ACRP

Final Report

Program Coordinator:
Klima- und Energiefond

Program execution:
Kommunalkredit Public Consulting GmbH (KPC)

1 Project information

Project acronym:	HOM-START	
Project title:	Homogenisation of climate series on a daily basis, an application to the StartClim dataset	
Project number:	K09AC0K00025	
Program:	**ACRP** **1st Call for Proposal**	
Applicant:	Dr. Ingeborg Auer (Central Institute for Meteorology and Geodynamics)	
Project partner:	Mag. Johanna Nemec (Central Institute for Meteorology and Geodynamics) Mag. Christine Gruber (Central Institute for Meteorology and Geodynamics) Mag. Barbara Chimani (Central Institute for Meteorology and Geodynamics) Konrad Türk (Central Institute for Meteorology and Geodynamics)	
Project start and duration:	Start: 01.01.2010	End: 31.12.2010

SYNOPSIS:

The main objective of the project was to create a homogenised dataset of daily extreme temperatures and precipitation, suitable for any kind of climate extreme studies. This dataset is based on the quality controlled StartClim dataset (Schöner et al., 2003). The main innovations of the project are the newly developed methods for homogenisation of daily time series and additionally an estimation of uncertainties accompanying the break adjustment. A first analysis of extreme events based on this dataset is performed, including trends in climate change detection indices (Alexander et al., 2006, Klein Tank et al., 2009) and trend uncertainties.

2 Technical and Scientific description of the project

2.1 Project summary

2.1.1 Abstract:

Instrumental time series of different climate elements are an important requisite for climate and climate impact studies. Long-term time series can essentially improve our understanding of climate change during the last century. However, as extensively discussed in literature (e.g. Aguilar et al., 2003, Auer et al., 2007) most instrumental time series are affected by inhomogeneities which can mask or amplify climate change signals. Causes for these inhomogeneities are manifold, e.g. station relocation, instrumentation changes or changes in observing times. It is widely accepted that inhomogeneities in time series have to be detected and if necessary adjusted before performing any kind of climate change analysis (Aguilar et al., 2003, Brunet et al., 2007).

During the last decade, various procedures for the detection and homogenisation of inhomogeneities in time series have been developed (Alexandersson and Moberg, 1997; Caussinus and Mestre, 2004; Böhm et al., 2001; Easterling and Peterson, 1995). In general, these methods are based on comparisons with neighbouring (so-called reference) stations, relying on the availability of highly-correlated measurements. However, most methods were primarily designed for and applied to annual or monthly time series and mostly only adjust the mean state of the time series. Since many climate research studies are recently focusing on changes in extreme events the need for quality controlled, homogenised data on a sub-monthly scale is steadily growing.

During the last few years first approaches have been developed to solve this problem (e.g. Vincent et al., 2001; Trewin and Trevitt, 1996; Della-Marta and Wanner, 2006, Brandsma and van der Meulen, 2008). These attempts to cope with potential inhomogeneities in daily data range from simple time series classifications (useful, doubtful and suspect time series) as given in the European ECA&D dataset (Wijngaard et al., 2003) to more sophisticated methods which detect multiple inhomogeneities and apply temperature dependent adjustments.

The main challenge of the homogenisation of daily compared to monthly data is that - at least in the case of temperature - the magnitude of inhomogeneities may differ with varying weather situations. The most promising methods are based on the estimation of changes in the overall distribution of an element (Trewin and Trevitt, 1996; Della-Marta and Wanner, 2006; Mestre et al., 2010; Stepanek and Zahradnicek, 2008). Even though these methods do not account for different meteorological parameters that characterize special weather situations, they do examine the distribution of the element itself and apply variable adjustments depending on the percentiles. These methods have mostly been tested on small, regional datasets. However, recently Kuglitsch et al. (2009) applied the method PHENHOM to a greater dataset of daily summer maximum temperature series in the Greater Mediterranean Region, followed by a heat wave analyses in the eastern Mediterranean Region including homogenised daily minimum temperatures (Kuglitsch et al., 2010). This method was further improved by an additional treatment of autocorrelation and an improved choice of regression parameters (Toreti et al., 2010). However, the uncertainties accompanying the break adjustment have not been studied sufficiently so far.

The method opted for the homogenisation of daily extreme temperatures in Austria contains the method PRODIGE (Caussinus and Mestre, 2004) for the detection of a multiple number of breakpoints and the method SPLIDHOM (Mestre et al., 2010) for the calculation of adjustments. The homogenisation procedure further includes an automated selection of highly correlated reference stations, data retrieve from the database, data handling and presentation of results. In case of precipitation the break adjustment module is replaced by an adapted version of INTERP (Vincent et al., 2001).

The method was tested and applied to 71 daily minimum temperature, maximum temperature and precipitation series in Austria, resulting in a new dataset of homogenised daily precipitation totals and extreme temperatures. This new dataset makes reliable studies on changes in climate extreme events possible. Here, 27 climate change detection indices suggested by the WMO (Alexander et al., 2006, Klein Tank et. al, 2009) were evaluated and tested for significance. The temperature-related

indices focus on the tails of the temperature distribution, such as high night-time temperatures or long-lasting cold periods, which can have major impacts on human health and well-being (e.g. Fischer and Schär, 2010) and can affect our environment. On the contrary, the precipitation-related indices focus on intensity and length of heavy precipitation events as well as long lasting dry periods.

2.1.2 Results and Conclusions:

Daily minimum (TN) and maximum temperatures (TX) series:

The homogenisation method for daily extreme temperatures was applied to and tested at 142 daily temperature series. At some of the stations (17 TX and 14 TN) homogenisation was not possible due to a lack of highly correlated reference stations or large uncertainties in the break adjustments. A temperature dependent break adjustment was used to correct the detected breaks.

A comprehensive analysis was performed with the remaining temperature time series, showing a widespread warming trend in both TN and TX series. The warming is generally amplified due to the homogenisation. Contrary to other studies in neighbouring countries (Simolo et al., 2010, Brunetti et al., 2006, Brunet et al., 2007) the mean trends in the indices associated with TN and TX respectively are generally consistent. The trends of the annual average TX and TN over all stations as well as the trend in the average TX10p (cold day-times: TX below the 10th percentile) and TN10p (cold night-times: TN below the 10th percentile) are almost identical. Even the mean trends in TN10p and TX10p have equal amplitudes. The only exception is the trend associated with the number of warm nights (TN90p) which is +0.2 days/decade stronger. However, DTR (diurnal temperature range) does not show a clear trend. Another interesting fact is the cooling trend in TX during autumn, with positive trend of TX10p and icing days (TX < 0°C) and a negative trend of TX90p and summer days (TX > 25 °C).

Daily precipitation series:

The slightly different homogenisation method for daily precipitation series was applied to the same stations as above. Since precipitation is a more variable parameter than temperature, the detection of significant breaks is more difficult. Therefore, after break detection, 68% of the precipitation series are expected to be homogeneous. At 11 stations homogenisation was impossible due to missing reference stations or large uncertainties in the break adjustments. A seasonal break adjustment was applied to the remaining 11 stations.

The evaluation of precipitation-related climate change detection indices reflects the variable nature of precipitation. The number of days with heavy (>20mm) and extremely heavy (>30mm) precipitation is significantly increasing in the southeast of Austria. On the contrary, the number of consecutive dry days (CDD) is significantly increasing in the south and slightly decreasing in the north of the alpine divide. However, the apparent CDD pattern is not balanced by reversed trends in the CWD (consecutive wet days) index.

2.1.3 Outlook:

The new homogenised and quality controlled dataset of daily maximum and minimum temperature as well as daily precipitation totals covering a period of 61 years (1948-2009) is now available for further analysis and investigations. In order to perform climate change studies based on extreme values in Austria this dataset forms an essential basis. From our point of view the following ideas for further use of this dataset are considered:

- The evaluated indices will be compared to an output from a regional climate model, in order to assess the model uncertainties.
- Grids will be constructed on the basis of the homogenised temperature data in order to evaluate the 2D changes related to the homogenisation.
- Different climate extreme studies will be performed on the basis of this dataset, e.g. dealing with the evolution of dry periods in the south of Austria or the autumn trend reversal connected to TX.

2.2 Content and Results of the project

2.2.1 Motivation

The project is based on two basic ideas:

- Development and improvement of daily homogenisation methods for extreme temperatures and precipitation totals.
- Evaluation of climate change detection indices based on the new homogenised dataset.

Various procedures already exist for the homogenisation of monthly and annual time series (e.g. Alexandersson and Moberg, 1997; Caussinus and Mestre, 2004; Böhm et al., 2001; Easterling and Peterson, 1995). Since many climate research studies are recently focusing on changes in the extreme events such as number of frost days, duration of heat waves, heavy precipitation events the need for quality controlled homogenised data on a sub-monthly scale is steadily growing. Up to now, these climate extreme studies in Austria were based on the Startclim dataset (Schöner et al., 2003), which is an outlier controlled but not homogenised daily temperature and precipitation dataset. During the last years first approaches have been developed for the homogenisation of daily temperature time series (e.g. Vincent et al., 2001; Trewin and Trevitt, 1996; Della-Marta and Wanner, 2006). Within this project some of the already existing methods were adapted and applied to Austrian time series of TX, TN and precipitation.

2.2.2 Goals

Following the above mentioned basic ideas of the project the major goals are:

- Development of a method for homogenisation of daily extreme temperature and precipitation series.
- An estimation of uncertainties accompanying the break adjustment as well as an estimation of the benefit gained by the homogenisation.
- A first climate change analysis based on the new homogenised dataset.

2.2.3 Method

Extreme temperature:

A combined application of the method PRODIGE (Caussinus and Mestre, 2004) for the detection of an unknown number of breakpoints and the method SPLIDHOM (Mestre et al., 2010) for the calculation of adjustments and the correction of time series was selected for the homogenisation of the extreme temperature series in Austria. The performance of different detection and homogenisation methods was tested in a pre-project, resulting in the above mentioned selection.

However before any detection of breakpoints, the first step of the homogenisation procedure is the optimal choice of reference stations. Reference stations are chosen according to their horizontal distance (less than 100 km) and their vertical distance (less than 200 m) from the candidate series and most importantly a high correlation coefficient ($\rho > 0.8$) of the temperature series. The distance criteria were included to prevent spurious correlations. The map in Figure 1 shows all stations which are utilized in this study. The larger black circles indicate the location of all candidate series, which are part of the STARTCLIM dataset (Schöner et al., 2003), while the black points indicate all additional climate stations which are used as reference stations. Additional information about the stations which were tested for inhomogeneities is given in table 1.

The complete procedure of homogenisation will be explained in detail in the following three sections. As an example the minimum temperature time series of the station **Mürzzuschlag** (number 59 in Figure 1) was selected. This candidate time series covers the period from 1948 to 2009. 12 surrounding stations fulfill the criteria to be selected as reference stations.

- Break detection

Following Caussinus and Mestre (2004) an adapted penalized log-likelihood procedure is used to detect an unknown number of multiple breakpoints in annual, seasonal or monthly temperature difference series following the equation:

$$C_K(Y) = \ln\left\{1 - \frac{\sum_{j=1}^{k+1} n_j\left(\bar{Y}_j - \bar{Y}\right)^2}{\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2}\right\} + \frac{2k}{(n-1)}\ln(n)$$

where n is the number of observations, k is the number of possible breakpoints, n_j is the number of observations within one homogeneous sub-period (between two breakpoints), $\bar{Y}_j$ is the mean of the difference time series within the sub-period and $\bar{Y}$ the mean of the entire difference time series. Difference time series were calculated for each time series with all available reference stations covering a common period greater than 5 years and not more than 1000 missing values.

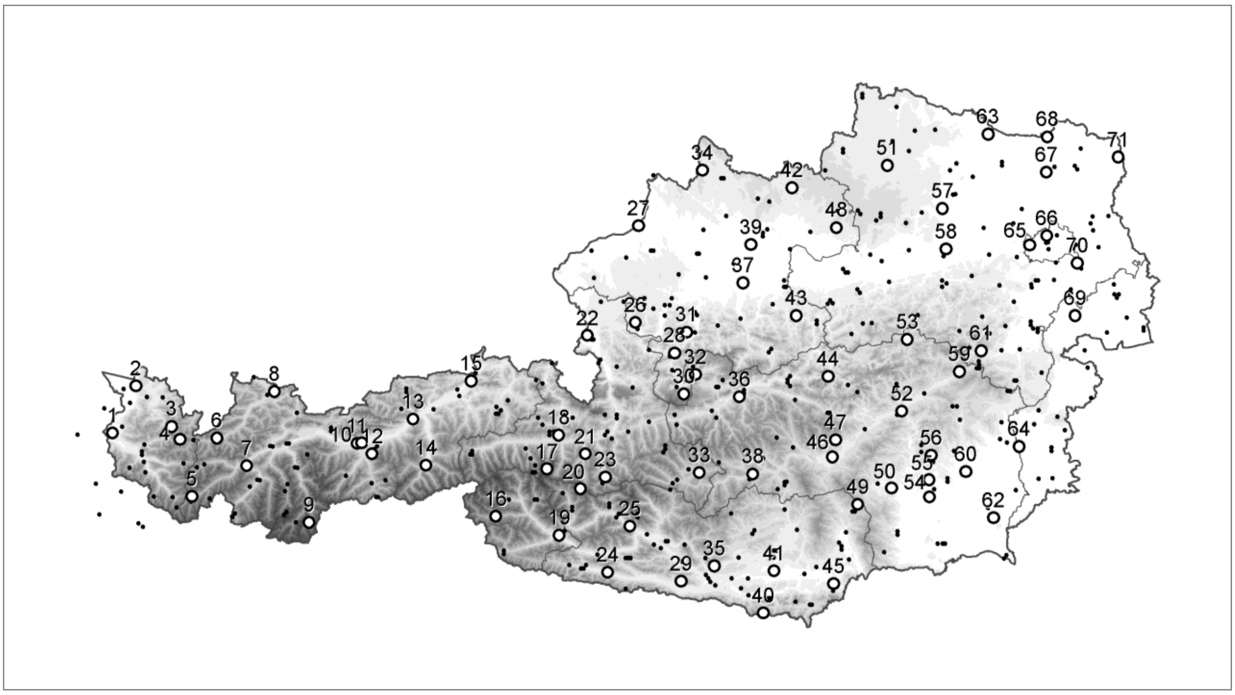

Figure 1: Location of the examined stations (large black circles – candidate station) and all other stations available in Austria (black points – reference stations). Note that not all reference station series cover the same period of time. Stations outside of Austria were provided by METEO Swiss. Numbers correspond to table 1.

These difference series were then tested for inhomogeneities following the equation above. The number of breakpoints and their location is determined according to their likelihood by minimizing $C_K(Y)$. Since the likelihood increases with an increasing number of breakpoints (overfitting), a penalize criterion has to be defined to overcome this problem. In literature different kind of criteria can be found. According to Mestre et al. (2010) the most recommended are those of Caussinus and Lyazrhi (1997), Jong et al. (2003) and Lebarbier (2005). Here breaks were detected using all three criteria (in the following denoted with CAU, JON, LEB). Additionally, breaks where detected in time series of annual mean values, winter means (DJF and NDJFM) and summer mean values (JJA and MJJAS). In order to make a sound first guess of break points the statistically detected breaks and metadata from the station archive are jointly plotted.

Metadata include all kind of information about the stations history, location, instrumentation, etc. and is very important for the homogenisation process, in order to evaluate the statistical break detection and to specify the exact break date. Metadata for all stations in table 1 were digitised from various types of old documents and are now available in a digital form for future investigation. Documents from which metadata is extracted range from letters directly addressed to the "Central Institute of Meteorology in Vienna", to bills, acknowledgement receipts of new measurement equipment or white colour to repaint the shelter, station pictures, maps and drawings. In general, metadata is remarkably good and complete for most stations, even though the quality strongly depends on the responsible observers and the persons responsible for stations inspections.

Figure 2 depicts meta information and results from the statistical break detection for the TN series in **Mürzzuschlag**, in order to get a good overview of the detected breaks. Although an objective method is used to detect breaks, the assignment of the breaks to the individual station series must be done subjectively. Attempts to automate the procedure fully, failed so far. The additional use of metadata is of great importance, especially to fix the exact date of the breaks and also to evaluate the performance of the statistical break detection. Since the uncertainty of the break detection with PRODIGE lies in the range of ±1 year the assignment of a break to a specific date strongly relies on the metadata information. However, even though the quality of metadata is remarkably good in Austria, the information is not available continuously and we cannot rely on the existence of metadata at every detected break. The first guess is generally selected following the self-defined criteria that significant breaks should be visible in at least two seasons and in at least two penalizing criteria. In Figure 2 the obvious choice of break date is the year 1977, which is supported by meta information on a station relocation on the 25th of April in the same year.

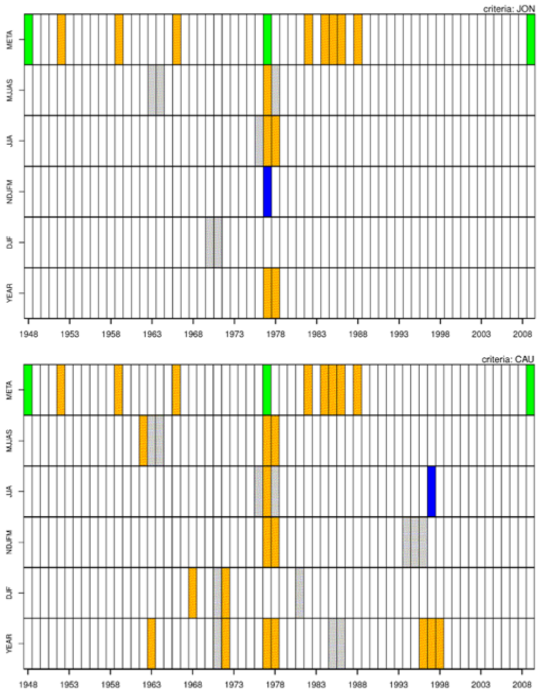

Figure 2: Visual break detection of the TN series of Mürzzuschlag using different penalizing criteria: JON top and CAU bottom. In the first line different colours show different meta events (e.g green: station relocation, orange: changes in the instrumentation). In the following lines the results of the statistical break detection for the summer half year, summer season, winter half year, winter season and the whole year are displayed. Orange lines indicate a significant number of breaks detected in the temperature difference series, red lines indicate that breaks were detected in more than 2 ratio series, blue in more than 1 series and grey one detected break within ±1 year.

	Name	Classification	Altitude [m]	TX info	TN info	PRECIP info
1	Feldkirch	city	439	1	1	0
2	**Bregenz**	lake side; city	436	0	0	1
3	Schoppernau	valley; village	835	0	0	0
4	Schröcken	valley; village	1260	1	1	0
5	**Galtür**	narrow valley; village	1587	2	2	1
6	Holzgau	valley; village	1100	2	2	0
7	**Landeck**	valley; village	818	1	1	1
8	Reutte	valley; village	870	1	1	0
9	Obergurgl	narrow valley; village	1938	2	2	0
10	Innsbruck airport	valley; airport	579	1	0	0
11	**Innsbruck university**	valley; city centre	577	1	1	0
12	Patscherkofel	moutain	2247	2	2	1
13	Jenbach	valley; village	530	1	1	0
14	Mayrhofen	valley; village	643	1	1	1
15	Kufstein	valley; municipality	492	0	0	0
16	St. Jakob im Def.	narrow valley; village	1388	1	0	0
17	Mooserboden	moutain	2036	0	2	2
18	Zell am See	lake side; city	751	2	1	0
19	Lienz	valley; city	659	1	1	0
20	Sonnblick	moutain	3105	2	2	2
21	Rauris	valley, village	941	1	1	2
22	**Salzburg airport**	airport	430	1	1	1
23	Bad Gastein	valley; village	1089	2	2	2
24	Reisach	valley; village	646	1	1	0
25	**Kolbnitz**	valley; village	603	1	1	1
26	**Mondsee**	lake side; village	482	1	2	0
27	Reichersberg	lowland; village	350	0	1	0
28	Bad Ischl	valley; village	469	1	1	0
29	Villacher Alpe	moutain	2140	2	2	0
30	Krippenstein	moutain	2050	2	2	1
31	Feuerkogel	moutain	1618	2	2	2
32	Bad Aussee	lake side; village	660	1	2	1
33	Tamsweg	valley; village	1022	1	1	2
34	Kollerschlag	lowland; village	725	0	1	0
35	Kanzelhöhe	moutain	1526	1	1	1
36	**Irdning - Gumpenstein**	valley; municipality	710	1	1	0
37	Kremsmünster	lowland; monostary	383	1	1	0
38	Stolzalpe	valley; village	1299	1	1	0
39	Hoersching	village; airport	298	1	0	0
40	Loibl	moutain; pass	1098	1	1	0
41	Klagenfurt	valley; city	447	2	1	0
42	Freistadt	valley; municipality	548	1	1	2
43	Großraming	valley; village	379	1	1	0
44	Hieflau	valley; village	779	1	0	0
45	St. Michael ob Bleiburg	valley; village	500	0	0	0
46	Zeltweg	valley; municipality	670	0	0	0
47	Seckau	valley; municipality	874	0	1	0
48	Pabneukirchen	lowland; municipality	595	1	1	0
49	Preitenegg	small moutain; village	1060	1	1	0
50	Lobming	lowland; village	414	1	1	0
51	Stift Zwettl	lowland; monostary	505	1	0	0
52	Bruck an der Mur	valley; small city	489	0	0	0
53	**Mariazell**	valley; village	865	1	2	0
54	**Graz airport**	city; airport	337	1	1	0
55	Graz university	city centre	366	1	1	0
56	Schöckl	moutain	1436	2	2	1
57	**Krems**	river side, city	190	1	1	2
58	**St. Pölten**	city centre	272	1	1	2
59	**Mürzzuschlag**	valley; small city	758	0	1	0
60	Gleisdorf	lowland; village	375	0	1	0
61	Reichenau an der Rax	valley; municipality	485	0	1	0
62	Bad Gleichenberg	lowland; village	300	0	1	0
63	Retz	lowland; village	256	2	2	0
64	Wörterberg	lowland; village	400	1	2	0
65	Wien - Mariabrunn	city	227	2	2	2
66	Wien - Hohe Warte	city	198	1	1	0
67	Oberleis	lowland; village	420	1	0	2
68	Laa an der Thaya	lowland; village	185	1	1	0
69	Eisenstadt	small city	184	1	1	0
70	**Schwechat**	airport	184	1	1	0
71	Hohenau	lowland; village	155	1	1	2

Table 1: Information about the candidate stations (0 - no homogenisation necessary; 1 - homogenisation; 2 - homogenisation not possible)

- Homogenisation – Break adjustment

After the first guess break detection the method SPLIDHOM (Mestre et. al, 2010) was used for correcting the breaks. In practice break detection and break adjustment were realized alternately, by evaluating the applied adjustment, if necessary adapting the break date, recalculating the adjustment etc. SPLIDHOM is a method for sequential adjustment of breaks in time series, relying on the good relationship between the candidate series and the highest correlated reference station. It is based on a nonlinear regression function between the temperature measurements. In a first step the nonlinear regression between the 2 series is estimated for both the period before and after the break point. To circumvent the problem of additional inhomogeneities in the reference series, the regression function is estimated using a classical smoothing spline. The smoothing parameter of the cubic spline is estimated for each regression by means of a standard cross-validation technique, in order to avoid over fitting. Figure 3 shows the adjustments for the selected break point in 1977 in the TN series of Mürzzuschlag for season 1 (winter: december/january/february), season 2 (spring: march/april/may) and season 4 (autumn: september/october/november). The thin red line in the upper panel indicates the adjustment before the smoothing while in the lower panel the thicker red line indicates the adjustment after applying the spline smoothing. The adjustments are generally positive, with amplitudes of up to 2°C for very low temperatures in autumn.

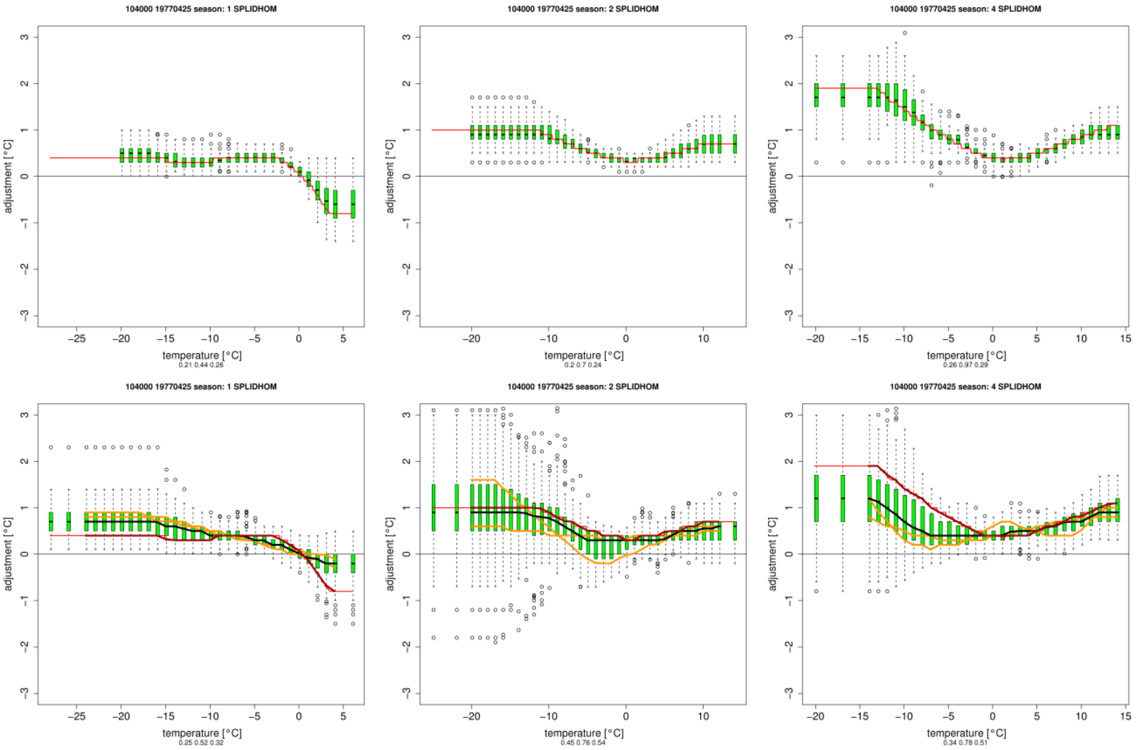

Figure 3: top: The red lines indicated the adjustment for the TN series in Mürzzuschlag calculated by SPLIDHOM using the highest correlated reference station. The boxplots represent the uncertainties of the correction, which was calculated with a bootstrapping method. Each boxplot is based on 50 samples. The dotted line shows the data range, while the small circles indicate outliers. Season 1, 2 and 4 (shown in the different columns) represent winter, spring and autumn respectively. bottom: Similar to upper row but including adjustments calculated with two further reference stations. Red is again the adjustment of the highest correlated station and orange of the two other reference stations. The black line indicates the mean of the 3 adjustments.

- Uncertainties of the adjustment

The uncertainties of the adjusted breaks are determined by means of a bootstrapping method and by altering reference stations. In that way not only the break intensity but also the break uncertainties are evaluated in order to decide which breaks need to and can be corrected. The uncertainties associated with the 1977 break adjustment in the TN series in **Mürzzuschlag** are shown in Figure 3 for 2 different seasons. The boxplots, which were calculated by a boostrapping method with a sample size of 50, indicate the uncertainty of the applied adjustment. The orange lines in the lower panel in Figure 3 depict the adjustments calculated with reference series 2 and 3. Especially in the winter and spring months the uncertainties of the adjustment calculated with the highest correlated reference station are very small. Concerning the other two reference stations, uncertainties rise up to the order of magnitude of the adjustment itself for the lower temperatures. These differences might be connected to local phenomena like cold air pools. However, since the shape and slope of the adjustments are similar we can still consider the break adjustment to be reliable.

Precipitation:

Similar to temperature, a combined application of the method PRODIGE (Caussinus and Mestre, 2004) for the detection of an unknown number of breakpoints and an adapted version of INTERP (Vincent et al., 2001) for the calculation of adjustments and the correction of time series was selected for the homogenisation of daily precipitation time series in Austria.

Before starting the homogenisation procedure, reference stations had to be chosen. Since precipitation is a more variable parameter than temperature the threshold for the correlation coefficient had to be slightly modified and is selected to be ρ > 0.7 on a monthly basis and ρ > 0.6 on a daily basis. Furthermore, precipitation stations from the hydrographic service of Austria (HZB) were included as reference stations.

The map in Figure 4 shows all stations which were tested for inhomogenities (large black circles) and all available reference stations (red: ZAMG stations and blue: HZB stations). Additional criteria for the selection of reference stations are a common minimum length of 5 years and not more than 1000 missing values. More information about the stations selected for homogenisation can be found in Table 1.

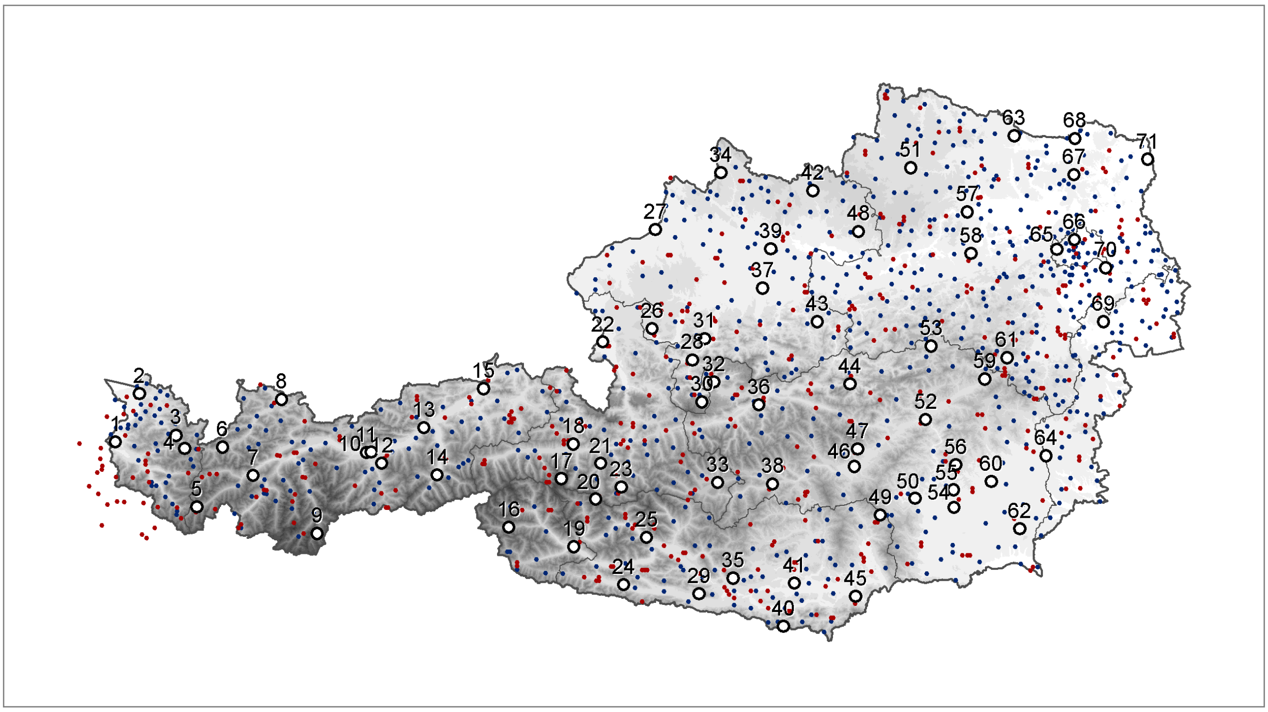

Figure 4: Map of Austria with all STARTCLIM stations (large black circle), plus additional reference stations operated by ZAMG (red) and HZB (blue). Stations outside of Austria were provided by METEO Swiss. Numbers correspond to table 1.

- Break detection:

The method PRODIGE (Caussinus and Mestre, 2004) was used to detect a multiple number of breaks in daily precipitation series. Contrary to temperature series, precipitation time series were tested for changes in precipitation sums and also precipitation frequency. Therefore monthly or seasonal time series with the number of days exceeding 5mm of precipitation were constructed. This time series were compared to the respective series from the neighboring stations in order to perform the break detection. Concerning precipitation sums, monthly ratio (candidate/reference) time series were tested for inhomogeneities. A more detailed explanation of PRODIGE can be found in Caussinus and Mestre (2004) or the temperature homogenisation part of this final report.
The break detection method together with the selection of reference stations was tested with a monthly precipitation benchmark dataset provided by the COST-Action Home (ES0601, ftp://ftp.meteo.uni-bonn.de/pub/victor/costhome/). In general the method works well for large breaks, but drastically underestimates the number of smaller breaks.

The different steps of the homogenisation procedure will be illustrated by an example daily precipitation series from **Salzburg airport** (number 22 in Figure 4). Figure 5 shows the location of the candidate station (black circle, number 63000) and all reference stations which were used for break detection. A total number of 19 reference stations were found with a maximum distance of approximately 75 km from **Salzburg airport**.

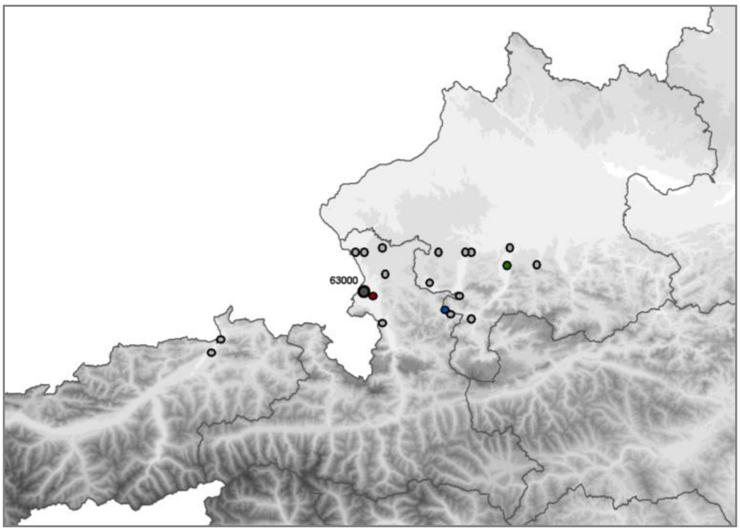

Figure 5: Map of surrounding of Salzburg: Salzburg airport (black), first reference (red), second reference (blue), third reference (green), additional reference stations (grey) for break detection.

The statistically detected breaks as well as the available meta data are shown in Figure 6 and Figure 7, for the daily precipitation totals and the frequency series respectively. The plots are similar to those of the break detection in the temperature series. Breaks are detected with three different criteria (CAU, JON and LEB, more info in the temperature part) - here only two of them are shown. The second line in each plot indicates the metadata information, with green bars showing station relocations and orange bars changes in instrumentation. The following 5 lines show breaks detected in the summer half year, summer month, winter half year, winter month and annual time series. Here, breaks which are indicated in orange were detected in more than 50% of the difference time series and are considered as significant. Blue boxes show years where only one break was detected in one difference series and red boxes years where a break was detected in the same year in at least two series. Grey are those years where the sum of detected breaks within +/- 1 year is larger than two.

In Figure 6 a break can be identified in the years between 1995 and 1997 in the winter season and on an annual basis. The break date is additionally supported and localized by metadata information.

The station was relocated further away from the airport building and closer to the runway on the 17th of December 1997. Figure 7 shows very similar features for the frequency series, with slightly more pronounced breaks in the winter months. A general rule for break identification in Figure 6 and Figure 7 is the existence of at least 2 yellow bars within 1 year in at least two criteria.

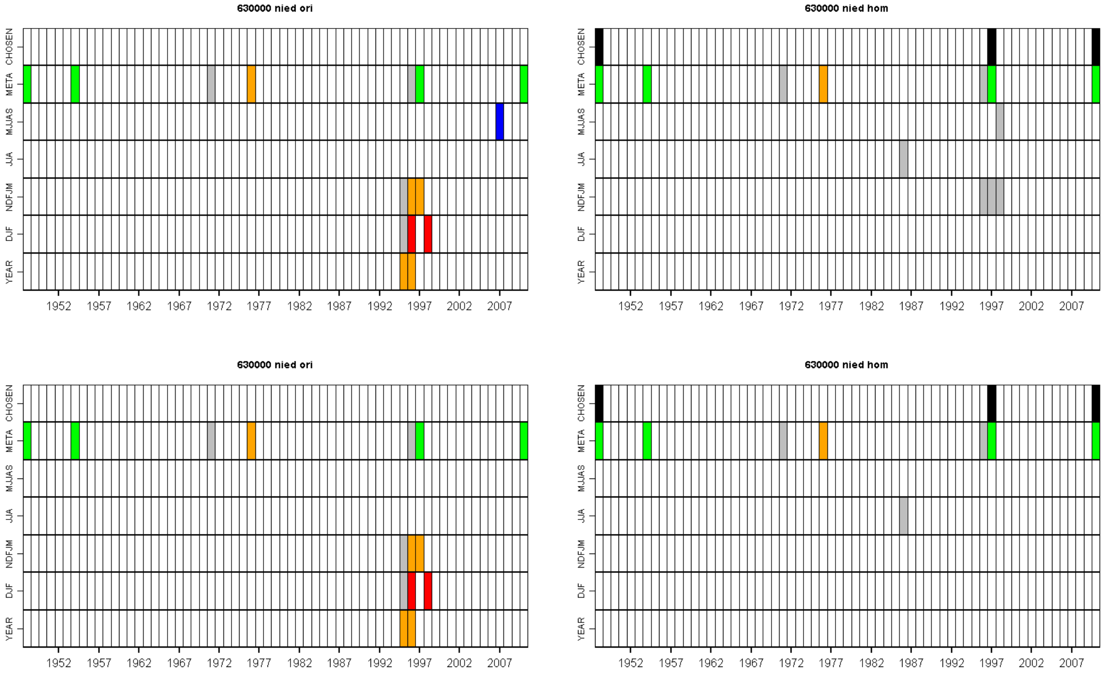

Figure 6: Prodige results analysing precipitation amounts for original data (left side) and homogenised data (right side) at Salzburg airport. In the two rows two out of three different criteria are displayed (top: CAU, bottom: JON). The black lines in the first row of each graph on the right show the location of the beginning and ending of the examined time series and the timing of the break. In the second row metadata information is displayed. Different colours show different events (e.g green: station relocation, orange: changes in the instrumentation). In the following rows the results of the statistical break detection for the summer half year, summer season, winter half year, winter season and the whole year are displayed. Orange lines indicate a significant number of breaks detected in the precipitation ratio series, red lines indicate that breaks were detected in more than 2 ratio series, blue in more than 1 series and grey one detected break within ±1 year.

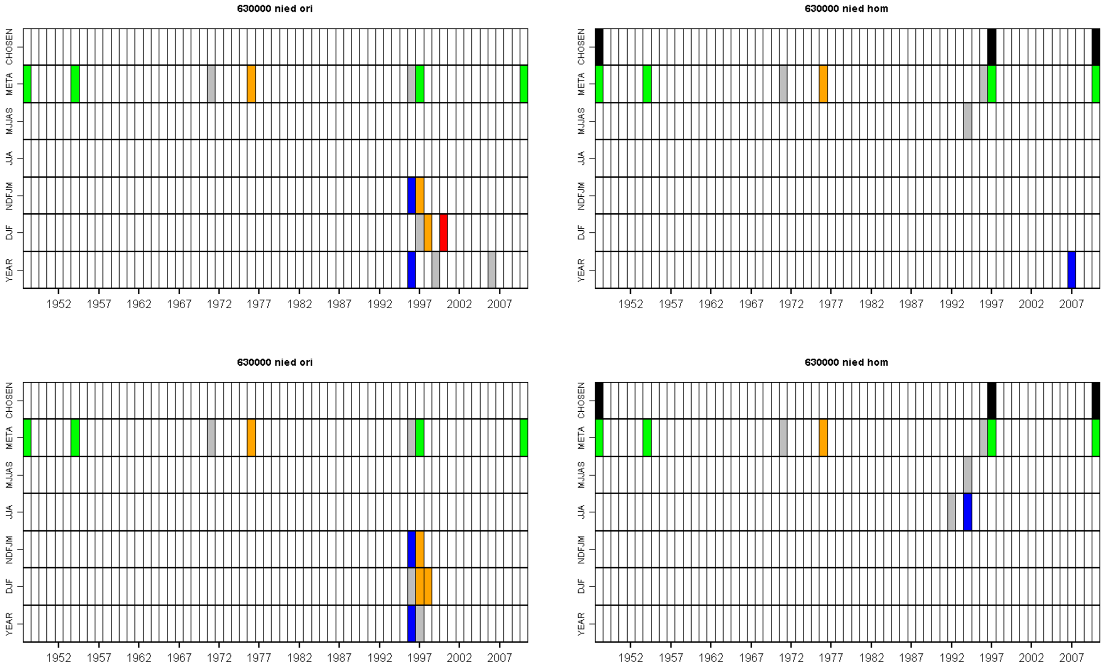

Figure 7: Same as Figure 6 but for the monthly frequency series.

- Break adjustment:

After the first guess break detection (in the case of **Salzburg airport**: 17/12/1997) a correction method following the basic idea of the INTERP procedure (Vincent et al., 2001) is applied to the daily precipitation time series. Vincent et al. (2001) interpolates breaks found in monthly extreme temperature series in Canada on a daily basis by means of a transformation matrix.
The method was adopted in two ways: First the adjustments are calculated on a seasonal rather than a monthly basis and second the adjustments are not smoothed nor interpolated on a daily basis. In case of temperature it is reasonable to relate daily temperatures of candidate and reference series before a break with daily temperatures of candidate and reference series after a break in order to gain an adjustment factor for the break correction. Since precipitation is a temporally and spatially highly variable parameter, a daily relationship between candidate and reference series is not appropriate. Therefore monthly totals were calculated for each time series (e.g. $cand_{bef,season}$: monthly precipitation totals of the candidate time series before the break; before means in the earlier years). For each season the median of the ratio between the monthly candidate and reference series was calculated for the period before and after the break. The ratio of those two yields to the seasonal adjustment factor (see equation 1). The adjustment is calculated on a seasonal basis to decrease the influence of potential outliers by increasing the number of values which are used to calculate the median. The median is more appropriate than the arithmetic mean due to the statistical distribution of precipitation sums. Further, monthly precipitations sums are only calculated using days with non-zero precipitation at the candidate and reference station.

$$adjustment[season] = \frac{median\left(\frac{cand_{aft,season}}{ref_{aft,season}}\right)}{median\left(\frac{cand_{bef,season}}{ref_{bef,season}}\right)} \qquad (1)$$

Contrary to INTERP, the adjustments are not smoothed in this method as the differences between the seasons are less pronounced than for temperature and any kind of smoothing would increase the uncertainty of the adjustments. Moreover, the adjustment for precipitation is multiplicative meaning that each daily measurement is multiplied by a specific factor which makes the absolute adjustment dependent on the precipitation sum itself. The adjustment for the 1997 break at the airport station in Salzburg is shown in Figure 8.

- Adjustment uncertainties:

The uncertainties of the adjustments are estimated by means of bootstrapping and by comparing adjustments calculated with different reference stations.
In general, bootstrapping is a resampling technique e.g. used to estimate uncertainties of statistics. Here, the monthly dataset is resampled 50 times in order to recalculate the seasonal adjustments and to gain information about the possible range of values. In Figure 8 the adjustment, calculated with the highest correlated reference station is plotted together with the 5% and 95% quantiles of the bootstrapping distribution of possible adjustments. In this case the range between the different bootstrapping adjustments is small throughout the different seasons, indicating an adequate break adjustment. The amplitude of the break is the largest in winter and is then decreasing from season to season reaching almost one in autumn.

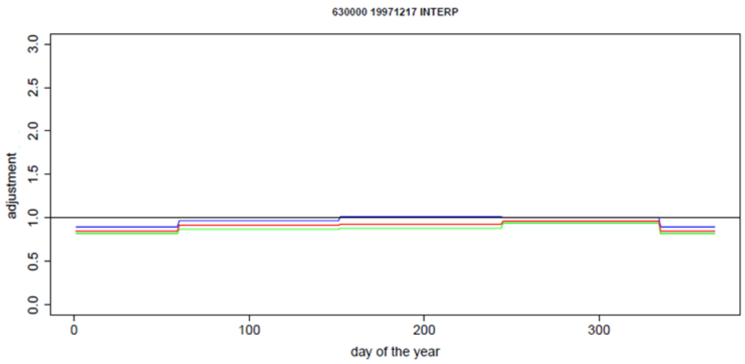

Figure 8: Adjustment of the 1997 break at Salzburg airport, calculated by a comparison of the data with the highest correlated reference station (in red). The blue and green lines show the 5th and 95th percentile of the bootstrapping adjustments. On the y-axes the adjustment factor is displayed - no correction is applied with a factor 1.

Uncertainties are further estimated by comparing the adjustments calculated with the highest correlated reference station with those adjustments gained with other reference stations. Figure 9 shows the adjustments of three reference stations plus the mean of these adjustments. The red lines in Figure 8 and Figure 9 are identical and show the adjustments calculated with the highest correlated reference station, which was further used for the homogenisation. The green and blue lines in Figure 9 show the adjustments calculated from the 2nd and 3rd reference and the black line the mean of the different adjustments. Especially in spring and autumn there are only small differences between the adjustments from the different reference stations. In summer the differences between the results are less pronounced than in winter and nearly no differences can be notices during spring and autumn.

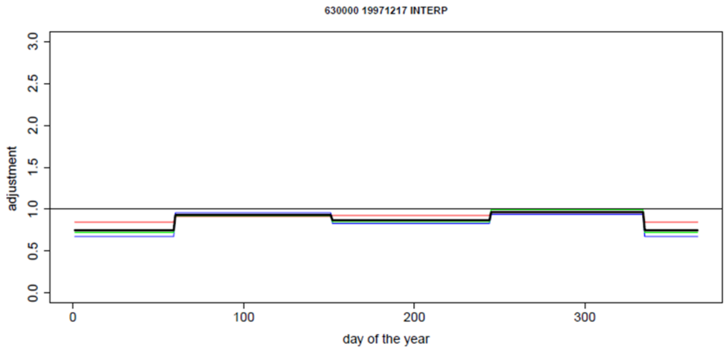

Figure 9: As Figure 8 but for different reference stations (1. red, 2. blue, 3. green) and the mean of these adjustments (black) for each season.

Figure 10 a scatter plot of daily precipitation totals of the original (x-axes) and the homogenised series (y-axes) is displayed. The points along the identity represent the part of the time series which was not homogenised. The other points, arranged along different lines display the data of the different seasons which are corrected with different adjustment factors.

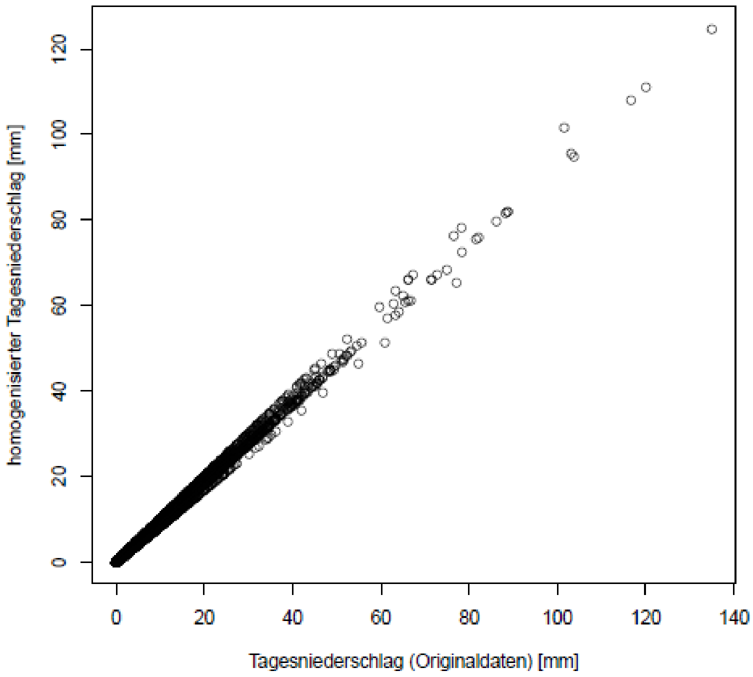

Figure 10: Comparison between original (x-axes) and homogenized (y-axes) daily precipitation data [mm]. The different lines represent for different seasons and the not homogenised part of the data (identity).

In general, a visual recognition of breaks in seasonal or annual precipitation series is hard due to the large interannual variations. However, a good and illustrative counterexample was found at the station **Galtür** (number 5 in Figure 4). Figure 11 displays the annual precipitation sum of this station. A period of higher precipitation sums is evident in the original precipitation sums (black line) between 1987 and 1974. In the homogenised datasets (red and orange lines) these breaks are removed by adjustments of up to 40% between 1974 and 1987 and very small adjustments before the first break.

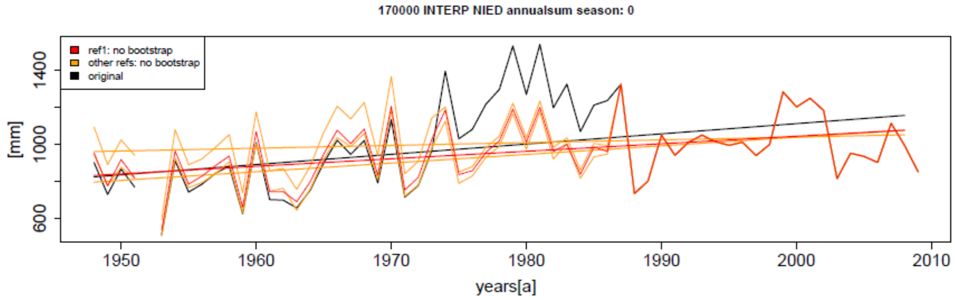

Figure 11: Yearly precipitation sum [mm] for Galtür (170000). The black line displays the original data, red the applied homogenization and orange the homogenization if one of the other two reference stations would have been used.

After applying the adjustments, break detection with PRODIGE is repeated for the homogenised time series, to see if the homogenisation had a positive effect and the time series is more homogeneous. The results for Salzburg airport are shown in Figure 6 (intensity) and Figure 7 (frequency) in the right column. The black bar in the first line indicates the break year, the end and the beginning of the time series. After the homogenisation no break signal is found in the corrected data. The break, visible in the frequency of 5mm-precipitation sums in the original data (Figure 6, left side), is removed by the homogenisation as well.

The removal of breaks in the frequency is a common feature in most of the precipitation homogenisations as the correction of the precipitation amount by a factor changes the frequency of precipitation events exceeding 5mm as well. Therefore the removal of breaks in the frequency is therefore an indicator, that the correction of the precipitation data is trustworthy.

2.2.4 Results and milestones

<u>Extreme temperatures:</u>
The method described in the previous section was applied to 71 minimum (TN) and maximum (TX) temperature series in Austria (Figure 1). For some series homogenisation was not possible due to large uncertainties in the break adjustments or a lack of suitable reference stations. These stations, 14 TN and 17 TX series, are indicated with grey circles in Figure 12. Most of the series where homogenisation was not possible are either located at high elevations where station coverage is low (e.g Feuerkogel, Patscherkofel, Sonnblick, Krippenstein), in narrow valleys (e.g. Galtür, Obergurgel, Bad Gastein) or close to lakes (e.g. Mondsee – only TN, Bad Aussee – only TN, Zell am See – only TX). The latter two are strongly influenced by local effects, topographic or hydrological, which drastically reduce the number of highly correlated reference stations and increase uncertainties in the adjustments.

- Break statistics

In the remaining 57 TN and 54 TX stations a total number of 139 (TX: 74 and TN: 65) breaks were detected. Almost half of the temperature series were affected by only one break, another 20% by two breaks, approximately 25% of the stations were classified as homogeneous after break detection while in a small number of stations more than two breaks were detected (see Figure 12).

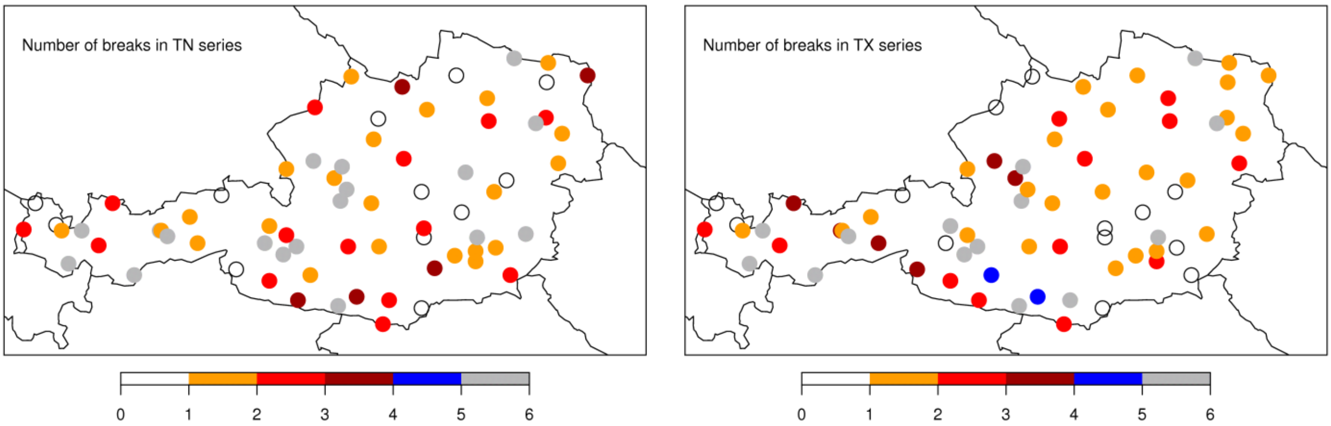

Figure 12: Number of detected breaks in TN (left) and TX (right) series. White circles: homogeneous time series, yellow dots: series with one break, red dots: series with 2 breaks, dark red dots: series with 3 breaks, blue dots: series with 4 breaks, grey dots: stations where homogenisation was not possible.

Compared to many other European countries, metadata quality in Austria is remarkably good and a high number of detected breaks coincide with events recorded in the station archive. In Table 2 a list of metadata events together with the number of breaks occurring at the same time is given. Remarkable 74% of the events match with information from the station archive, with 36% being caused by station relocation. Only 16% of the breaks could not be confirmed by meta information.

Metadata event	**Number**
Station Relocation	50
Instrumentation change	23
Screen shelter	16
Observer change	8
other information	6
break without metadata	36
Total	139

Table 2: Typ and number of metadata events accompanied by a detected and adjusted break point.

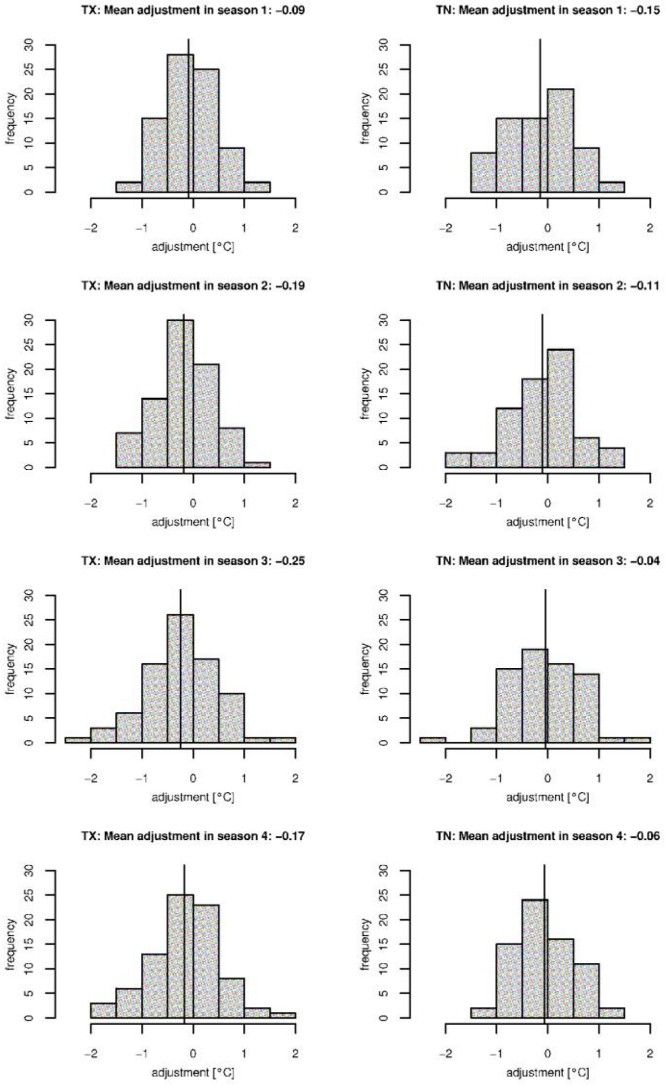

Figure 13: Mean break adjustment of all homogenised time series for the different seasons (1: winter, 2: spring, 3: summer, 4: autumn), left for TX and right for TN. In the title and as a vertical line the mean adjustment is indicated.

The strength of the mean break adjustments are evaluated in Figure 13, with seasonal adjustment for TX on the right compared to seasonal adjustments for TN on the left.

In general, the mean seasonal adjustment over all stations is negative, although almost zero for TN in summer and autumn and for TX in the winter months, indicating an intensification of the overall warming trend. Largest adjustments occur in the summer months, with amplitudes of up to 2.5 °C. In winter adjustments stay within the range of ±1.5°C, which is linked to the lower variations in the temperature distribution. However, most adjustments are rather small within a range of ±0.5°C.

- Trends in climate change detection indices

16 temperature based climate change detection indices, namely frost days (FD), summer days (SU), icing days (ID), tropical nights (TR), growing season length (GSL), monthly maximum of TX (TXx), monthly maximum of TN (TNx), monthly minimum of TX (TXn), monthly minimum of TN (TNn), cold nights (TN10p), cold day-times (TX10p), warm nights (TN90p), warm day-times (TX90p), warm spell duration index (WSDI), cold spell duration index (CSDI) and diurnal temperature range (DTR), were evaluated for the homogenised as well as the original temperature time series following the WMO guidelines (Alexander et al., 2006, Klein Tank et. al, 2009). The first 5 indices (FD, SU, ID, TR, GSL) result from a “peak-over-threshold” method and represent the number of days where temperatures exceed a predefined threshold, such as summer days being days with TX higher than 25°C. The following 4 indices (TXx, TXn, TNx, TNn) refer to absolute extreme values and therefore very much dependent on data quality. The subsequent indices are based on a so-called “block-maximum” method. Here the 10th and 90th percentiles are calculated for a 5 day window centred on each calendar day within a defined base period, resulting in an annual cycle of e.g. 10th percentiles of TX. Similar to the “peak over threshold” method the number of days exceeding this threshold is counted. Klein Tank and Konnen (2003) note that indices based on percentiles, since being site specific, should be preferred for spatial comparisons. Finally, duration indices (WSDI & CSDI) define periods of persistent cold or warmth. A full descriptive list of the indices can be obtained from http://cccma.seos.uvic.ca/ETCCDMI/list_27_indices.shtml. For the trend assessment, a simple least squares method is applied to the annual and seasonal indices.

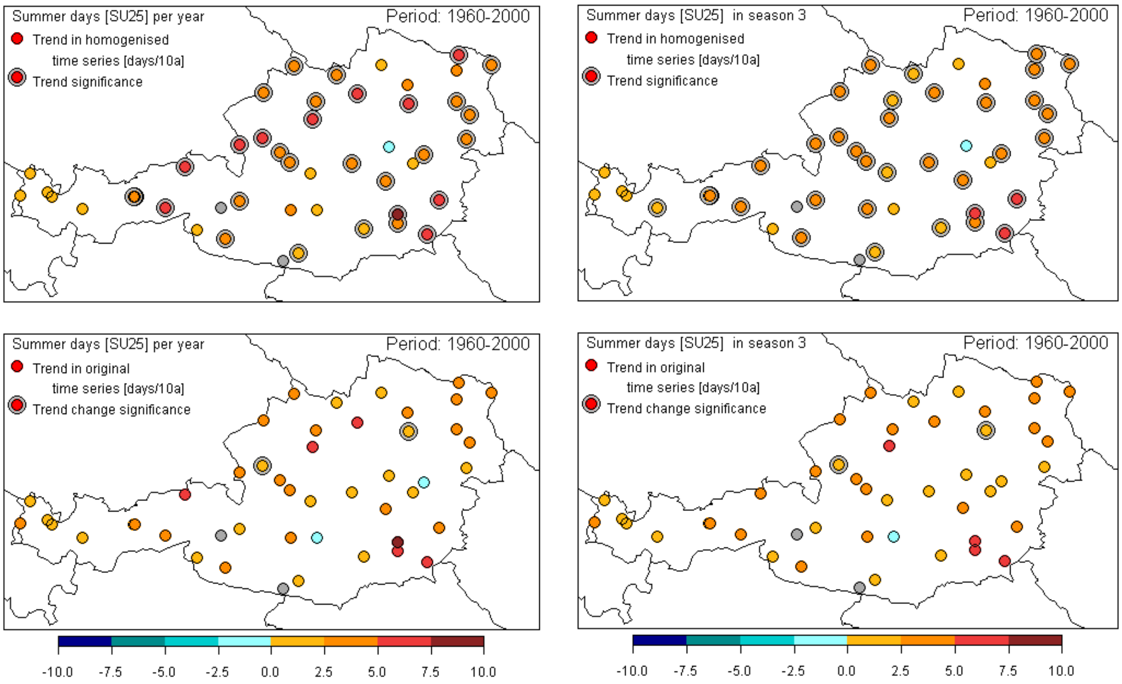

Figure 14: Comparison of trends in the number of summer days [days/decade] before and after homogenisation for the period 1960-2000 for all stations Austria. The map shows bullets with concentric bands for each station. The inner circle in the upper panel shows the amplitude of the trend in summer days of the homogenised time series. The grey bands indicate whether the trend is significant. The lower panel shows the trend amplitude before homogenisation.Trend change significance is again indicates with a grey band. On the left trends are shown for the annual number of summer days and on the right for the number of summer days during the summer months (season 3).

The inner circles in Figure 14, Figure 16 and Figure 17 indicate the magnitude of the trend, for both the homogenised time series and the original time series in Figure 14 and Figure 17 and only the homogenised time series in Figure 16. Using a so-called moving-block-bootstrap procedure (Kiktev et al., 2003) the uncertainty of the trend is calculated on a 5% significance level. The time series of each station is sampled 50 times and instead of sampling single values a sequence of consecutive values is chosen to account for the autocorrelation in the data. The length of each sequence depends on the autocorrelation. Following Moberg and Jones (2005) each sequence is chosen to consist of 2 values. A trend is considered as significant if this confidence interval does not contain a zero trend. In Figure 14, Figure 16 and Figure 17 the significant trends are indicated with grey bands around the circle of the trend magnitude of the homogenised time series. Further, trends in homogenised data are considered significantly different from trends in original data if the uncertainty range of the trends calculated from original and homogeneous data do not overlap. In Figure 14 and Figure 17 the significant trend changes are indicated with grey bands around the trend circles of the original time series.

The period 1960-2000 has been chosen for evaluation. Thus maps include all stations where homogenisation was possible and which cover the whole period, adding up to 47 TX series and 43 TN series. Figure 14 illustrate trend magnitudes, trend significance and trend change significance for the climate change detection index summer days (SU) for the annual values and seasonal summer values. Summer days are defined as days where TX exceeds 25°C. A widespread significant positive trend in summer days is visible in all 4 graphs. For the annual and seasonal values the trend generally increases due to the homogenisation. However, trend changes due to the homogenisation are only significant at two stations, **Mondsee** and **St. Pölten** (number 26 and 58 in Figure 4). The trend change due to the homogenisation in **St. Pölten** is shown in more detail in Figure 15.

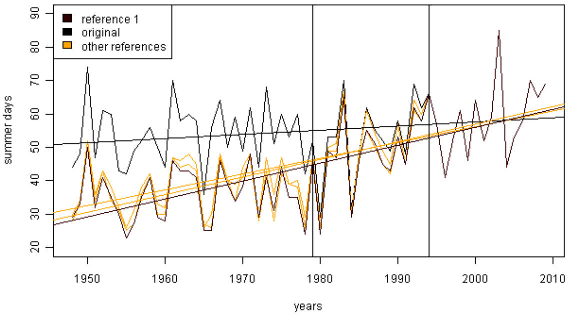

Figure 15: Number of summer days at the station in St. Pölten: in black the original time series, red the homogenised time series and orange the time series homogenised with the 2nd and 3rd highest correlated reference station.

The black line indicates the number of summer days calculated on the basis of the original TX series, while the red and orange lines show the summer days based on the homogenised data set. Especially the break adjustment in 1979 (horizontal black line) drastically reduces the number of summer days and accordingly raises the trend. Uncertainties related to the choice of reference stations are rather small, indicating a reliable break adjustment.

In Figure 16 trends and trend significances of cold day-times (TX10p) are shown for all 4 seasons. In winter (season 1) trends cover a wide range from -0.02 days/decade in **Krems** (number 57 in Figure 4) up to -4.9 days/decade at stations in the alpine regions (e.g. **Innsbruck** or **Irdning**; number 11 and 36 in Figure 4). The range between the stations is slightly decreasing towards the summer months, while the mean trend over all stations is growing more negative reaching -2.9 days/decade in the summer season. However, in autumn the trends are partly reversing the sign suggesting a slight increase in cold days especially in the eastern parts of Austria. The same feature is found in other climate change indices based on daily TX series, e.g. TX90p, SU25, ID (icing days: TX < 0°C), while TN series show only a weak signal in TN10p. On a monthly basis the HISTALP dataset (Auer et. al. 2007) shows similar features, with less warming in the months September, October and November. The distinct behaviour of extreme temperatures based indices in autumn is also confirmed for other countries (e.g. Yan et al, 2002, Cahynová and Huth, 2009). Cahynová and Huth (2009) further analysed the relationship between trends in daily TX, TN and mean temperatures and the circulation pattern for the Czech Republic and found that, depending on the classification of synoptic patterns, changes in the atmospheric circulation can explain a great part of this cooling trend.

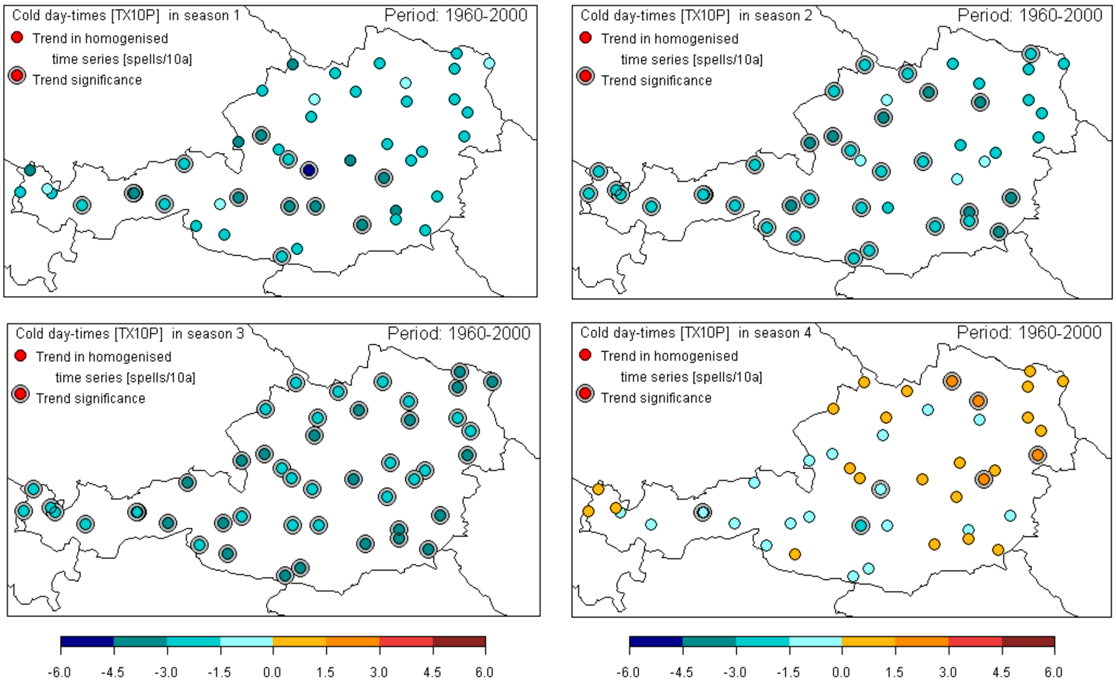

Figure 16: Same as upper panel in Figure 14 but for TX10p (cold day time) for all seasons (1: winter, 2: spring, 3: summer, 4: autumn)

Figure 17 depicts the two percentile threshold based indices for TN, cold nights (TN10p) and warm nights (TN90p). Both indices show significant trends at almost all stations, with an increasing number of warm nights and a decreasing number of cold nights. The only station with a reverse trend in both indices is located in the narrow Defreggen valley in the Southern Alps. The reason is puzzling, as the trend seems to represent a climatic signal because no breaks where detected and no adjustment was applied to the series.

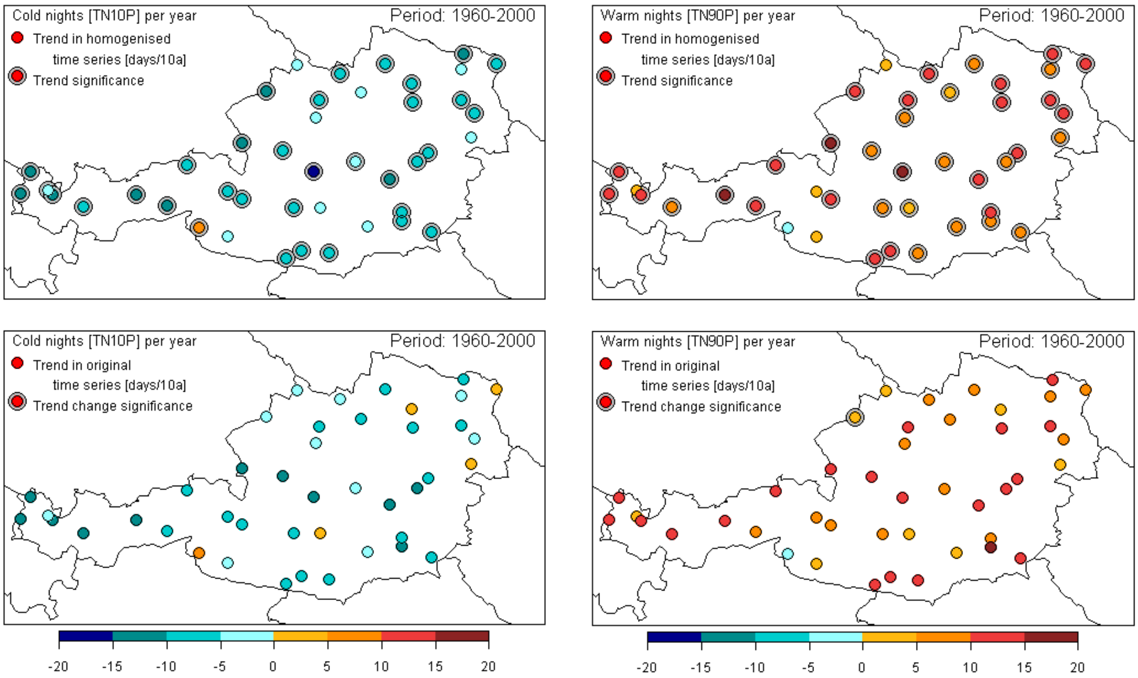

Figure 17: Same as Figure 14 but for TN10p (cold night times) on the left and TN90P (warm night times) on the right.

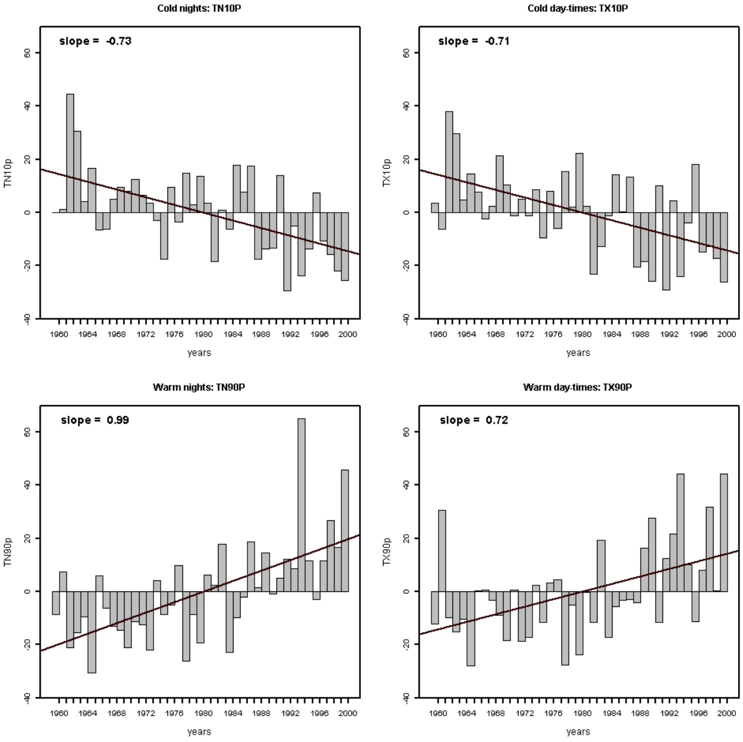

Figure 18: Anomalies of the mean number of cold nights, cold day-times, warm nights and warm day-times over all stations in the dataset. The red line shows the linear trend.

Finally, the trends of percentile based indices for both TX and TN are compared by building the anomaly of the annual mean over all indices of all available homogenised stations in the period 1960 to 2000 (Figure 18). Even though the inter-annual variability is strong for all indices, a clear warming trend is visible. The trends in the 10th and 90th percentile of the TX series have the same magnitude, indicating a consistent warming of maximum temperatures. On the contrary, the trend of the higher percentiles of the minimum temperature series is stronger than for the lower percentiles (Figure 18, left column). In the diurnal temperature range (DTR) this trend is not clearly visible. A slight increase in DTR can be found in the southern parts of Austria, while the signal is rather diverse in the other parts of the country. Alexander et al. (2006) supports these results on a global scale showing that trends in indices derived from minimum temperature show more distinct changes than those based on maximum temperatures. However, similar studies in Italy (Simolo et al., 2010, Brunetti et al., 2006, Toreti et al., 2006) or Spain (Brunet et al., 2007) show more pronounced trends in the TX series.

Precipitation:

The homogenisation method described above was applied to 71 daily precipitation series (see Figure 4). Contrary to the extreme temperature series, significant breaks could only be detected in a small number of precipitation series. At these stations the break adjustment method was applied. For another 11 stations homogenisation efforts turned out to be unsuccessful, due to missing reference stations or large uncertainties in the adjustments (see table 3). A list of all stations with information about the homogenisation is given in Table 1.

	number	percentage
homogeneous	49	69%
homogenisation not possible	11	15.5%
homogenised	11	15.5%
	71	100%

Table 3: Statistics of the homogenisation of the precipitation dataset.

- Trends in climate change detection indices

Based on the new homogenised dataset of daily precipitation totals 10 precipitation-related climate change detection indices were evaluated (Alexander et al., 2006, Klein Tank et al, 2009). Among those are: Maximum one-day precipitation (RX1day) per year, maximum five-day precipitation (RX5day) per year, simple daily intensity index (SDII) which is the mean precipitation amount on a wet day, heavy precipitation days (>10mm - R10mm), very heavy precipitation days (>20mm, R20mm), extremely heavy precipitation days (>30mm, R30mm), consecutive dry days (CDD), consecutive wet days (CWD), precipitation due to wet days (>95th percentile; R95pTOT), precipitation due to very wet days (>99th percentile; R99pTOT) and total precipitation sums on wet days (PRCPTOT). Wet days are defined as days with more than 1mm of precipitation. A full descriptive list of all climate change indices can be obtained from http://cccma.seos.uvic.ca/ETCCDMI/list_27_indices.shtml.
The calculation period was defined to be 1971-2000, because 55 out of 60 precipitation series cover the full 30-year period. Five mountain stations were excluded from this analysis due to large uncertainties in the measurements caused by stronger wind speeds (Sevruk et al., 1994). In contrary to the temperature-based climate change indices, precipitation indices are generally much more variable and show far greater regional differences.

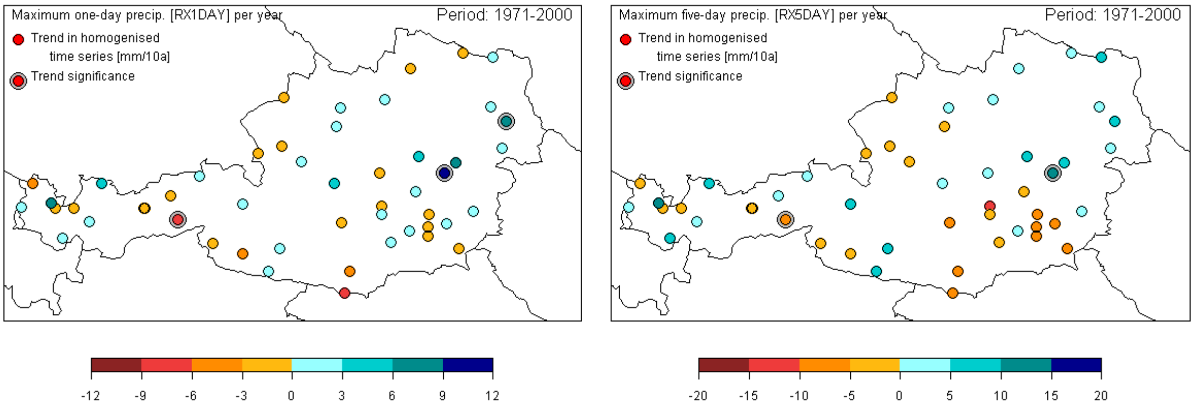

Figure 19: Trend of maximum one-day precipitation for the period 1971-2000 for all homogenised precipitation series in Austria (left). On the right trends of maximum five-day precipitation for the same period and the same stations are shown.

Both graphs in Figure 19 clearly show the variable behavior of daily precipitation sums, especially related to absolute maxima. A tendency, although not very significant, towards weaker precipitation events can be seen in the southeastern parts of Austria. The northeast experiences a weak intensification of maximum five-day precipitation sums, which is however less pronounced in the one-day precipitation sums. In the western, alpine regions the signal is even more variable with stations with positive and negative trends located very close to each other.

Looking in detail at the station in **Schwechat** (number 70 in Figure 4; in the southeast of Vienna, figure 20 left) we realize the effect of one single precipitation events on the overall 30 year trend (see figure 20, right). The most prominent event, with a maximum one day precipitation sum of more than 90 mm in 1995, is related to a 3 day period with widespread precipitation in all parts of Austria in mid September. The spatial distribution of precipitation sums at various stations surrounding **Schwechat** on the 14th of September in 1995 is illustrated in Figure 20 on the left. At the airport station in **Schwechat** a total sum of 90,2 mm was registered on that day, whereas in Fischamend (some kilometers to the east) the total daily precipitation only adds up to 51,5 mm. Most probably an intense convective cell was situated just above the station in **Schwechat** which drastically increased the rain amount. The fact that the exact location of a convective cell is influenced by many other meteorological parameters makes this measurement, even though reliable, not representative for a larger region. Following this argument, trends in absolute precipitation amounts may be correct for one single station but should not be interpreted as characteristic for a larger area.

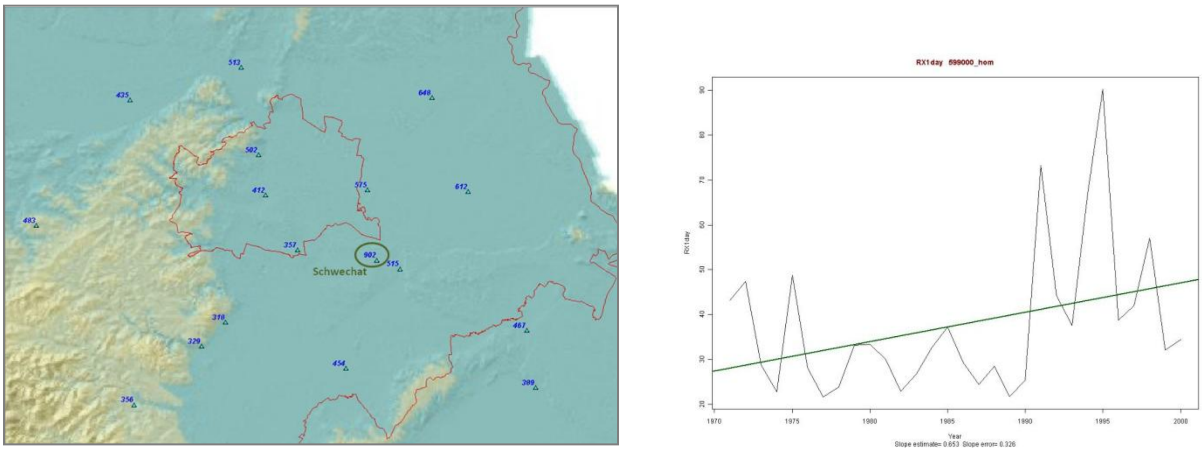

Figure 20: Right: Daily precipitation amounts at stations surrounding Vienna on the 14th of September 1995 (given in tenth mm). Left: Annual maximum one day precipitation at the station Schwechat with a linear trend in green.

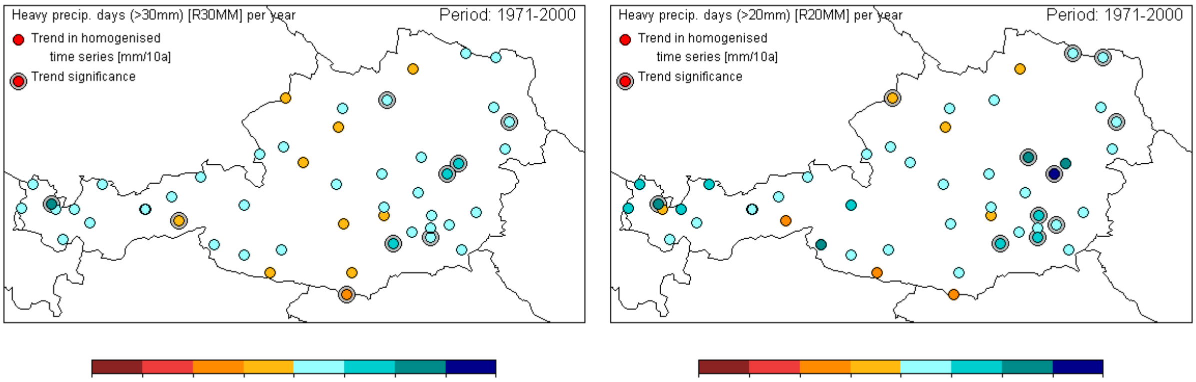

Figure 21: Left: Trend of the number of days with precipitation sums greater 30 mm for all homogenised precipitation series in Austria. Right: Trend of the number of days exceeding a precipitation sum of 20 mm for the same stations.

In contrast to absolute indices, exceedance indices seem more representative and more robust when dealing with precipitation data. Especially the right graph in Figure 21 shows an intensification of precipitation events larger than 20 mm/day in the east and southeast of Austria, with **Mürzzuschlag** and **Mariazell** (number 59 and 53 in Figure 4) being in the center of increasing heavy precipitation days. The rest of the stations do not show a uniform geographical pattern, but a rather random distribution with slightly more stations with positive trends.

Figure 22 shows the number of wet days exceeding 20mm per year for the stations in **Mariazell** and **Graz airport** (number 54 in Figure 4). Especially **Mariazell** shows a significant positive trend over the whole period indicating an intensification of heavy precipitation in this region.

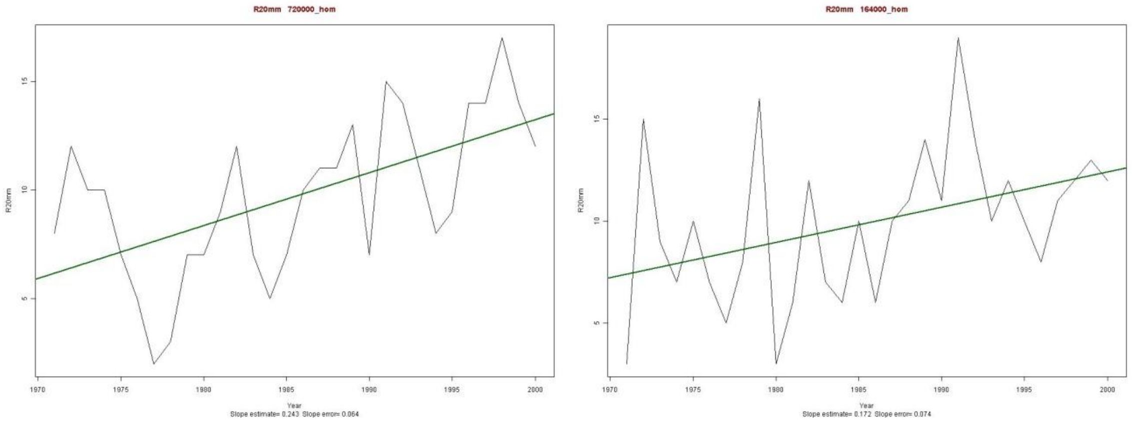

Figure 22: Days exceeding a precipitation sum of 20mm at the stations in Mariazell (left) and Graz (right). The green line indicates a linear trend.

Another interesting feature is the strong and significant trend in heavy precipitation days (RR>20mm) at the station in **Mürzzuschlag** (black line, figure 22). In order to gain confidence in the trend, the annual precipitation totals were compared to those of (on an annual basis highly correlated) neighboring stations. Figure 23 (right) shows the location of these stations. The plot on the left shows the annual precipitation sums of these 5 stations and the linear trend for the period 1970 to 2009. All trends, even though on a higher level than at the station in **Mürzzuschlag**, have very similar slopes indicating a strong increase in annual precipitation sums in this region.

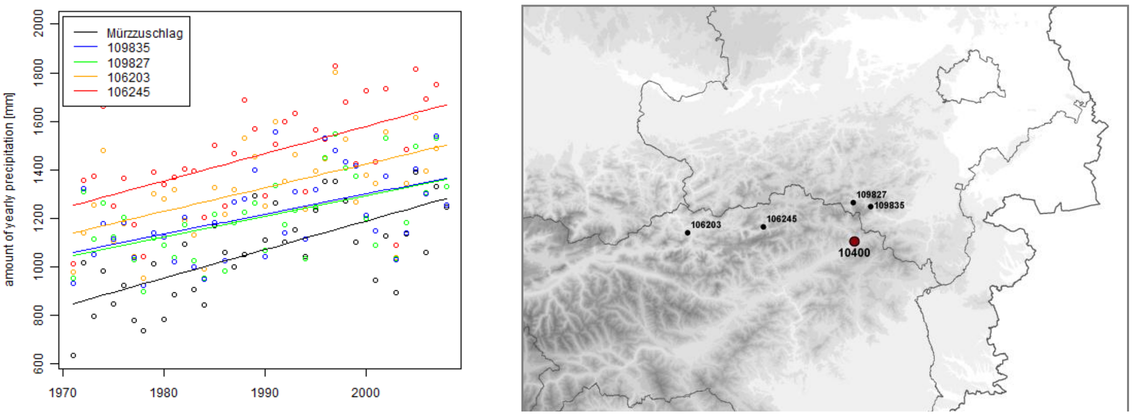

Figure 23: Annual preciptation totals for the station Mürzzuschlag (10400) and 4 highly correlation stations in the neighbourhood. The solid lines indicate a linear trend for all stations.

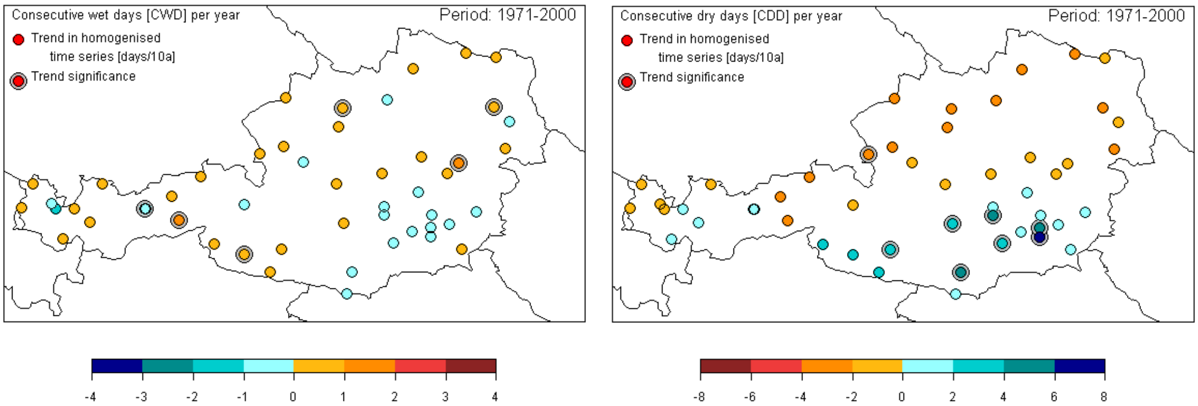

Figure 24: Left: Trend of number of consecutive wet days (CWD) per year for all Austrian stations for the period 1970 to 2000. Right: Trend of the number of consecutive dry days (CDD) per year for the same stations and the same period.

The consecutive dry days (CDD) index is the only evaluated precipitation index which shows a clear geographic pattern. The CDD index is defined as the maximum number of consecutive days with less than 1mm of precipitation. South of the alpine divide a trend towards longer dry periods, with most of the trends being significant, is evident in Figure 24 (right). In the northern part CDD trends are solely but not significantly negative. In the west (Tirol and Vorarlberg) the signal is even less pronounced with weaker trends.
However, the apparent CDD pattern is not balanced by reversed trends in the CWD (consecutive wet days) index. The CWD trends are shown in Figure 24 (left).

- The effect of homogenisation on the precipitation series

The effect of the homogenisation on some selected climate change detection indices is demonstrated on the basis of the stations **Landeck**, **Bregenz** and **Kolbnitz** (number 7, 2 and 25 in Figure 4).

A break, caused by instrumentation changes, in 1972 was homogenised in the precipitation series in **Landeck**. Figure 25 shows the simple daily intensity index (SDII) for the original compared to the homogenised time series. The SDI index is defined as the mean daily precipitation total on wet days. The homogenisation causes an obvious amplification of the trend. The reduction of precipitation in the earlier period of the time series reverses the trend in the very heavy precipitation days (figure 26).

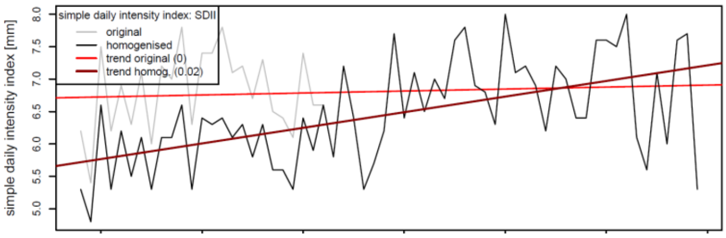

Figure 25: Simple daily intensity index for the original and the homogenised time series from Landeck.

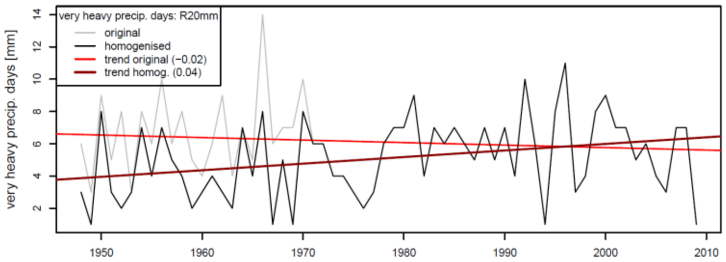

Figure 26: Very heavy precipitation days per year for the original and homogenised time series in Landeck.

Similar to the series from Landeck, the homogenisation of the precipitation series in **Bregenz** reverses the trend of maximum five day precipitation sums. The precipitation amount before the break, again caused by station relocation, in 1982 was reduced by about 20% (figure 27).

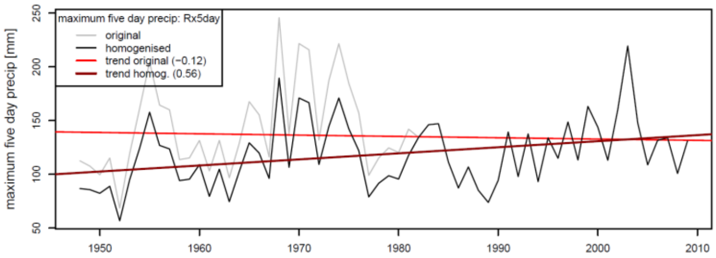

Figure 27: Maximum five day precipitation totals and trends for the original and the homgenised time series from Bregenz.

A strong increase in total precipitation on wet days was caused by a break in 1996 at the station in **Kolbnitz**. After eliminating this break the already negative trend in the original data set is further increased (figure 28).

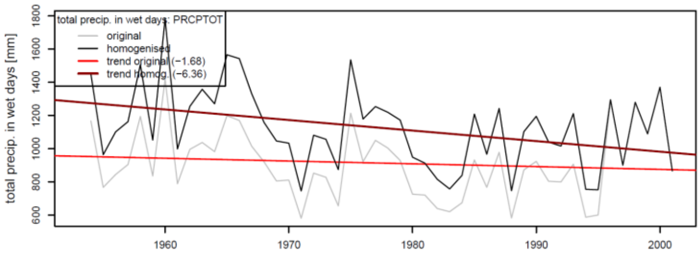

Figure 28: Total precipitation sum on wet days for the original and the homgenised time series from Kolbnitz.

2.2.5 Difficulties

The major difficulties concerning the temperature homogenisation occurred at the mountain stations. In most cases the number of reference stations was insufficient for reliable break detections, even after expanding the distance criteria. Similar problem emerged at stations which are located in narrow valleys or close to lakes.

Further, an automatisation of the homogenisation method was not accomplished which made the whole procedure of homogenisation very labor intensive. The main problem of the automatisation is based on the, even though remarkable complete, not continuous compilation of metadata.

Concerning precipitation, the main problem is that a daily precipitation benchmark dataset is not available up to now. Therefore a proper testing of break adjustment procedures was not possible. The break adjustment can only be verified on a statistical basis with the break detection method PRODIGE.

2.2.6 Highlights

The absolute highlight of the project is the new homogenised dataset of daily minimum temperature, daily maximum temperature and daily precipitation totals. This dataset makes reliable analysis of climate variability and climate extremes on a daily basis over the last 61 years possible. A first analysis of the time series was performed within the project.

Beside the new dataset a homogenisation method for daily extreme temperatures and daily precipitation totals is now available and was (at least in case of extreme temperature series) extensively tested.

2.2.7 Deviations from original proposal

The project was realized as originally planned.

2.3 Conclusion

We presented a homogenisation procedure for daily minimum and maximum temperature series. The method consists of an automated data retrieve from the data base, a selection of highly correlated reference stations, break detection, break visualization, break adjustment and finally a presentation of results. The final choice of the break date is realized subjectively, on the basis of the statistically detected break points and additional information from the station metadata. The homogenisation of the time series is processed iteratively, by analyzing the resulting homogenised time series and the uncertainties of the adjustment and subsequently adapting the break date.
The method was applied to and tested at 142 daily extreme temperature series. At some of the stations (14 TN and 17 TX) homogenisation was not possible due to missing reference stations or large uncertainties in the break adjustments. Most of the series where homogenisation was not possible are either located at high elevations where station coverage is low (e.g Feuerkogel, Patscherkofel, Sonnblick, Krippenstein), in narrow valleys (e.g. Galtür, Obergurgel, Bad Gastein) or close to lakes (e.g. Mondsee – only TN, Bad Aussee – only TN, Zell am See – only TX). The latter two are strongly influenced by local effects, topographic or hydrological, which drastically reduce the number of highly correlated reference stations and increase uncertainties in the adjustment.
A comprehensive analysis was performed with the remaining temperature series, showing a widespread warming trend in both TN and TX series. The warming trend is generally amplified due to the homogenisation. Contrary to similar studies in neighboring countries (Simolo et al., 2010, Brunetti et al., 2006, Brunet et al., 2007), the mean trend in the indices associated with TN and TX generally show consistent trends. The average annual mean TX and TN trends as well as the TX10p and TN10p trend are almost identical. Even the mean trends in TN10p and TX10p have equal amplitudes. The only exception is the trend associates with the number of warm nights (TN90p) which is +0.2 days/decade stronger. However, DTR (diurnal temperature range) does not show a clear trend signal. Another interesting fact is the cooling trend in TX in autumn, with positive trend of TX10p and icing days (TX < 0°C) and a negative trend of TX90p and summer days (TX > 25 °C).

Further, a method for the homogenisation of daily precipitation series was presented. The method is designed similar to the homogenisation procedure for daily extreme temperatures. Breaks are detected in both the precipitation intensity and precipitation frequency. In consideration of the statistically detected breaks and the metadata a break date is defined. Break adjustment is realized with an adapted INTERP method. The adjustments are calculated on a seasonal basis with additional uncertainty estimations. The uncertainties of the adjustment are determined by means of a bootstrapping method and by altering reference stations.
The method was applied to 71 daily precipitation series. Contrary to the extreme temperature series, significant breaks could only be detected in a small number of precipitation series. At these stations the break adjustment method was applied. For another 11 stations homogenisation efforts turned out to be unsuccessful, due to missing reference stations or large uncertainties in the adjustments.
10 precipitation related climate change detection indices were evaluated on the basis of the new homogenised daily precipitation dataset. The analysis show the variable behavior of daily precipitation totals, especially related to absolute maxima. A tendency, although not strongly significant, towards weaker one-day and five-day precipitation events are found in the southeastern parts of Austria. Further, we showed the large influence of single precipitation events on the overall trend in these absolute extreme indices. In contrast to absolute indices, exceedance indices seem more representative and more robust when dealing with precipitation data. We found an intensification of precipitation events larger than 20 mm/day in the east and southeast of Austria. The rest of the stations do not show a uniform geographical pattern, but a rather random distribution with slightly more stations with positive trends. The consecutive dry days (CDD) index is the only evaluated precipitation index which shows a clear geographic pattern. The CDD index is defined as the maximum number of consecutive days with less than 1mm of precipitation. South of the alpine divide a trend towards longer dry periods, with most of the trends being significant, is evident in. However, the apparent CDD pattern is not balanced by reversed trends in the CWD (consecutive wet days) index.

2.5 Literature

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4 Applicability and use of the project results

The new homogenised and quality controlled dataset of daily maximum and minimum temperature as well as daily precipitation totals covering a period of 61 years (1948-2009) is now available for further analysis and investigations. Information on the homogenisation methods and the homogenised data will be stored on http://www.zamg.ac.at/histalp/.

In order to perform climate change studies based on extreme values in Austria this dataset forms an essential basis. From our point of view the following ideas for further use of this dataset are considered:

- The new dataset can be compared to output from a regional climate model, in order to assess the model uncertainties and to make more reliable statements concerning the future of climate extremes. Therefore climate change indices are calculated from both the simulated time series and the homogenised daily time series covering a period of at least 30 years. After interpolation of the measurement series on a 2D field the data can be compared. Results will shed light on the reliability of climate model output on a daily basis and on the potential of regional climate model for reliable statements concerning the future evolution of climate extreme.
- Grids will be constructed on the basis of the homogenised temperature data in order to evaluate the 2D changes related to the homogenisation. These grids already exists based on the STARTCLIM data and should be updated using the homogenised dataset.
- Different climate extreme studies will be performed on the basis of this dataset, e.g. dealing with the evolution of dry periods in the south of Austria or the autumn trend reversal connected to TX. Within this project climate change detection indices were evaluated for one fixed period for extreme temperatures and an even shorter period for precipitation series. An additional analysis of other periods and the trend changes between different periods could be one possibility. The autumn trend reversal should be investigated in more detail, e.g. in combination with an analysis on the circulation pattern.

Furthermore, the homogenisation methods for daily extreme temperatures and daily precipitation totals are readily available for further application. The only requirement of the method is the existence of a sufficient number of reference stations. In any project dealing with daily time series this method, if not already done, should be applied on the time series in order to make results more accurate.

5 Outlook

A scientific publication will soon be submitted about the daily extreme temperature indices and the first evaluation of the temperature-related climate change detection indices.

Concerning temperature homogenisation the international community is putting efforts in the homogenisation of data on a sub daily time scale.

In the field of daily precipitation homogenisation there is still a high potential for further development of the method. The break adjustment method which was used in this project could unfortunately not be validated or compared to other methods because no benchmark dataset exists for daily precipitation series. However, within the COST-Action Home (ES0601) the development of a benchmark dataset for daily precipitation time series is planed, which can be used to validate our homogenisation method. After proper validation results can be compared to those from other methods, to find advantages and disadvantages of different approaches and to further improve the procedures.