stations utilized with the two periods, starting in 1871 (blue) and additionally starting in 1901 (green).



1.2 High-resolution grid dataset

Fig. 3: Mean annual precipitation (mm per year) for the period 1971-2008 in the high-resolution grid dataset APGD.



The Alpine precipitation grid dataset (APGD, Fig. 3) is a high-resolution grid dataset of daily precipitation covering the entire Alpine region. It builds on efforts initiated 20-years back in compiling and jointly analysing data from all the high-resolution rain-gauge networks in the region (Frei and Schär 1998). MeteoSwiss has re-established the APGD as part of the EURO4M project (Isotta et al. 2014). APGD incorporates more than 5500 rain-gauge measurements on average per day for the Alpine sections of Austria, Croatia, France, Germany, Italy, Slovenia and Switzerland. With 10-15 km station spacing, the dataset is one of the densest in-situ observation networks over a high-alpine topography worldwide. The procedure of spatial analysis uses local regression (PRISM) to incorporate physiographic influences on precipitation and angular distance weighting (SYMAP) for daily anomalies (Isotta et al. 2014). Currently, APGD is a static (not updated) dataset spanning the period 1971-2008. Recently, in the UERRA project, a probabilistic version of the APGD has been developed, providing ensembles of area-average precipitation over more than 500 hydrological catchments in the Alps. APGD is freely available upon registration and for non-commercial use at (http://www.meteoswiss.ch).

2. Method and Settings

The reconstruction method adopted to derive LAPrec is denoted as "Reduced Space Optimal Interpolation" (RSOI). It combines information from the primary long-term precipitation series with statistical information distilled from a high-resolution gridded analysis. In essence, RSOI establishes a linear model between station data and high-resolution grids, calibrated over a period when both are available. Technically, RSOI involves a Principal Component Analysis (PCA) of the high-resolution grid dataset, followed by an Optimal Interpolation (OI) using the long-term station data. Here, we summarize these two steps briefly and then detail the settings used in the present application. Detailed technical descriptions of RSOI are given in Kaplan et al. (1997), Schmidli et al. (2001), and Schiemann et al. (2010). Further insight into the potential of this method can be found in Masson & Frei (2016) and Isotta et al. (2019).

A PCA is calculated using the fields of the high-resolution precipitation grids of APGD. The resulting PC-loadings define patterns in space, which describe the complex spatial correlation structure of precipitation. The full set of patterns can precisely reproduce any of the observed monthly fields by linear combination with pertinent coefficients (PC-scores). Even, a subset of 'leading' loadings allows close approximation of the fields, thanks to the ordering by explained variance. The possibility for such truncation, with limited impacts on accuracy, is the main purpose of the PCA step. It renders the reconstruction problem regular and robust.

In the derivation of LAPrec, the PCA was calculated from all the monthly fields of APGD between 1971-2008 (38x12 months in total). Rather than using original precipitation (in mm per month), the data was square-root transformed. This reduces skewness, improves homoscedasticity and makes the result more compliant with the assumptions of the subsequent OI. The PCA was executed with the variance-covariance matrix of the transformed data. No seasonal stratification was made in the definition of the reduced space, because of robustness concerns with the reduced sample size. The resulting PC-loadings show features of Alpine precipitation variability familiar from earlier studies (see e.g. Schmidli et al. 2001) but with more spatial detail, thanks to the higher resolution of APGD. The first 25 (50) modes explain 90% (93%) of the total variance.

The OI step establishes a linear relationship between the long-term station data and the PC scores of the pertinent monthly fields using data from a calibration period when both data sources are available. In general, this relationship is overdetermined, when the PCA truncation is chosen smaller than the number of long-term stations. Additional robustness is introduced with a penalty for variance in high-order scores (see Kaplan et al. 1998). Once estimated, the linear model is applied to reconstruct precipitation fields for the entire reconstruction period, using the fully continuous high-quality station series only. It is possible to calculate an upper bound of the point-wise prediction error of RSOI, i.e. a field that informs about expected uncertainties.

In our application for LAPrec, the OI model is established, again, over the period 1971-2008, and using square-root transformed, rather than original precipitation data. As for the configuration of the number of scores retained (truncation L, see above), our choice was L =27 in the case of the long reconstruction LAPrec1871 (starting in 1871, 85 stations) and L=50 for the short reconstruction LAPrec1901 (starting in 1901, 164 stations). These settings were inferred by cross-validation experiments. The accuracy of the reconstruction does barely improve with settings beyond these marks. It is worth mentioning that the results are not overly sensitive to details of the truncation settings. The inherent penalty for variance in high-order modes limits the risk of overfitting with undue values of L.

Technically, the reconstruction is implemented in R (R Core Team 2012). It is computationally rather inexpensive for the 5-km grid over the Alps, completed within less than 10 seconds on a 2.8 GHz core, including the PCA.

3. Production and Access

The LAPrec dataset will be provided in NetCDF format, following the CF-1.6 convention (see http://cfconventions.org/cf-conventions/v1.6.0/cf-conventions.html). Besides the monthly precipitation fields, fields of geographical variables (longitude, longitude and elevation above sea level) and details on the coordinate reference system are included. The fields consist of a regular 5 km x km grid that is spatially referenced in ETRS89 / ETRS-LAEA (European Terrestrial Reference System 1989-Lambert Azimuthal Equal Area, see https://spatialreference.org/ref/epsg/etrs89-etrs-laea).

Two variants of the dataset exist reflecting the two different starting dates (January 1871 and January 1901) and respective different station numbers (currently 85 and 164). Future updates of dataset might change the exact number of ingoing stations but keep three criteria for missing data defined in chapter 1.1. as well as the starting years 1871 and 1901. Homogenised station series data (no deliverable of this project) are available from the HISTALP database of ZAMG and according files. In principle, the station series are updated annually. Due to national issues, the timing of the update varies within the year.

The LAPrec dataset will be updated on a two-year basis, by no later than the end of February in each second year. The latest version of the dataset will temporally extend until the end of the year before last (e.g. the update of early 2020 will include December 2018). Intermediate updates might occur if found necessary.

Versioning of the LAPrec dataset will be in the format vX.Y where an increment of X denotes methodical adaptations and an increment in Y denotes updates in input station data. The file names will consist of the dataset acronym, the staring year and the version number, e. g. *LAPrec1871.v1.0.nc* and *LAPrec1901.v1.0.nc*. The LAPrec dataset will be automatically uploaded to KNMI's FTP server and is publicly available via the project webpage
http://surfobs.climate.copernicus.eu/dataaccess/index.php.

4. Results

4.1 Reconstruction examples

The LAPrec datasets permit to analyse fields of monthly precipitation sums in the remote past, when only few stations were available. Figure 4 depicts examples of monthly sums in June 1876, October 1907 and June 1910, when heavy precipitation events occurred in the Alpine region. The examples illustrate how RSOI introduces small-scale structures (via the APGD grid dataset) that are not resolved explicitly by the low density station measurements (dots in Fig. 4).

Fig. 4: Reconstruction of the monthly precipitation in June 1876 (left, version LAPrec1871), October 1907 (center, version LAPrec1901) and June 1910 (right, version LAPrec1901), in mm/month. The dots represent the stations used for the reconstruction and the colour of the dot is the correspondent monthly sum from the station time series.

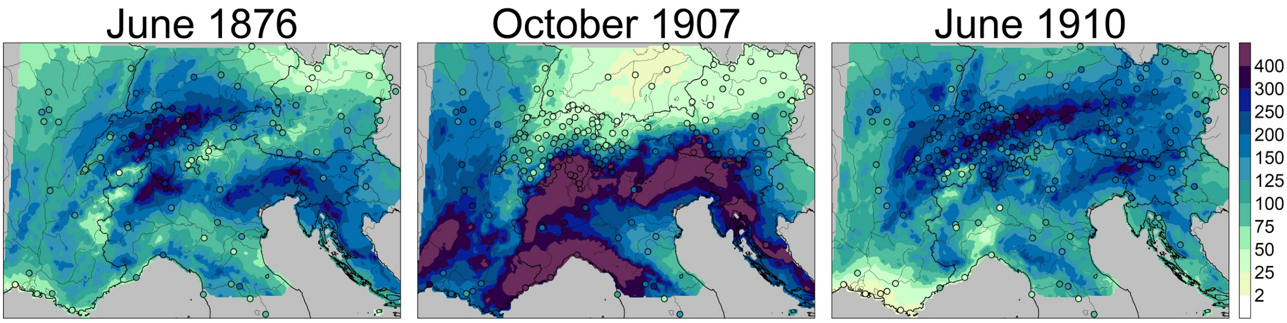
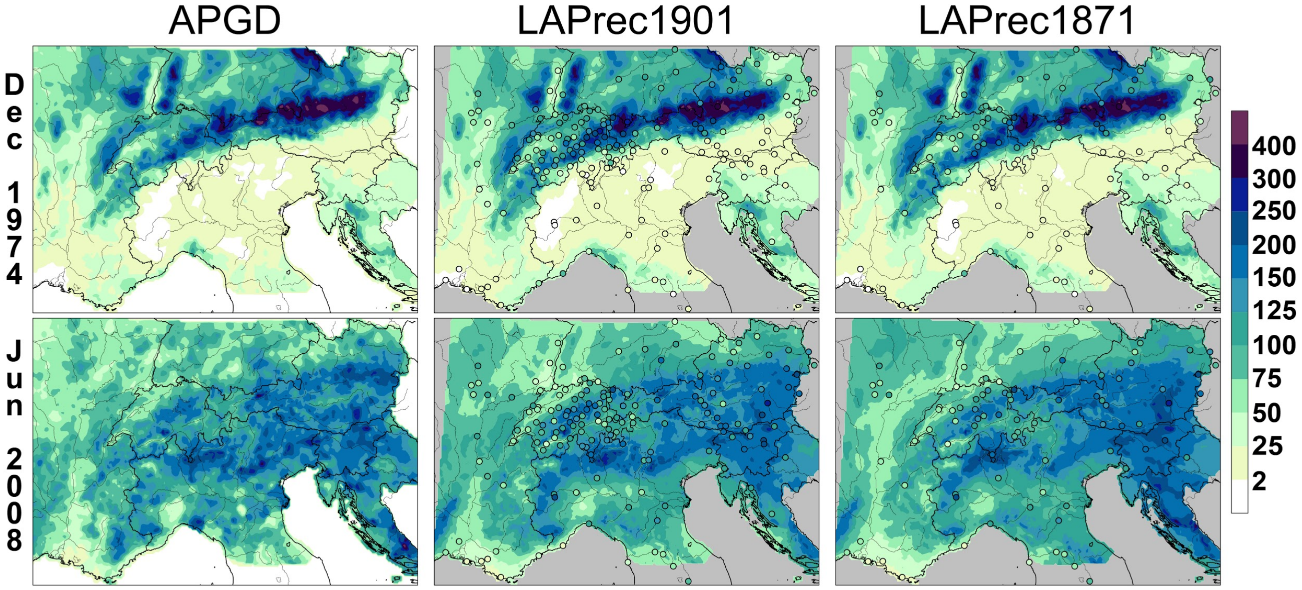


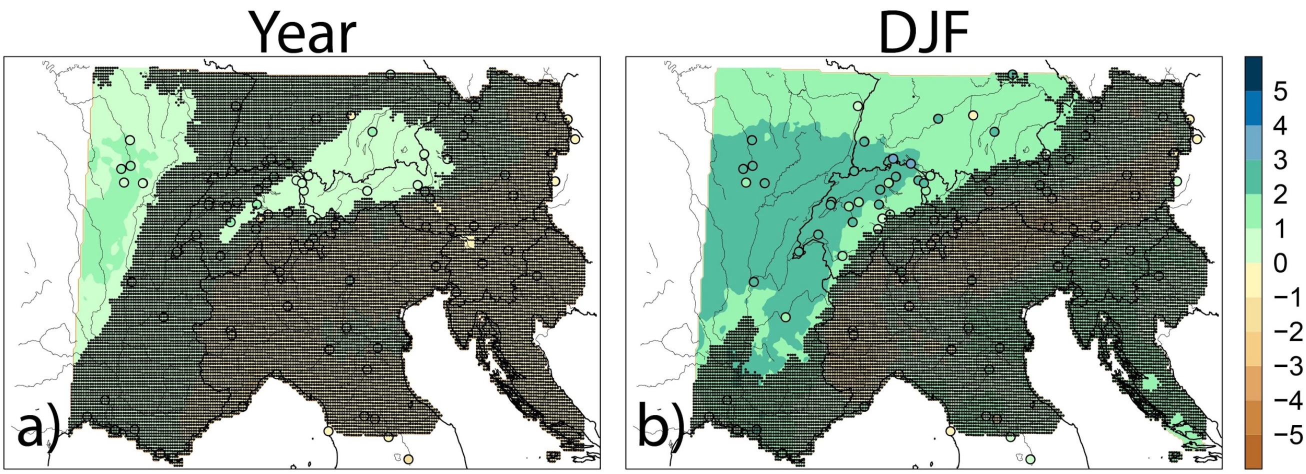
Figure 5 shows reconstructions of two months intentionally chosen during the period when APGD is available to allow comparison with the high-resolution dataset. The different columns are for APGD, LAPrec1901 and LAPrec1871. The examples are selected to represent a good (first row, December 1974) and a poor (second row, June 2008) reconstruction in terms of explained spatial variance compared to APGD (MSESS score, see Isotta et al. 2019 for a similar comparison).
In December 1974 the precipitation field has huge spatial variation (e.g. the strong difference of precipitation between the northern and the southern parts of the Alps), which is successfully reproduced in both reconstructions. Even small patterns (e.g. precipitation over the Dinaric Alps in Croatia or the maxima over the Bohemian Forest and the Black Forest) are nearly identical to APGD also in LAPrec1871, despite the low station density.
The major patterns are correctly reproduced in the second example (June 2008, second row), despite the low explained spatial variance. The spotty precipitation in APGD derives from the convective dominated precipitation, typical for late spring and summer. The reconstruction of such fields is typically affected by higher uncertainty. Compared to stratiform precipitation events as in the first example, convection is very localised and the patterns varies strongly. The reconstructions are much smoother compared to APGD and major differences are found (especially in LAPrec1871, e.g. in Croatia or northern part of France).

Fig. 5: APGD (first column) and reconstructions (LAPrec1901, second column and LAPrec1871, third column) of the monthly precipitation in December 1974 and June 2008, in mm/month. Note that reconstructions and references are made strictly independent, by excluding, in turn, data from each test month from the calibration (e.g., the direct interpolation of a test month was not available for the PCA and OI).



4.2 Trends

Fig. 6: Linear trend in yearly and seasonal precipitation in % change per 10 years relative to the yearly and the seasonal mean precipitation, respectively, in the period 1981–2010. Results are shown for the RSOI-based spatial reconstructions (fields) and for the sets of long-term stations used in the reconstruction (colored dots). Trends are shown for three periods: (first column) 1864–2017, (second column) 1901–2017, and (third column) 1961–2017. Statistically non-significant trends are displayed with stippling. Trends are estimated with the Theil-Sen slope. Statistical significance is assessed with the Mann-Kendall trend test, followed by a Benjamini-Hochberg meta-test with a critical false discovery rate of 0.05 (for detail, see section 5.2).



Most yearly and seasonal trends of precipitation over the whole available period of LAPrec1901 and LAPrec1871 are statistically not significant. The one with at least a small significant region in the Alps are shown in Figure 6, namely the yearly (left) and the winter (right) trends from 1871-2017. In the yearly analysis, precipitation is increasing with amounts of about 1% per decade with respect to the mean in the period 1981-2010 in the north-west part of France, in north-east Switzerland, west Austria and southern Germany. For winter, the whole area northern of the main Alpine ridge has a trend around 2% per decade.

Trends are estimated using the Theil-Sen slope (Sen, 1968; Theil, 1950) and the statistical significance is assessed based on the Mann-Kendall test (Kendall, 1975; Mann, 1945) applied individually to all grid points and a Benjamini-Hochberg meta test of the pertinent p values (Benjamini & Hochberg, 1995). The latter controls the false discovery rate at 5 %.

5. User Guidance

The construction of LAPrec deviates from the principles commonly used in the generation of spatial climate datasets. The underlying station dataset encompasses (almost) continuous time series only, with the compromise of a much coarser spatial density. The stationarity of the input data avoids disturbances of temporal consistency that have to be expected when station series start or end, or when the number of input data gradually varies over time. Such inconsistencies have been documented in datasets that are produced, more conventionally, by integrating all available information at any particular time (Hofstra et al. 2010; Begueria et al. 2016; Frei 2014; Isotta et al. 2019).

The adopted construction principle designates LAPrec, specifically, for applications with a need in long-term temporal coverage and high temporal consistency. Primary areas of application are in climate and environmental monitoring, such as in glaciology, water-balance hydrology, ecosystem development, as well as in studies of climate variability and for climate reconstruction. Basically, all applications with an emphasis on accurate anomalies in time and dealing with slow processes, where monthly temporal resolution is sufficient. LAPrec is, however, less suited for applications where the interest is in small-scale spatial patterns (scales smaller than ~20 km), or require high absolute precision, such as for distributed runoff modelling, for the assessment of local risks (avalanches or flooding), or for the construction of crop suitability maps.

We encourage users to carefully assess the suitability of LAPrec before engaging in a concrete application. The purpose of such an assessment would be to evaluate the requirements of the targeted application and to face these with the error characteristics of the presented dataset. The following issues are particularly worth of consideration.

- Grid spacing vs. effective resolution: LAPrec is provided on a grid spacing of 5 km. This scale should not be understood as the length scale that is effectively resolved in the dataset. LAPrec can reproduce, to some extent, spatial features below the spacing of the underlying station network (i.e. < 100–150 km) but it will not reach the effective resolution of a high-resolution rain-gauge network (i.e. > 20 km). Users should, therefore, not rely on estimates at single or very few grid points. If spatial detail below 20 km matters for an application, LAPrec is not very informative. Also, the dataset is not suitable to derive statistics on local extremes. It is likely that the effective spatial resolution of LAPrec is variable in space, because of the heterogeneity of the underlying station dataset (Figure 2). Finally, it is generally coarser in LAPrec1871 than in LAPrec1901.

- Interpolation errors: A leave-one-out cross-validation was calculated to estimate interpolation errors. This reveals the magnitude of errors for the case when values at a gridpoint are interpreted as local point estimates. In fact, such interpretation should rather be avoided. But these numbers serve as conservative error measures when the analyses are

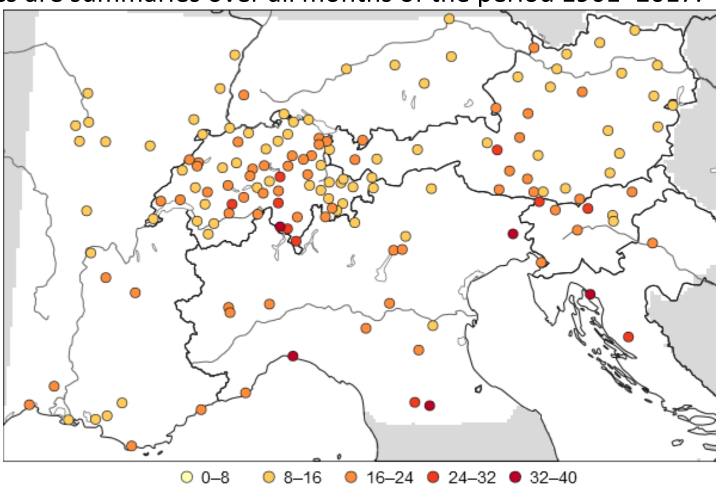
interpreted as local averages. Note, it is impossible to derive error statistics for the recommended interpretation at larger scales, because there is no observational reference.
Numbers for the bias (mean error) and the mean absolute error (MAE) are listed in Table 2. The two columns are for the two variants of the dataset. The results of the two columns are not strictly comparable, because the station samples, from which statistics are summarized, differ. The bias is close to zero, about an order of magnitude smaller than the mean absolute error. There seems to be a tendency for overestimation (bias is positive). Closer examination suggests that this comes from a tendency of LAPrec to overestimate precipitation during dry months.

Table 2: Error measures (in mm per month) from a leave-one-out cross-validation using all reconstruction stations of the respective reconstruction window

Dataset	LAPrec1871	LAPrec1901
evaluation period	1871–2017	1901–2017
bias	0.8	2.1
mean absolute error	18.6	17.3

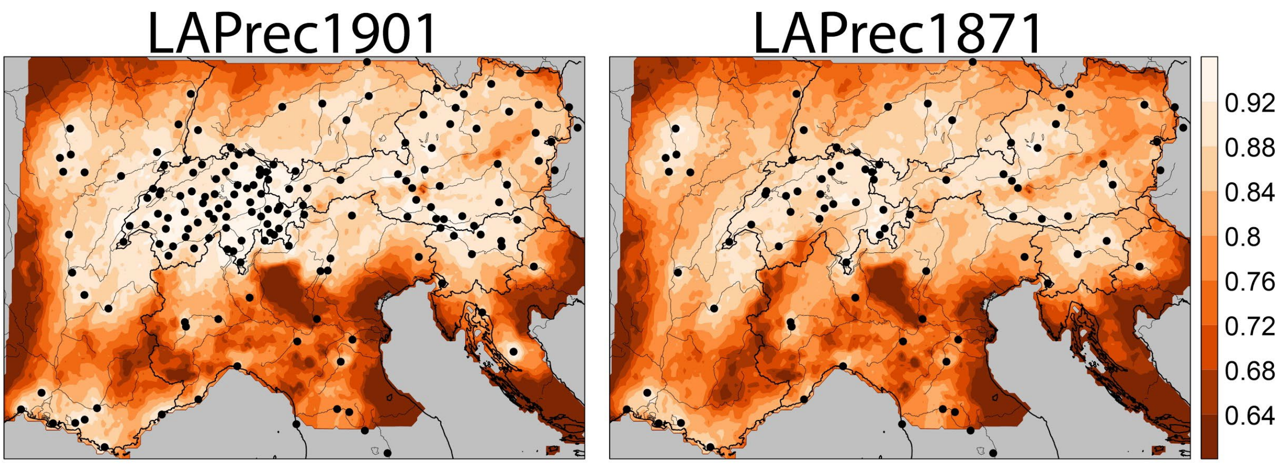
The mean absolute error (MAE) is about 18 mm per month. Nominally, the error is only marginally larger in the longer dataset, but this may be due to differences between the station samples from which the statistics has been calculated. Indeed, the mean absolute error varies considerably between test station, as is shown in Figure 7. MAE is typically twice as large in areas of complex topography (Switzerland, Austria), and in areas of coarse station density (Italy and Croatia), compared to densely sampled flatlands (Swiss Plateau, Eastern France).
In terms of seasonal variation, the mean absolute error is largest in summer, when the monthly sums are larger and when convection induces, generally, smaller-scale precipitation anomalies.

Fig. 7: Mean absolute error (MAE, mm per month) from a leave-one-out cross-validation for dataset LAPrec1901. The statistics are summaries over all months of the period 1901–2017.



Further insight of the quality of the reconstruction are obtained comparing the high-resolution component APGD and the reconstructions for each grid-cell. Figure 8 depicts maps of a skill score (MSESS, see Isotta et al. 2019 for details in a similar comparison) defining how much of the temporal variance over time is explained in the reconstructions as a function of the location. A value equal 1 means a perfect agreement between the reference APGD and the reconstruction. The datasets show lower values at the edges of the domain, where no stations are available and in regions of low station density and/or complex topography (southern France except the coast, Italy and Croatia). LAPrec1871 has accordingly slightly higher values due to the reduced amount of stations available for reconstruction.

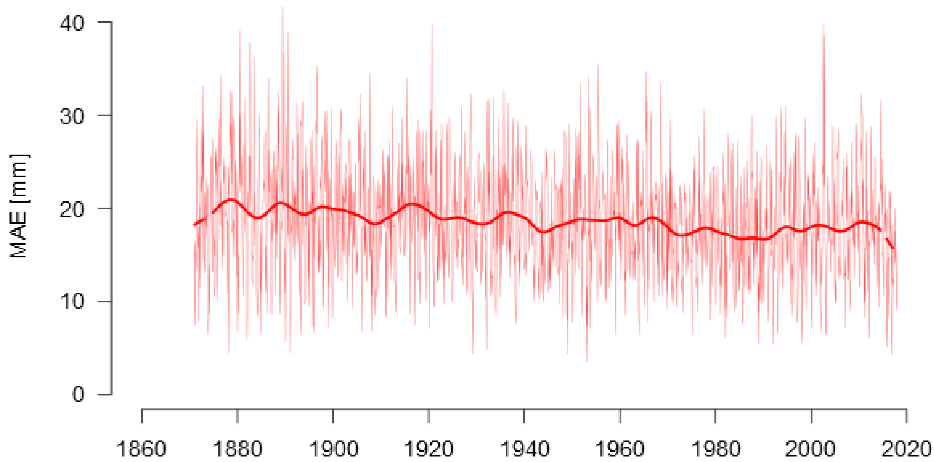
Fig. 8: Explained temporal variance (MSESS) of the reconstructions for precipitation in all months 1971–2008 for the reconstructions from 1901 (left) and 1871 (right). The reference is APGD (high-resolution component).



- High elevations: The construction of LAPrec relies on very few stations only that represent conditions at high altitudes (> 1500 msl). The reconstruction for such locations is therefore strongly influenced from stations at lower elevations. As a result, the estimates must be considered more uncertain than for low elevations. Most importantly, the cross-validation numbers listed above may not be particularly representative for such conditions. As a consequence, it is likely that the transition between major regimes of climate variability, often occurring across major mountain massifs of high elevation, may not be reproduced exactly.

- Temporal consistency: The adopted reconstruction method, together with the efforts made in homogenizing the underlying station data, assure for LAPrec a much better temporal consistency than what can be expected in other datasets available for the region. Residual inconsistencies can, however, not be excluded. First, the temporal evolution of the mean absolute error, depicted in Figure 9 for LAPrec1871, reveals slightly smaller errors after 1970 compared to before. This suggests a slightly better performance of the reconstruction during the calibration period (1971-2008), likely because the reduced space representation is specifically defined from data of this period (see section 2). Second, Figure 9 also suggests that there are variations in reconstruction error before 1970, evident in a gradual decrease of MAE with time. Closer inspection revealed that this trend is a superposition of several major shifts in performance at different times for individual countries. A clear understanding of these performance steps is still lacking. They could be related to major changes in national networks and consequences for the quality and homogenization processing of the data. They could also be related to a violation of the stationarity assumption inherent to the statistical reconstruction. (Though previous studies suggest a small sensitivity, see Schmidli et al. 2002, Isotta et al. 2019). These observations from Figure 9, should caution users of the possibility of some residual temporal inconsistency. The observed gradual performance trend is small in relation to the month-to-month variation of the error (see Figure 9). Hence, the effects of the residual inhomogeneity are likely small, but they are not entirely clear at present.

Fig. 9: Temporal evolution of the MAE (in mm per month) from a leave-one-out cross validation of LAPrec1871 over the period 1871–2017. Shown are the monthly error values (thin line) and the 11-year Gaussian filtered running mean (bold line)



- Updating: The two LAPrec datasets are updated every two years. To this end, data of the long-term stations is requested from the owners, the extended time series are newly homogenized and reconstructions re-calculated. Two issues with this updating should be considered: First, even if no changes have been made in past data in the original time series, the reconstructions of the past may still vary with an update. This is because the homogenization adjusts the data to the most recent measurement conditions, which then affects the entire time series. The differences are, however, mostly small. Second, for some of the long-term stations, the updating may be delayed. In this case, preliminary estimates will be derived for these stations. (Method based on Schneider 2001.) The time period (some recent months) affected by such incomplete (estimated) data is labelled as "preliminary" in the datasets. This may temporally affect the consistency of LAPrec in recent months.

- Systematic measurement errors: Measurements by rain gauges are subject to systematic errors. Wind-induced deflection of hydrometeors over the gauge orifice results in an underestimation of true precipitation. The measurements used for LAPrec have not been corrected for this "gauge undercatch". The bias is comparatively larger for wind-exposed stations, in climates with a large fraction of snowfall, or during periods with small rainfall intensity (Neff 1977, Yang et al. 1999). Sevruk (1985) estimates the systematic measurement error in Switzerland to range from about 4% at low elevations in summer, to occasionally more than 40% above 1500 mMSL in winter. This range may be representative for other Alpine countries. LAPrec must therefore be expected to generally underestimate precipitation, particularly in winter months and at high elevations.

- Combination with other data: The strength of LAPrec is its length and reliable representation of temporal variations. The accuracy for time-mean precipitation on a local scale is, however, limited. If, for a particular application, there is reliable complementary information about mean precipitation, for instance from local measurements, it can be valuable to merge LAPrec with this complementary information. We suggest that the merging is constructed such that the final result preserves relative anomalies from LAPrec, i.e. with a multiplicative correction. Except from such an adjustment of means, we discourage combinations with other datasets. Most importantly, we disadvise replacing recent years in LAPrec with other spatial analyses, for instance, because of their higher resolution or better local accuracy. For example, the two variants of LAPrec should not be mixed together. There is a risk of disturbing the temporal consistency, which was the main motivation for the present development.

6. Conclusion

This user guide and technical report describes the two reconstruction grid datasets LAPrec1871 and LAPrec1901 for the European Alps. They are covering more than a century of monthly precipitation sums and are an important basis for monitoring climate variations and long-term change, satisfying high standards in climate consistency.

LAPrec builds on a statistical reconstruction method denoted as “Reduced Space Optimal Interpolation” (RSOI, references in chapter 2) that integrates information from two data sources: a set of high-quality station series, taken from the HISTALP station data archive (e.g. Auer et al. 2007), and a high-resolution spatial analysis, the Alpine Precipitation Grid Dataset (Isotta et al. 2014).

Reconstruction examples and comparisons with APGD show the successful reconstructions in the Alpine Region, introducing small-scale structures (via the APGD grid dataset) that are not resolved explicitly by the low density station measurements. In presence of convective precipitation, which is very localized and the patterns varies strongly, the reconstruction performance may be lower.

Most yearly and seasonal trends of precipitation are statistically not significant, except the yearly (about 1% per decade with respect to the mean in the period 1981-2010 in the north-west part of France, in north-east Switzerland, west Austria and southern Germany) and the winter trends (about 2% northern of the main Alpine ridge) from 1871-2017.

LAPrec is particularly suitable for applications with a need in long-term temporal coverage and high temporal consistency, as for climate and environmental monitoring, studies of climate variability and for climate reconstruction. However, the datasets are less suited for applications where the interest is in small-scale spatial patterns (scales smaller than ~20 km), or require high absolute precision.

User of LAPrec should be aware of some issues, listed in detail in chapter 5: the effective grid spacing (the grid spacing of 5 km is not the length scale that is effectively resolved in the dataset), the typical errors (mean absolute errors are in the order of 20 mm per month with higher values in complex topography, areas of coarse station density and in convective situations), the underrepresentation of high altitudes in the station distribution, the presence of residual temporal inconsistencies and the presence of systematic measurements errors (e.g wind induced deflection), resulting in a general tendency to underestimate precipitation. In addition, notice that the datasets are updated every two years. The delay in the update of some long-term stations may affect the temporal consistency of the most recent years of LAPrec. Finally, users should avoid to mix both variants of LAPrec if the temporal consistency is required.

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7. References

Auer I., Böhm R., Jurkovic A., Orlik A., Potzmann R., Schöner W., ... Mercalli L. (2005). A new instrumental precipitation dataset for the Greater Alpine Region for the period 1800–2002. Int. J. Climatol., 25, 139–166. http://doi.org/10.1002/joc.1135

Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., … Nieplova, E. (2007). HISTALP - historical instrumental climatological surface time series of the Greater Alpine Region. Int. J. Climatol., 27 (July 2006), 17–46. http://doi.org/10.1002/joc.1377

Begueria, S., Vicente-Serrano, S. M., Tomas-Burguera, M., & Maneta, M. (2016). Bias in the variance of gridded data sets leads to misleading conclusions about changes in climate variability. Int. J. Climatol., 36(9), 3413–3422. http://doi.org/10.1002/joc.4561

Benjamini, Y., Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. Journal of the Royal Statistical Society. Series B (Methodological), 57(1), 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Caussinus, H. and Mestre, O. (2004). Detection and correction of artificial shifts in climate series, Journal of the Royal Statistical Society: Series C (Applied Statistics) 53(3): 405-425.

Chimani, B., Böhm, R., Matulla, C., & Ganekind, M. (2011). Development of a longterm dataset of solid/liquid precipitation. Advances in Science and Research, 6, 39–43. http://doi.org/10.5194/asr-6-39-2011

Chimani, B., Matulla, C., Böhm, R., & Hofstätter, M. (2013). A new high resolution absolute temperature grid for the Greater Alpine Region back to 1780. Int. J. Climatol., 33, 2129–2141. http://doi.org/10.1002/joc.3574

Craddock J.M. (1979). Methods of comparing annual rainfall records for climatic purposes. Weather 34, 332–346

Efthymiadis, D., Jones, P. D., Briffa, K. R., Auer, I., Böhm, R., Schönder, W., … Schöner, W. (2006). Construction of a 10-min gridded precipitation dataset for the Greater Alpine Region 1800-2003. J. Geophys. Res., 111(D1), D01105. http://doi.org/10.1029/2005JD006120

Frank, D., & Esper, J. (2005). Temperature reconstruction and comparisons with instrumental data from a tree-ring network for the European Alps. Int. J. Climatol., 25, 1437–1454. http://doi.org/10.1002/joc.1210

Frei, C. (2014). Interpolation of temperature in a mountainous region using nonlinear profiles and non-Euclidean distances. Int. J. Climatol., 34, 1585–1605. http://doi.org/10.1002/joc.3786

Frei, C., & Schär, C. 1998. A precipitation climatology of the Alps from high-resolution rain-gauge observations. Int. J. Climatol., 18:873-900.

Hofstra, N., New, M., & McSweeney, C. (2010). The influence of interpolation and station network density on the distributions and trends of climate variables in gridded daily data. Climate Dyn., 35, 841–858.

Isotta, F. A. and co-authors. 2014. The climate of daily precipitation in the Alps: development and analysis of a high-resolution grid dataset from pan-Alpine rain-gauge data. Int. J. Climatol., 34(5), 1657-1675.

Isotta, F. A., Begert, M., & Frei, C. (2019). Long-Term Consistent Monthly Temperature and Precipitation Grid Data Sets for Switzerland Over the Past 150 Years Journal of Geophysical Research : Atmospheres. J. Geophys. Res. Atmos., 123, 1–17. http://doi.org/10.1029/2018JD029910

Kendall, M. G. (1975). Rank Correlation Methods (4th ed.). London: Charles Griffin.

Kaplan, A., Kushnir, Y., Cane, M. A., & Blumenthal, M. B. (1997). Reduced space optimal analysis for historical data sets: 136 years of Atlantic sea surface temperatures. J. Geophys. Res., 102, 27835–27860.

Kittel, T. G. F., Rosenbloom, N., States, U., Survey, G., & Daly, C. (2004). VEMAP Phase 2 bioclimatic database . I . Gridded historical (20th century) climate for modeling ecosystem dynamics across the conterminous USA. Clim. Res., 27(November), 151–170. http://doi.org/10.3354/cr027151

Mann, H. B. (1945). Nonparametric tests against trend. Econometrica, 13(3), 245–259. https://doi.org/10.2307/1907187

Masson, D., & Frei, C. (2016). Long-term variations and trends of mesoscale precipitation in the Alps: Recalculation and update for 1901-2008. Int. J. Climatol., 36, 492–500. http://doi.org/10.1002/joc.4343

Mestre, O., Domonkos, P., Picard, F., Auer, I., Robin, S., Lebarbier, E., Böhm, R., Aguilar, E., Guijarro, J.A., Vertacnik, G., Klancar, M., Dubuisson, B., & Stepanek, P. (2013). HOMER: a homogenization software – methods and applications, Időjárás., 117(1), 47-67

*Neff, E.L., (1977). How much rain does a rain gage gage?. J. Hydrology,**35,**213-220.*

R Core Team. (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/. Retrieved from www.r-project.org

Schiemann, R., Liniger, M., & Frei, C. (2010). Reduced-space optimal interpolation of daily rain-gauge precipitation in Switzerland. J. Geophys. Res., 115. http://doi.org/10.1029/2009JD013047

Schmidli, J., Frei, C., & Schär, C. (2001). Reconstruction of mesoscale precipitation fields from sparse observations in complex terrain. J. Climate, 14, 3289–3306.

Schmidli, J., Schmutz, C., Frei, C., Wanner, H., & Schär, C. (2002). Mesoscale precipitation in the region of the European Alps during the 20th century. Int. J. Climatol., 22(May), 1049–1074. http://doi.org/10.1002/joc.769

Schneider, T. (2001). Analysis of incomplete climate data: Estimation of mean values and covariance matrices and imputing of missing values. J. Climate, 14, 853–871.

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association, 63(324), 1379–1389. https://doi.org/10.2307/2285891

*Sevruk, B. (1985). Systematischer Niederschlagsmessfehler in der Schweiz. In: Der Niederschlag in der Schweiz. (Ed. Sevruk B.), Beiträge zur Geologie der Schweiz - Hydrologie, **31,**65-75.*

Theil, H. (1950). A rank- invariant method of linear and polynomial regression analysis. In Proceedings of the Royal Netherlands Academy of Sciences, 53, part I: 386-392, part II: 521-525, Part III: 1397-1412.

van der Schrier, G., van den Besselaar, E. J. M., Klein Tank, A. M. G., & Verver, G. (2013). Monitoring European average temperature based on the E-OBS gridded data set. Journal of Geophysical Research: Atmospheres, 118(11), 5120–5135. http://doi.org/10.1002/jgrd.50444

Venema, V. K. C., Mestre, O., Aguilar, E., Auer, I., Guijarro, J. A., Domonkos, P., … Szentimrey, T. (2012). Benchmarking homogenization algorithms for monthly data. Clim. Past, 8, 89–115. http://doi.org/10.5194/cp-8-89-2012

Yang, D.Q., E. Elomaa, A. Tuominen, A. Aaltonen, B. Goodison, T. Gunther, V. Golubev, B. Sevruk, H. Madsen, & J. Milkovic (1999). Wind-induced precipitation undercatch of the Hellmann gauges. Nordic Hydrol., 30,57-80.