Received: 15 February 2023 | Revised: 14 September 2023 | Accepted: 22 September 2023

DOI: 10.1002/joc.8270

RESEARCH ARTICLE

International Journal of Climatology RMetS

Revisiting HISTALP precipitation dataset

Barbara Chimani[1] | **Oliver Bochníček**[2] | **Michele Brunetti**[3] | **Manfred Ganekind**[1] | **Juraj Holec**[2] | **Beatrix Izsák**[4] | **Mónika Lakatos**[4] | **Melita Perčec Tadić**[5] | **Veronica Manara**[6] | **Maurizio Maugeri**[6] | **Pavel Šťastný**[2] | **Olivér Szentes**[4] | **Dino Zardi**[7]

[1]GeoSphere Austria, Vienna, Austria

[2]Slovak Hydrometeorological Institute (SMHU), Bratislava, Slovak Republic

[3]National Research Council, Institute of Atmospheric Sciences and Climate (CNR-ISAC), Bologna, Italy

[4]Országos Meteorológiai Szolgálat (OMSZ), Budapest, Hungary

[5]Croatian Meteorological and Hydrological Service (DHMZ), Zagreb, Croatia

[6]Department of Environmental Science and Policy, Universitá degli Studi di Milano, Milano, Italy

[7]Department of Civil, Environmental and Mechanical Engineering (DICAM), University of Trento, Trento, Italy

Correspondence

Barbara Chimani, GeoSphere Austria, Hohe Warte 38, 1190 Vienna, Austria.
Email: barbara.chimani@geosphere.at

Funding information

Copernicus Climate Change Service, Grant/Award Number: C3S_311a_Lot4; Ministero dell'Università e delle Ricerca of Italy, Grant/Award Number: FSE-REACT, DM 10/08/2021 – n. 1062; National Multidisciplinary Laboratory for Climate Change; Sustainable Development and Technologies National Programme of the Hungarian Academy of Sciences, Grant/Award Number: RRF-2.3.1-21-2022-00014

Abstract

The article presents a recent update of a comprehensive dataset of long-term series of precipitation data from instrumental observations in the Greater Alpine Region (GAR), that is, the region of Europe including the Alpine mountain range and their nearer surroundings (4°–19° E in longitude and 43°–49° N in latitude). A comparison to different national homogenized datasets is also presented. Results show that in the national homogenized datasets more breaks have been detected due to higher station density. They also demonstrate the necessity of constant exchange with data providers. The resulting trends in all datasets are mainly weak and only a minority of them is statistically significant. In most cases the similarity of statistical index numbers are promising, with, for example, small RMSE between the presented new HISTALP homogenization and the time series of the national homogenized datasets. Nevertheless, for some stations higher differences occur and break signals are not what would be expected due to possible causes in the station history. The differences between the national and the HISTALP new homogenization—due to, for example, different methods used, different points in time when the homogenization took place, different options of data handling (combination of station data, gap filling routines, …) and different reference stations—illustrate the inherent uncertainty unavoidably associated to homogenization and point out the need of careful communication and use of the data. On the other hand, the results highlight the advantage of consistently homogenized datasets, versus the risks associated with mixing results from different homogenizations.

KEYWORDS

Alpine region, comparison, CRADDOCK, HISTALP, HOMER, homogenization, MASH, precipitation

1 | INTRODUCTION

In the last decades, climate change has been increasingly brought by the scientific community to the attention of the society, in particular to policymakers, as one of the most urgent societal challenges and a threat to human wellbeing and health of the planet (IPCC, 2021).

Scientific evidence of past and present trends has increasingly been provided by analysing reliable datasets from extensive instrumental observations. This reliability is granted by the fact that most of those observations have been performed on a regular and standardized basis in the last two centuries. Also, projections of future climate scenarios heavily rely on datasets from observations, as a basis for model testing.

Although modifications of the earth's climate have been shown to occur at global level, yet changes are known to exhibit different intensities and variable rates for different regions of the world. This implies that specific impacts may be quite different for different regional systems (cf., IPCC, 2021, Chap. 10). In particular, extended mountainous regions have been shown to be affected by peculiar, and sometimes amplified, changes (Beniston, 2003).

Among these mountainous regions, the Alps are one of the most extensively investigated ranges, since more than one century (Barry, 2008; Volkert, 2009). They are quite centrally located in Europe, and act as a natural barrier between the inner continent and the extended Mediterranean area. Comprehensive overviews on the Alpine climate, including its major drivers and feedbacks to larger-scale flow conditions, has been provided by Schär et al. (1998) and Gobiet et al. (2014). Being an area rich in natural resources, the Alps are densely populated in most of their parts. With elevations ranging from mean sea level to more than 4800 m, the Alps are subjected to a strong topographic variety. Accordingly, the spatio-temporal variability and long-term changes of the Alpine climate, along with their impacts on various natural and socio-economic sectors, have been extensively investigated for a long time by analysing a large number of essential climate variables (e.g., Auer et al., 2005, 2007; Beniston & Jungo, 2002; Brunetti, Maugeri, Monti, et al., 2006; Brunetti, Maugeri, Nanni, et al., 2006; Brunetti et al., 2009; Giorgi et al., 2016; Haeberli & Beniston, 1998; Marty et al., 2017; Matiu et al., 2021; Scherrer, 2020). These studies greatly benefited from having in the Alps some of the world's longest standardized observational time series of climatic parameters and a comparatively high-density observational network (Hiebl et al., 2009; Isotta et al., 2014; Schär et al., 1998).

However, a well-known criticality affecting long time series of data from instrumental observations consists in discontinuities due to changes in either instruments, or observers, or methods of observation, or setup and location of stations (WMO, 2020). To overcome these problems, various methods have been proposed to homogenize the series.

Homogenization is a main process trying to improve the usability of time series for long-term climate change assessment. It aims to make data temporally homogeneous, that is, to reduce the effects of non-climatic signals to get a better estimate of climatic change (whether forced or due to internal variability). By the use of neighbouring reference stations also spatial consistency is addressed. Beside widely used methods available since the beginning of homogenization, such as the Craddock (1979) test, a variety of other techniques have been recently developed or improved: these include MASH (Szentimrey, 2017), HOMER (Mestre et al., 2013), ACMANT (Domonkos, 2021), Climatol (Guijarro, 2021), PMTred (Van Malderen et al., 2020) and IGN-AgroParisTech Method (Van Malderen et al., 2020). These methods differ among them not only in the statistical approach, but also in the data temporal resolution that is required as input (daily, monthly). Many comparisons of the various techniques, in different versions, applied to different variables (i.e., temperature, precipitation, etc.) and for different resolution have been performed during the last years (Domonkos, 2011; Domonkos et al., 2012; Ribeiro et al., 2016; Venema et al., 2012). While some of them focused on break detection algorithms, others focused on the characteristics of the final time series. They show that all methods used in this field there are based on reliable grounds. The choice of one method rather than another in the different organizations is usually made for subjective reasons, according to specific situations. Additionally, during the last years, the number of available homogenized datasets has increased: most countries have collected new series and have set-up updated and improved national datasets of homogenized series, for example, also in connection to the current climate normal period 1991–2020 and the possible comparisons between different climate normal periods (e.g., Auer et al., 2010; Brunetti, Maugeri, Monti, et al., 2006; Izsák, Szentimrey, Lakatos, Pongrácz, & Szentes, 2022; Marcolini et al., 2019; Nemec et al., 2012). This progress allows comparing the new version of the HISTALP dataset with the different homogenized national datasets, offering organizations a possibility to evaluate their own homogenization effort, as well as assessing part of the uncertainties associated with homogenization procedures.

Among the various datasets produced in the last decades, the HISTALP archive stands out as a pan-alpine dataset of long-term climate data, containing time series from many stations disseminated within the Greater Alpine Region (GAR, 4–19° E, 43–49° N). It was created as a result of a number of national and international projects between 1997 and 2008 (e.g., Aschwanden et al., 1996; Auer, 1993; Auer et al., 2001a, 2001b, 2001c; Auer et al., 2005, 2007; Begert et al., 2005; Böhm, 1992; Brunetti et al., 2000; Brunetti, Maugeri, Nanni, et al., 2006; Buffoni et al., 1999; Gajić-Čapka & Zaninović, 1997; Gisler et al., 1997; Herzog & Müller-Westermeier, 1998; Likso, 2004; Maugeri & Nanni, 1998; Zaninović & Gajić-Čapka, 2000). HISTALP was one of the first international databases with homogenized data and encouraging cooperation for sharing and exchanging data between national and sub-national administrative entities. HISTALP is still a frequently used dataset in research (e.g., Haslinger & Mayer, 2022; Laimighofer & Laaha, 2022; Serra et al., 2022; Valler et al., 2021) as well as in education. It consists of monthly means/totals and therefore derived seasonal and annual values. Part of the time series extend back to 1760 for temperature and air pressure and to 1800 for precipitation. Regular updates are done on an annual basis. While adaptations were done to adjust for station relocation, in order to keep the dataset as homogeneous as possible after the first homogenization process was finished (Auer et al., 2007), a thorough re-homogenization seemed necessary.

This proved also beneficial to consider changes in network conditions and results from more recent data-rescue initiatives and to revisit the original time series. This check pointed out differences between the HISTALP time series and the corresponding ones in the national databases. These differences may be due to later quality-control checks, different data sources or a pre-homogenized data version that was provided to the original HISTALP dataset. Finally, as HISTALP has become a widely used dataset in a broad community of users, a thorough analysis of the new version seemed necessary to make users aware of the differences and their possible impact on the analyses. This article focuses on precipitation, as this variable is used for the Copernicus dataset LAPrec (https://surfobs.climate.copernicus.eu/dataaccess/access_laprec.php).

The article is organized as follows: changes in the station network are presented in Section 2, while Section 3 provides information on the homogenization methods used; in Section 4, the results of the homogenization and comparisons to the former HISTALP version as well as to national datasets are presented and in Section 5, results are discussed and some conclusions are drawn.

2 | STATION NETWORK

The HISTALP dataset version described in this article differs from the original one (Auer et al., 2001a, 2001b, 2001c, 2005, 2007; Böhm et al., 2001), as to the station network. These changes originated from a variety of factors, such as the establishment of a Swiss National Basic Climatological Network, changes in the data providers in Italy, correction of the original HISTALP data by the data providers (e.g., France). The main changes affecting the stations are summarized in Figure 1. More than 70 stations have been added, ⅔ of them in Switzerland, 9 stations in Switzerland where removed and for 60 stations the original data has been modified. It has to be noted that not all of the provided data, referring to stations shown in the graphic, have finally been included in the homogenized dataset or used for homogenization, in particular those which had too short time series (see Section 3.1.1.). However, the final homogenized dataset does not differ significantly in the number of stations (besides Switzerland) or data length. Some stations that had been included in HISTALP already, or were additionally provided, were removed from the dataset due to difficulties during the homogenization (see Section 3 for further details). Stations from Switzerland have been provided as already homogenized data (https://www.meteoswiss.admin.ch/climate/climate-change/changes-in-temperature-precipitation-and-sunshine/homogeneous-data-series-since-1864/homogenization-of-series-of-climatic-measurements.html (last visited 24 July 2023), Begert et al., 2005). The distribution of the stations contributing to the new dataset of homogenized HISTALP precipitation series is shown in Figure 2, and stations' characteristics are provided in Table 1.

3 | METHODS

3.1 | Homogenization

3.1.1 | HISTALP

New approach

Homogenization of the HISTALP dataset was performed using HOMER (Mestre et al., 2013). This method was developed as a result of the COST-Action ES0601 on Homogenization (Venema et al., 2012) combining best performing methods (Venema et al., 2012), such as PRODIGE (Caussinus & Mestre, 2004), ACMANT (Domonkos, 2011), and the joint segmentation method cghseg (Picard et al., 2011). The procedure implemented in HOMER requires that stations are divided manually into networks. As a consequence, a candidate series is checked using as reference only series included in its networks. The final decision on which stations within the network are to be chosen as reference stations for homogenizing the candidate series is made automatically, based on the number of reference stations (at least 5) and on the correlation of the first order difference time series between the candidate series and the potential reference

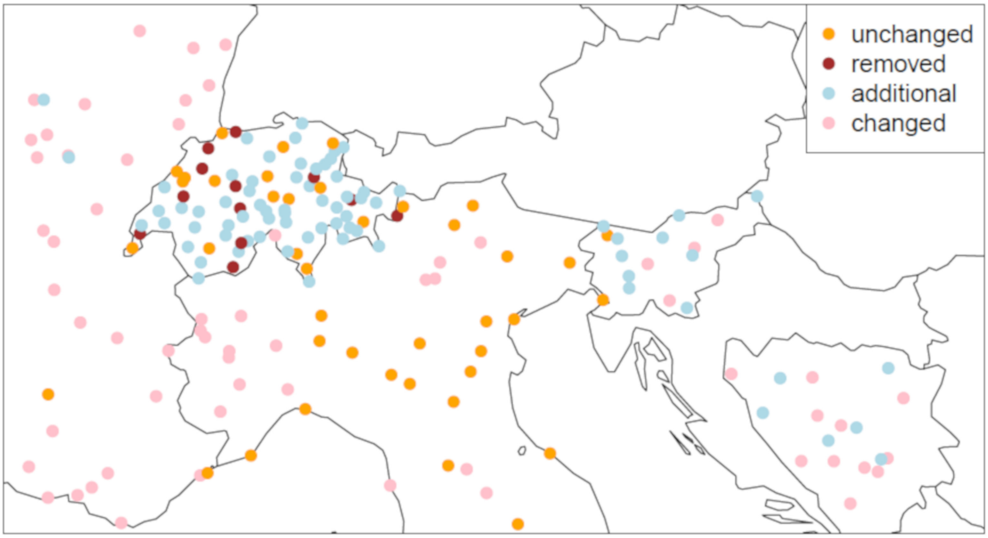

FIGURE 1 Changes between the original HISTALP station network (orange: unchanged; brown: removed; blue: additional; pink: changes in the original data or long-term update, including changes in data sources). [Colour figure can be viewed at wileyonlinelibrary.com]

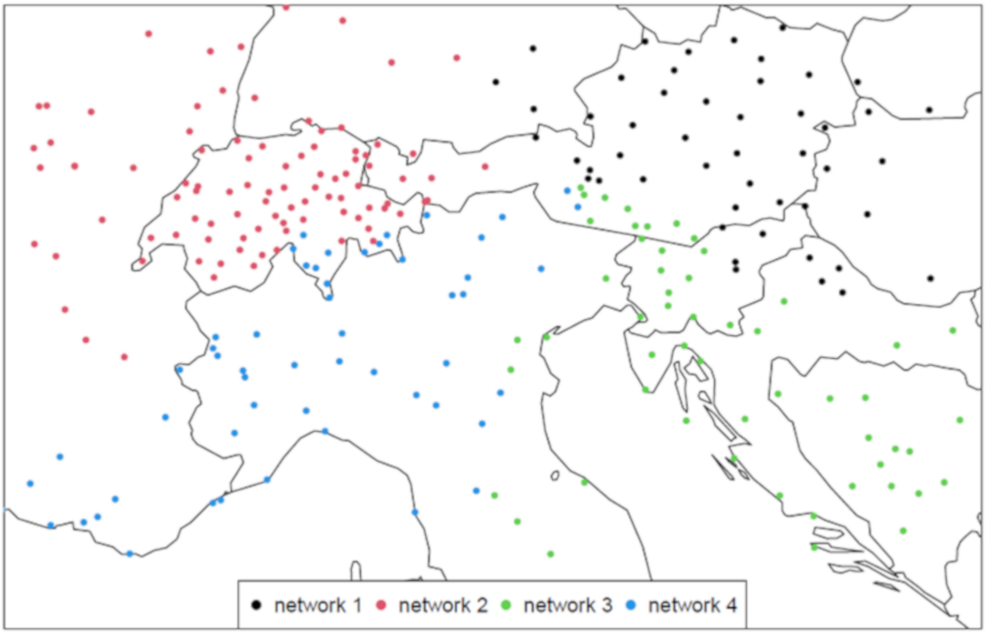

FIGURE 2 Station distribution in the different sub-networks used for homogenization. Stations are grouped according to the four climatic sub-regions of the Greater Alpine Region outlined in Auer et al. (2007). Network 1—sub-region NE, network 2—sub-region NW, network 3—sub-region SE, network 4—sub-region SW. [Colour figure can be viewed at wileyonlinelibrary.com]

station (≥0.6). If too few reference stations fulfilling the correlation criteria are available in the network, then stations with lower correlation are used to complete the required minimum number of reference stations. For the HISTALP homogenization procedure, stations were grouped into networks, outlined by applying Principal Component Analysis (PCA) to annual time series for different parameters focusing on the first four leading EOFs for each element (Auer et al., 2007). Based on those results the final regionalisation was defined. By this method the main climatological areas of the Alpine region are distinguished, separating the area north and south of the Alpine ridge as well as the oceanic influenced western and continentally influenced eastern part of the region.

For the identification of breaks a pairwise detection procedure was applied, based on maximum likelihood method optimal segmentation with dynamical programming (Hawkins, 2001), named 'C&L (Caussinus and Lyazrhi) criterion' (Caussinus & Lyazrhi, 1997). In order to be identified as such, a break has to be detected by more than 50% of the reference stations, whereby the break does not have to be detected in the same year in all stations, but only in a temporal vicinity. For the homogenization of some stations, for which it was not possible to identify a sufficient number of reference stations within the main networks, specific networks were created (Table 1). For those stations the result of the homogenization in their own network was used as the original time series for a second round of homogenization within the

TABLE 1 List of the stations used for the homogenization.

Statnr	Name	Country	Longitude	Latitude	Height	Sub-region	Statnr	Name	Country	Longitude	Latitude	Height	Sub-region
1	Admont	AT	14.46	47.57	646	NE	83	Mantova	IT	10.79	45.15	20	SW
2	Aix-En-Provence	FR	5.44	43.50	106	SW	84	Maribor	SI	15.65	46.54	275	NE
4	Altdorf	CH	8.62	46.89	438	NW	*85	Marienberg/ Montemaria	IT	10.49	46.74	1323	SW
6	Arezzo	IT	11.88	43.45	274	SE	86	Marigny-Le-Cahouet	FR	4.46	47.46	310	NW
7	Arles—Salins de Giraud	FR	4.72	43.41	1	SW	87	Marseille—Marignagne airpt	FR	5.23	43.44	5	SW
9	Bad Bleiberg	AT	13.69	46.63	907	SE	88	Milano-Brera	IT	9.19	45.47	122	SW
10	Badgastein	AT	13.13	47.11	1092	NE	89	Millstatt	AT	13.57	46.81	719	SE
11	Bad Gleichenberg	AT	15.91	46.88	280	NE	90	Montpellier	FR	3.96	43.58	2	SW
12	Bad Ischl	AT	13.65	47.71	512	NE	91	Mosonmagyarovar	HU	17.27	47.85	121	NE
13	Balme	IT	7.21	45.31	1432	SW	92	München-Stadt	DE	11.55	48.17	525	NE
14	Bardonecchia	IT	6.70	45.08	1340	SW	94	Nauders	AT	10.50	46.90	1360	NW
15	Basel/Binningen	CH	7.58	47.54	316	NW	95	Neuchatel	CH	6.95	47.00	485	NW
16	Belluno	IT	12.25	46.16	376	SW	96	Nice airport	FR	7.21	43.65	2	SW
17	Bern/Zollikofen	CH	7.46	46.99	553	NW	97	Nimes airport	FR	4.41	43.86	59	SW
*19	Bologna	IT	11.34	44.50	60	SW	98	Osijek	HR	18.56	45.50	89	SE
20	Bozen/Bolzano	IT	11.33	46.50	272	SW	99	Ovada	IT	8.64	44.64	187	SW
21	Bra	IT	7.84	44.70	290	SW	100	Padova	IT	11.88	45.40	14	SE
22	Bratislava	SK	17.10	48.17	280	NE	101	Parma	IT	10.33	44.81	79	SW
23	Bregenz	AT	9.74	47.50	424	NW	102	Pavia	IT	9.15	45.17	75	SW
24	Brixen/Bressanone	IT	11.65	46.72	569	SW	104	Pécs	HU	18.22	46.06	150	NE
25	Bruck/Mur	AT	15.25	47.41	482	NE	*105	Perugia	IT	12.39	43.10	520	SE
26	Casale Monferrato	IT	8.46	45.13	113	SW	107	Piacenza	IT	9.68	45.05	71	SW
*27	Celje	SI	15.23	46.24	241	NE	108	Pouilly-En-Auxois	FR	4.56	47.25	408	NW
28	Ceresole Reale	IT	7.25	45.43	1579	SW	*109	Pula	HR	13.85	44.87	43	SE
29	Chanceaux	FR	4.72	47.52	462	NW	111	Radstadt	AT	13.44	47.38	835	NE
31	Chaumont	CH	6.98	47.05	1136	NW	112	Rauris	AT	12.99	47.22	941	NE
32	Crikvenica	HR	14.69	45.17	2	SE	113	Reggio Emilia	IT	10.63	44.70	72	SW
34	Davos	CH	9.84	46.81	1594	NW	115	Retz	AT	15.95	48.75	256	NE

(Continues)

TABLE 1 (Continued)

Statnr	Name	Country	Longitude	Latitude	Height	Sub-region	Statnr	Name	Country	Longitude	Latitude	Height	Sub-region
36	Deutschlandsberg	AT	15.23	46.82	354	NE	117	Ried	AT	13.48	48.22	431	NE
37	Dijon-Longvic airport	FR	5.09	47.27	219	NW	118	Torbole-Riva	IT	10.88	45.88	73	SW
40	Elm	CH	9.18	46.92	958	NW	119	Rovereto	IT	11.05	45.89	206	SW
41	Engelberg	CH	8.41	46.82	1036	NW	121	Saint-Paul-Les-Durance	FR	5.71	43.69	296	SW
42	Feldkirch	AT	9.61	47.27	440	NW	122	Salzburg-Flughafen	AT	13.00	47.80	450	NE
43	Ferrara	IT	11.62	44.83	26	SW	123	Samedan airport	CH	9.88	46.53	1709	SW
45	Firenze-Ximeniano	IT	11.25	43.78	75	SW	125	Seckau	AT	14.78	47.27	855	NE
46	Formazza Ponte	IT	8.44	46.38	1300	SW	126	Sion	CH	7.33	46.22	482	NW
47	Freistadt	AT	14.51	48.49	539	NE	128	Sopron	HU	16.60	47.68	234	NE
48	Genève-Cointrin	CH	6.13	46.25	411	NW	131	St. Gallen	CH	9.40	47.43	776	NW
49	Genova-University	IT	8.93	44.42	53	SW	132	St. Sebastian	AT	15.30	47.79	872	NE
51	Gospic	HR	15.37	44.55	564	SE	134	Stift Zwettl	AT	15.21	48.62	505	NE
*53	Graz—Universität	AT	15.45	47.08	377	NE	135	Strasbourg—Entzheim airpt	FR	7.64	48.55	150	NW
55	Heiligenblut	AT	12.85	47.04	1315	SE	136	Stuttgart-Schnarrenberg	DE	9.20	48.83	311	NW
57	Hurbanovo	SK	18.20	47.87	124	NE	137	Szombathely	HU	16.63	47.24	221	NE
*58	Hvar	HR	16.44	43.17	20	SE	138	Tamsweg	AT	13.81	47.13	1025	NE
59	Innsbruck-Universität	AT	11.39	47.26	609	NW	139	Torino	IT	7.67	45.07	275	SW
61	Ivrea	IT	7.88	45.46	267	SW	140	Torino Moncalieri	IT	7.70	45.00	267	SW
63	Kals	AT	12.65	47.00	1338	SW	141	Trento	IT	11.12	46.07	199	SW
**64	Klagenfurt-Flughafen	AT	14.32	46.65	459	SE	142	Trieste	IT	13.77	45.65	67	SE
65	Kollerschlag	AT	13.84	48.61	725	NE	*143	Udine	IT	13.24	46.06	51	SE
66	Krems	AT	15.62	48.42	204	NE	*144	Vallombrosa	IT	11.53	43.73	955	SE
*67	Kremsmünster	AT	14.13	48.06	382	NE	146	Villach	AT	13.88	46.62	493	SE
68	Kufstein	AT	12.16	47.58	493	NE	149	Vix	FR	4.54	47.91	205	NW
69	La Chaux-de-Fonds	CH	6.79	47.08	1017	NW	150	Waidhofen/Ybbs	AT	14.81	47.95	384	NE
71	Landeck	AT	10.56	47.14	798	NW	151		AT	16.23	47.83	285	NE

International Journal of Climatology RMetS

TABLE 1 (Continued)

Statnr	Name	Country	Longitude	Latitude	Height	Sub-region	Statnr	Name	Country	Longitude	Latitude	Height	Sub-region
								Wiener Neustadt airport					
72	Langen	AT	10.12	47.13	1221	NW	152	Wien-Hohe Warte	AT	16.36	48.25	209	NE
74	Lemie—C.le.	IT	7.28	45.23	940	SW	153	Zagreb-Gric	HR	15.97	45.81	157	SE
75	Linz-Stadt	AT	14.29	48.30	263	NE	154	Zell am See	AT	12.80	47.33	766	NE
76	Livorno	IT	10.31	43.55	3	SW	157	Zürich/Fluntern	CH	8.57	47.38	556	NW
*77	Ljubljana	SI	14.51	46.07	299	SE	158	Imperia	IT	8.04	43.90	54	SW
78	Locarno-Monti	CH	8.79	46.17	367	SW	159	Augsburg	DE	10.95	48.43	463	NW
80	Lugano	CH	8.96	46.00	273	SW	160	Besancon	FR	5.99	47.25	307	NW
81	Luzern	CH	8.30	47.04	454	NW	161	Belfort	FR	6.85	47.64	422	NW
82	Lyon-Bron airport	FR	4.94	45.73	197	NW	162	Bihac	BA	15.88	44.82	246	SE
163	Bjelovar	HR	16.87	45.91	141	NE	318	Salovci	SI	16.30	46.84	513	NE
164	Banja Luka	BA	17.22	44.78	153	SE	319	Smartno_Slovenj Gradec_Dravograd	SI	15.03	46.61	384	NE
165	Brno-Turany	CZ	16.70	49.16	241	NE							
166	Cluny	FR	4.47	46.43	240	NW	322	Bled-Lesce-Radovljica	SI	14.10	46.36	477	SE
167	Colmar	FR	7.36	48.08	190	NW	323	Brion Sur Ource	FR	4.66	47.92	234	NW
169	Freiburg/Breisgau	DE	7.85	48.00	300	NW	324	Ouges	FR	5.09	47.27	219	NW
170	Embrun-Gap	FR	6.48	44.57	750	SW	*325	Bugojno	BA	17.45	44.06	562	SE
171	Grandfontaine	FR	7.17	48.50	515	NW	329	Sanski Most	BA	16.68	44.77	158	SE
172	Jajce	BA	17.27	44.35	431	SE	330	Zenica	BA	17.90	44.20	344	SE
174	Konstanz-Meersburg-Friedrichshafen	DE	9.18	47.68	443	NW	334	Grächen	CH	7.84	46.20	1605	NW
							335	Grimsel Hospiz	CH	8.33	46.57	1980	NW
175	Krizevci	HR	16.55	46.03	155	NE	336	Meiringen	CH	8.17	46.73	589	NW
176	Keszthely	HU	17.25	46.75	115	NE	337	Sargans	CH	9.44	47.05	590	NW
177	Karlovac	HR	15.57	45.49	110	SE	338	S. Bernardino	CH	9.18	46.46	1639	NW
178	La Cote St. André	FR	5.26	45.40	340	NW	339	Affoltern i. E.	CH	7.74	47.06	755	NW
179	Langres	FR	5.34	47.85	467	NW	340	Airolo	CH	8.60	46.53	1139	SW
180	Landshut	DE	12.12	48.53	393	NE	341	Altstätten, SG	CH	9.56	47.38	430	NW
181	Livno	BA	17.02	43.83	724	SE	342	Appenzell	CH	9.40	47.34	750	NW

(Continues)

TABLE 1 (Continued)

Statnr	Name	Country	Longitude	Latitude	Height	Sub-region	Statnr	Name	Country	Longitude	Latitude	Height	Sub-region
182	Macon	FR	4.80	46.30	216	NW	343	Bex	CH	7.00	46.24	402	NW
*183	Mali Losinj	HR	14.47	44.53	53	SE	344	Biasca	CH	8.98	46.34	278	SW
*185	Mostar	BA	17.80	43.35	99	SE	345	Binn	CH	8.19	46.37	1448	NW
186	Oberstdorf	DE	10.28	47.40	810	NW	346	Bivio	CH	9.67	46.46	1856	NW
187	Oderen	FR	6.97	47.91	450	NW	347	Brig	CH	7.97	46.31	665	NW
188	Orange	FR	4.86	44.15	57	SW	348	Brusio	CH	10.12	46.26	856	SW
189	Papa-Pannonhalma	HU	17.48	47.32	147	NE	349	Braunwald	CH	8.99	46.94	1299	NW
190	Pazin	HR	13.95	45.24	291	SE	350	Coldrerio	CH	9.00	45.85	347	SW
191	Pozega	HR	17.70	45.34	152	SE	351	Couvet	CH	6.66	46.93	728	NW
192	Prozor	BA	17.62	43.83	800	SE	352	Entlebuch	CH	8.07	46.99	768	NW
193	Regensburg	DE	12.10	49.05	366	NE	353	Eschenz	CH	8.87	47.65	414	NW
194	Rijeka—Kozala	HR	14.44	45.34	120	SE	354	Flühli, LU	CH	8.02	46.89	940	NW
195	Rosenheim	DE	12.13	47.88	444	NE	355	Göschenen	CH	8.60	46.69	950	NW
196	Sarajewo	BA	18.43	43.87	630	SE	356	Guttannen	CH	8.29	46.66	1055	NW
*197	Sibenik	HR	15.91	43.73	77	SE	357	Ilanz	CH	9.22	46.78	698	NW
198	Grenoble—Le Versoud	FR	5.85	45.22	220	NW	358	Kandersteg	CH	7.68	46.49	1178	NW
199	Toulon	FR	5.93	43.10	23	SW	359	Klosters	CH	9.89	46.87	1186	NW
200	Travnik	BA	17.68	44.23	581	SE	360	Langenbruck	CH	7.76	47.35	731	NW
201	Tuzla	BA	18.67	44.54	305	SE	361	Lachen/Galgenen	CH	8.86	47.18	468	NW
*202	Zadar	HR	15.21	44.13	5	SE	362	Leukerbad	CH	7.62	46.37	1286	NW
214	Bernstein	AT	16.26	47.41	600	NE	363	Lohn, SH	CH	8.68	47.75	585	NW
215	Budapest—Lörinc Airport	HU	19.27	47.43	130	NE	364	Longirod	CH	6.26	46.50	900	NW
216	Eisenkappel	AT	14.59	46.49	623	SE	365	Lausanne	CH	6.64	46.53	601	NW
217	Kocevje	SI	14.58	45.65	461	SE	366	Lauterbrunnen	CH	7.91	46.59	815	NW
219	Lienz	AT	12.81	46.83	659	SW	367	Martina	CH	10.46	46.88	1041	NW
220	Nice—Cap Ferrat	FR	7.33	43.68	138	SW	368	Mormont	CH	7.04	47.44	535	NW
221	St. Pölten	AT	15.61	48.18	285	NE	369	Montagnier, Bagnes	CH	7.23	46.07	839	NW
222	Ulm—Giengen	DE	9.95	48.38	567	NW	370	Mosogno	CH	8.64	46.20	771	SW
226	Château-d'Oex	CH	7.14	46.48	1029	NW	371	Muri, AG	CH	8.33	47.27	577	NW

TABLE 1 (Continued)

Statnr	Name	Country	Longitude	Latitude	Height	Sub-region	Statnr	Name	Country	Longitude	Latitude	Height	Sub-region
247	Segl-Maria	CH	9.76	46.43	1804	SW	372	Oberiberg	CH	8.78	47.04	1075	NW
270	Bucheben	AT	12.97	47.13	1143	NE	373	Romont	CH	6.93	46.70	692	NW
298	Beograd	RS	20.47	44.80	132	SE	374	Soglio	CH	9.54	46.34	1086	SW
302	Döllach	AT	12.90	46.96	1078	SE	375	Starkenbach	CH	9.25	47.18	897	NW
307	Koetschach-Mauthen-Kornat	AT	13.00	46.68	714	SE	376	Susch	CH	10.08	46.75	1416	NW
							377	Savognin	CH	9.60	46.59	1172	NW
308	Obervellach-Flattach-Kleindorf	AT	13.22	46.93	809	SE	378	Thusis	CH	9.44	46.71	672	NW
							379	Thun	CH	7.59	46.75	570	NW
**311	Doblice	SI	15.15	45.56	157	SE	380	Tschiertschen	CH	9.61	46.82	1273	NW
312	Kranjska Gora	SI	13.79	46.49	800	SE	381	La Valsainte	CH	7.18	46.65	1042	NW
313	Lasko	SI	15.23	46.16	221	NE	382	Weesen	CH	9.09	47.13	425	NW
314	Leskovica	SI	14.08	46.15	788	SE	383	Winterthur/Seen	CH	8.76	47.47	506	NW
315	Logatec	SI	14.20	45.91	485	SE	384	Wittnau	CH	7.97	47.48	463	NW
316	Luce	SI	14.75	46.35	513	SE							
317	Postojna	SI	14.19	45.77	533	SE							

Note: An asterisk in front of the stations number indicates stations for which a specific network for homogenization has been created (see Section 3.1.1.1). A double asterisk indicates stations whose data suffered from some issues with undetected breaks in the beginning of the time series due to missing reference stations.

main network. No further breaks were included in these time series.

For adjusting the data, the multiplicative model was used as customary with precipitation data (see e.g., Auer et al., 2005; Peterson et al., 1998 and Brunetti, Maugeri, Monti, et al., 2006; Brunetti, Maugeri, Nanni, et al., 2006, to mention few). The adjustment factors were calculated using a two-factor analysis of variance model without interaction (called ANOVA) (Mestre et al., 2013), assuming a constant station effect between breaks. As series from Swiss stations were provided as already homogenized, no further homogenization was made on them, and they were only used as reference stations.

Original approach

The HISTALP station data were originally homogenized using the HOCLIS system (Auer et al., 2005), which is a relative homogenization method. Part of the data the homogenization was done on has been prehomogenized by the data providers beforehand. For each station, a homogenization network was defined including up to 10 reference stations. A correlation higher than 0.5 was requested for a candidate station to be accepted as a reference station. Moreover, no other breaks were allowed around the timing of a break detected in the candidate station. The annual course of adjustment factors was smoothed to avoid erratic behaviour of the corrections. CRADDOCK test (Craddock, 1979, see also Section 3.1.3) was mainly applied for break detection, but also MASH test (Szentimrey, 1997, 1999, 2001, see also Section 3.1.5) and SNHT test (Alexandersson, 1986; Alexandersson & Moberg, 1997) were used. Metadata was extensively explored and taken into account. To avoid outliers, a visual spatial comparison of absolute and relative precipitation values was performed for each month for the whole GAR. A total of 192 stations have been examined and 966 breaks detected. As is the case in the current approach as well, the number of possible reference stations is reducing the farther back in time the data reaches.

3.1.2 | National Austrian series homogenization

For Austrian series a homogenization of daily data was done in 2021 for a variety of parameters, including precipitation, in connection with the update of climate normal to 1991–2020. The considered time period covered 1961 to 2020. A total of 192 stations were homogenized within 12 networks, taking into account climatological and topographic aspects. The number of stations per network varied between 10 and 24. The relative homogenization method ACMANT v4.4 (Domonkos, 2021; Domonkos & Coll, 2017) was applied, using the multiplicative data model. The option offered by the software to distinguish between a rainy and a snowy period in the precipitation time series was not used due to the fact that periods of precipitation falling as purely snow are short or not existing in most of the Austrian station. Missing values in the original time series were set to missing again after the homogenization.

ACMANT is an automatic, iterative system. Each station within the network is considered candidate station as well as a potential reference station for the other stations in the network. Any station can be used as reference depending on the degree of correlation with the other candidate stations. The reference stations are transformed into reference composite time series (Domonkos, 2021). Those vary during the homogenization process but are essentially a weighted combination of the available reference stations. Anomaly time series are used for break detection of precipitation after some quality checks, transformation and deseasonalization. Step-function-fitting with the C&L criterion (Caussinus & Lyazrhi, 1997) in combination with *T*-Test is used for break detection. Correction is calculated using ANOVA method (Caussinus & Mestre, 2004; Lindau & Venema, 2018).

3.1.3 | National Croatian series homogenization

Homogenization of the Croatian precipitation data was conducted on 406 stations, having at least 66% of monthly data available for the period 1960–2020. Prior to homogenization, data were clustered into 15 regions using hierarchical Ward's clustering method (Ward, 1963). These regions can be considered equivalent to precipitation climate regions, similar to temperature related climate regions in Perčec Tadić et al. (2022). At least one break of homogeneity was detected on half of the stations by SNHT implemented in the R package Climatol (Guijarro, 2019, 2021). SNHT was applied to the differences between candidate and composite reference series, both in normalized form. The normalization was calculated by subtracting the mean and dividing the difference by standard deviation over the entire data series. The homogenization was applied in two stages: in the first stage, over the overlapping windows of 120 terms sliding forward by 60 terms allowing for the detection of the multiple breakpoints; in the second stage, applying the SNHT over the entire data series. Three nearest stations were used to create reference series for each station. When a break was identified the data following it were retained, while the values before were corrected.

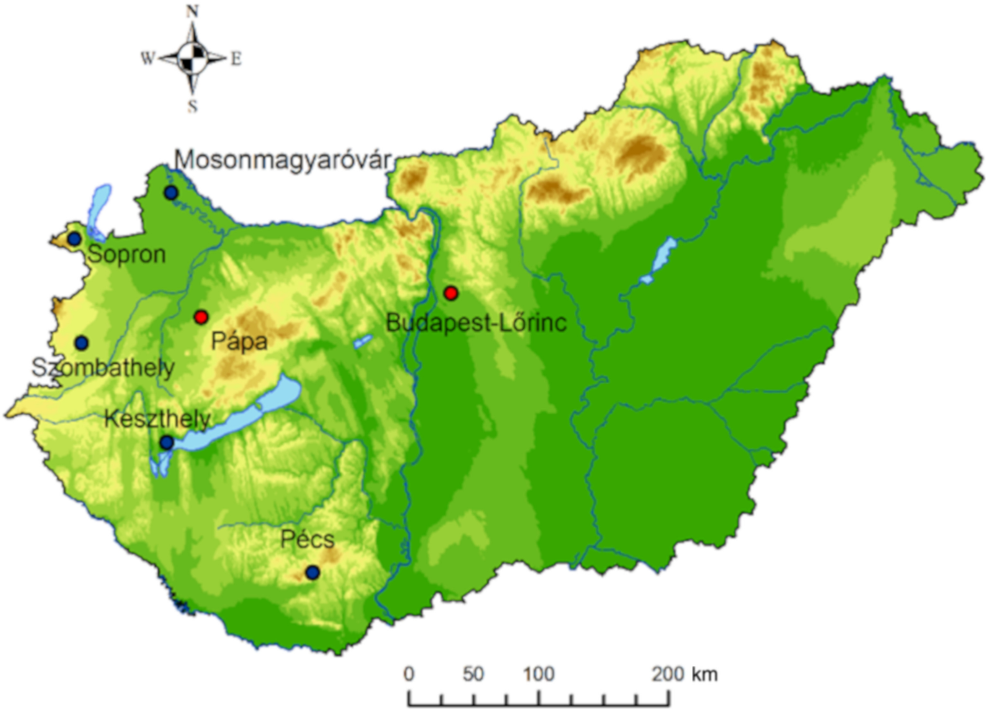

FIGURE 3 Map of the Hungarian stations included in the HISTALP database: five stations are active since 1870, only Pápa and Budapest-Lörnic are active since 1950. [Colour figure can be viewed at wileyonlinelibrary.com]

3.1.4 | National Hungarian series homogenization

The HISTALP database includes five Hungarian stations active from 1870 to 2021 (namely Mosonmagyaróvár, Pécs, Sopron, Szombathely and Keszthely) and two more from 1951 (namely Pápa and Budapest-Lőrinc). Figure 3 shows their locations. The five stations with longer data series were considered in this comparison. To create the national database (Izsák, Szentimrey, Lakatos, Pongrácz, & Szentes, 2022) the method MASHv3.03 (Multiple Analysis of Series of Homogenization; Szentimrey, 1999, 2017) was used for homogenization, missing data completion and data quality control.

MASH is a relative homogeneity test procedure based on hypothesis testing, including data quality control and missing data completion (Szentimrey et al., 2010). It is an iterative procedure: the role of the series (candidate, reference) changes in the course of the procedure, so that finally the whole network is homogenized. For precipitation a multiplicative model is used. Besides the monthly data also seasonal and annual series are homogenized. Break detection results in inhomogeneity information on monthly basis. Metadata, providing possible breakpoints (due to, e.g., changes concerning the location of the station, measurement systems, observers) are taken into account automatically. As the method is based on hypothesis testing, the success of the homogenization can be evaluated on the basis of verification tables generated automatically during the procedure. A 0.01 significance level was used for the homogenization of precipitation.

3.1.5 | National Italian series homogenization

The Italian dataset is composed of 36 series from stations located in northern-central Italy. All the series include more than 90 years of available data, with the longest series covering about 215 years. They are updated to 2017, with the longest series starting before 1800.

The Italian series are a subset of the homogenized dataset presented in Brunetti, Maugeri, Monti, et al. (2006), whose records were updated here from 2003 to 2017. The updating has been checked for homogeneity within a much larger dataset including more than 3000 records.

The homogenization presented in Brunetti, Maugeri, Monti, et al. (2006) was based on a procedure that checks each candidate series by means of the Craddock test against 10 reference series from stations located in the neighbouring area. In this procedure, if most of the reference series highlight a break in the candidate series, this is corrected under the hypothesis of the constancy of the ratios between reference and candidate series. Specifically, only those series, which exhibit a coherent behaviour in the estimated correcting factors, are selected as reference series. Then the final correcting factors are calculated as arithmetic mean between those obtained for each single reference series.

The homogenization of the recent period (i.e., after 2003) was based on a procedure that compares each series (candidate series) with a synthetic counterpart. In this procedure the synthetic counterpart is calculated as weighted mean among 10 neighbouring series (reference series) after they have been rescaled to the same climatology of the test series. The 10 reference series are those with the highest weights in terms of distance and angular weighting factors, selected among those with the corresponding available data. If an inhomogeneous period is detected in the test series, it is simply deleted (Crespi et al., 2020; Manara et al., 2019).

3.1.6 | National Slovakian series homogenization

The Slovakian dataset consists of two series from stations in the southwestern part of Slovakia, identified so as to correspond to the selection window established in HISTALP. One of them is Bratislava-Koliba with observations starting in 1857. The second is Hurbanovo with observations starting in 1872. Both stations are still active.

Data from Bratislava-Koliba before 1961 were composed from a number of five stations in Bratislava with different altitudes, slopes, urban or open locations, for example, on the airport. Hurbanovo station is of high quality from the point of view of its rural location and only minor changes occurred in its surroundings. For those stations a national homogenization with MASH (see Section 3.1.3 for details) was performed for the period starting in 1961 in connection with the new climate normal period 1991–2020.

3.2 | Comparison measures

Comparisons have been made on the common period between the homogenized new HISTALP precipitation dataset and the national homogenized datasets. The comparison period is individual for each time series, depending on the last available data in HISTALP (at the time the homogenization process was done) and the homogenization done by the national meteorological services. For better comparability, the time series have been transformed to multiplicative anomaly time series. The multiplicative anomaly was calculated relative to the 1971–2000 reference period. This reference period was chosen, as it lies within the time period of all datasets.

Trends were calculated by means of the Sen–Theil method (Sen, 1968; Theil, 1950), using the median of all slopes between neighbouring data points. The significance was calculated by using the p-value of the Mann–Kendall test (Sneyers, 1992) and a trend was defined as significant with a p-value $\leq$0.05, representing a 95% confidence interval.

In order to avoid biases caused by different timing of homogenizations, the time-series were additionally normalized to the mean of the common period of the new HISTALP-homogenization (Equation 1). Here RR indicates the precipitation time series, the index *Ntr* indicates 'national transformed' time series, while *N* indicates national datasets and *H* the homogenized HISTALP-data. The average is marked by an overbar, and *n* is the number of timesteps:

$$\mathrm{RR}_{Ntr_i} = \frac{\mathrm{RR}_{N_i}}{\overline{\mathrm{RR}_N}} \overline{\mathrm{RR}_H} \; i \in \{1, n\} \tag{1}$$

While the original (non-transformed) homogenized data were used to calculate arithmetic means and standard deviation (Equation 2), the transformed national homogenized time series (Equation 1) were used for RMSE (Equation 3) and MSESS (Mean Squared Error Skill Score, Equation 4) between those two datasets.

$$\mathrm{SD} = \sqrt{\frac{\sum_{i=1}^{n} \left(\mathrm{RR}_i - \underline{\mathrm{RR}}\right)^2}{n-1}} \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} \left(\mathrm{RR}_{H_i} - \mathrm{RR}_{Ntr_i}\right)^2}{n}} \tag{3}$$

$$\mathrm{MSESS} = 1 - \left(\frac{\mathrm{RMSE}}{\mathrm{SD}}\right)^2 \tag{4}$$

MSESS results in values between 1 (highest skill) and 0 (no skill), while RMSE and sd result in mm.

4 | RESULTS

For the next chapters the following wording will be used:

- Unhomogenized data = quality controlled measurement data
- Original homogenized HISTALP version = HISTAL Porihom
- Newly homogenized HISTALP version = HISTALPnew

4.1 | Homogenization results and comparison to former HISTALP version

All the 244 stations included in the final HISTALPnew dataset were homogenized using, for each station, at least five reference stations fulfilling the correlation criterion, with the only exception of Bologna and Hvar, with only three highly correlated reference stations. The median of the number of reference stations used in networks 1, 3 and 4 was between 11 and 17, with a maximum number of reference stations of 20–33. The number of reference stations in network 2 was higher due to the denser network of stations available in Switzerland (69 stations, only used as reference stations). There the lowest number of reference stations was 10, the highest 90 and the median 70. The correlations, considering the whole common period, were between 0.6 and 1, with some exceptions when not enough reference stations (i.e., more than the minimum of 5) with higher correlation were available.

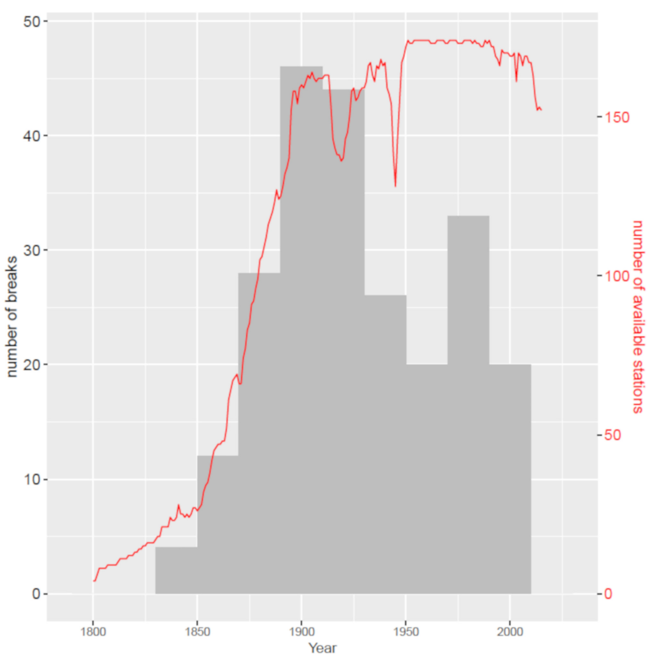

FIGURE 4 Number of breaks taken into account in the final dataset (histogram and left side y-axis) and number of available stations per year (with at least 1 month of data, line and right side y-axis). [Colour figure can be viewed at wileyonlinelibrary.com]

In 118 out of the 175 stations for which a homogenization was done at least one break was detected. For about one third of those some metadata was available. In most inhomogeneous stations only 1 break (in 47 stations) or 2 breaks (in 43 stations) were detected. The median of the number of breaks per station was 2, the maximum was 6. Most of them were detected for stations in Austria. Generally, most of the breaks were detected at the beginning of the 20th century (Figure 4). The reduction of detected breaks before that period was also caused by the reduction of available station data (Figure 4).

In general, the agreement regarding the range of precipitation amounts of the old and new homogenized series was rather fairly good, but for some countries the distribution of the monthly data changed clearly. In Switzerland, the major changes in the station network seemed to be the cause of this. The same is true for Slovenia, where the increase of stations led to a changed distribution of monthly precipitation sums (Figure 6).

Trends after homogenization were mostly not significant (Table 2). Two periods, namely 1961–2015 (223 stations) and 1900–2015 (205 stations), were analysed in order to have a recent one, covering all the national homogenized datasets, and a longer one, with still a high number of stations included. The ending year 2015 was chosen as this was the most recent in which data were available for most of the stations. In both analysed periods most of the trends were positive, with spring being the only season with more negative trends in both periods. The number of significant trends was higher in the longer period. Compared to the unhomogenized data

TABLE 2 Overview of the trends in the homogenized series.

Period	Season	Positive	Significative positive	Negative	Significative negative
1961–2015	Spring	69	0	148	3
	Summer	126	7	89	10
	Autumn	194	8	27	0
	Winter	59	0	158	3
	Year	136	9	82	7
1900–2015	Spring	89	9	112	28
	Summer	110	13	88	3
	Autumn	114	3	86	0
	Winter	119	25	83	10
	Year	116	29	86	19

Note: Numbers provide the amounts of stations within the respective criteria, as indicated in the column titles.

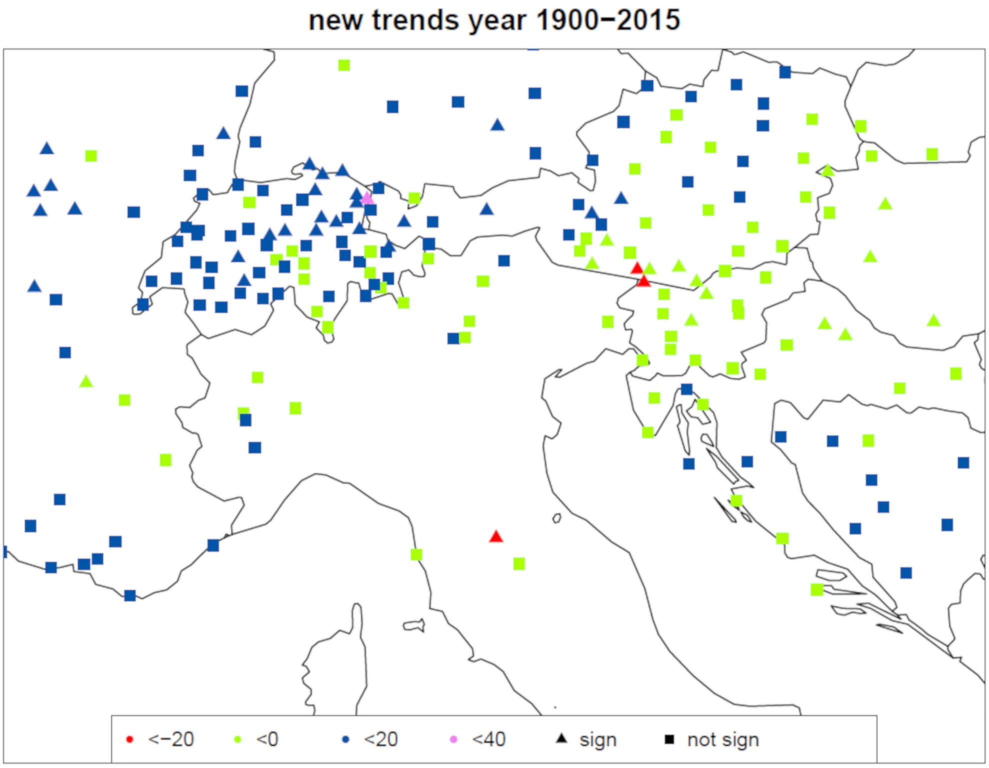

FIGURE 5 Annual trend of absolute values after homogenization in mm/decade for those stations covering the complete period 1900–2015. Due to difficulties in the update of Italian stations because of station closures the number or stations is lower in this area. [Colour figure can be viewed at wileyonlinelibrary.com]

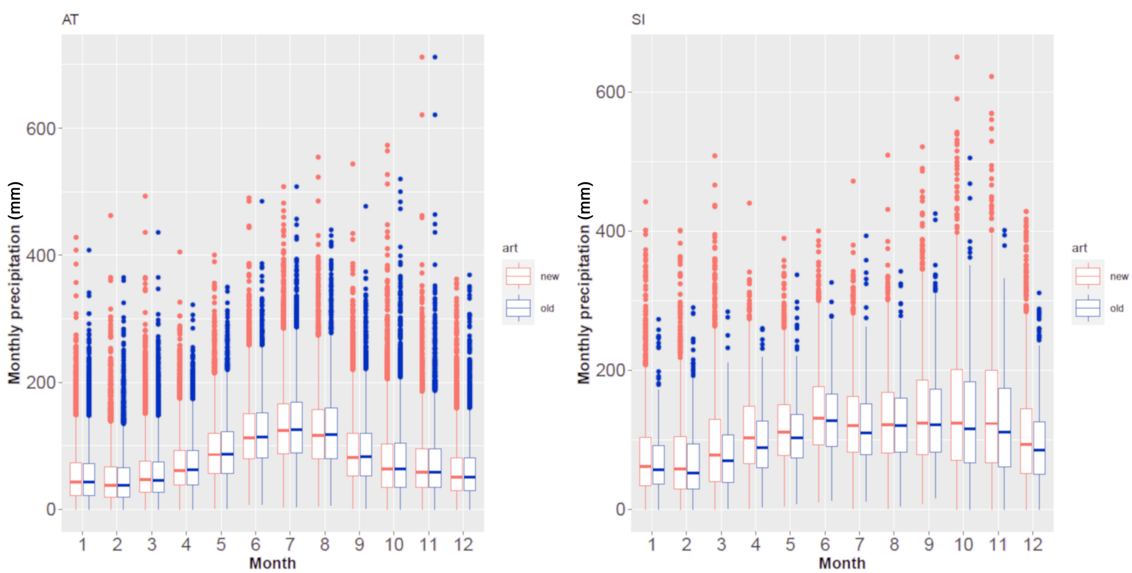

FIGURE 6 Monthly precipitation amount in the previous and in the new homogenization for Austria (left panel) and Slovenia (right panel) (in mm, based on absolute values). New dataset shown in as the first of each couple, old one as the secondone of the couple. [Colour figure can be viewed at wileyonlinelibrary.com]

the number of significant trends was reduced by the homogenization. While in the long period the number of positive trends increased after the homogenization in all seasons, this was only the case for annual and autumn season in the short period. Comparing the former (HISTALPorihom) to the current homogenization results (HISTALPnew), changes in the trend directions took place at about 20–40 stations depending on the season and period. Those trends are statistically insignificant in both homogenizations with only in some seasons single stations having a significant trend slope in one of the versions. Looking at annual trends of HISTALPnew, the negative ones were mostly located in the south-eastern region of the HISTALP area, while slightly positive trends could mainly be found in the northern part of GAR (see Figure 5 for the 1900–2015 trend distribution). The

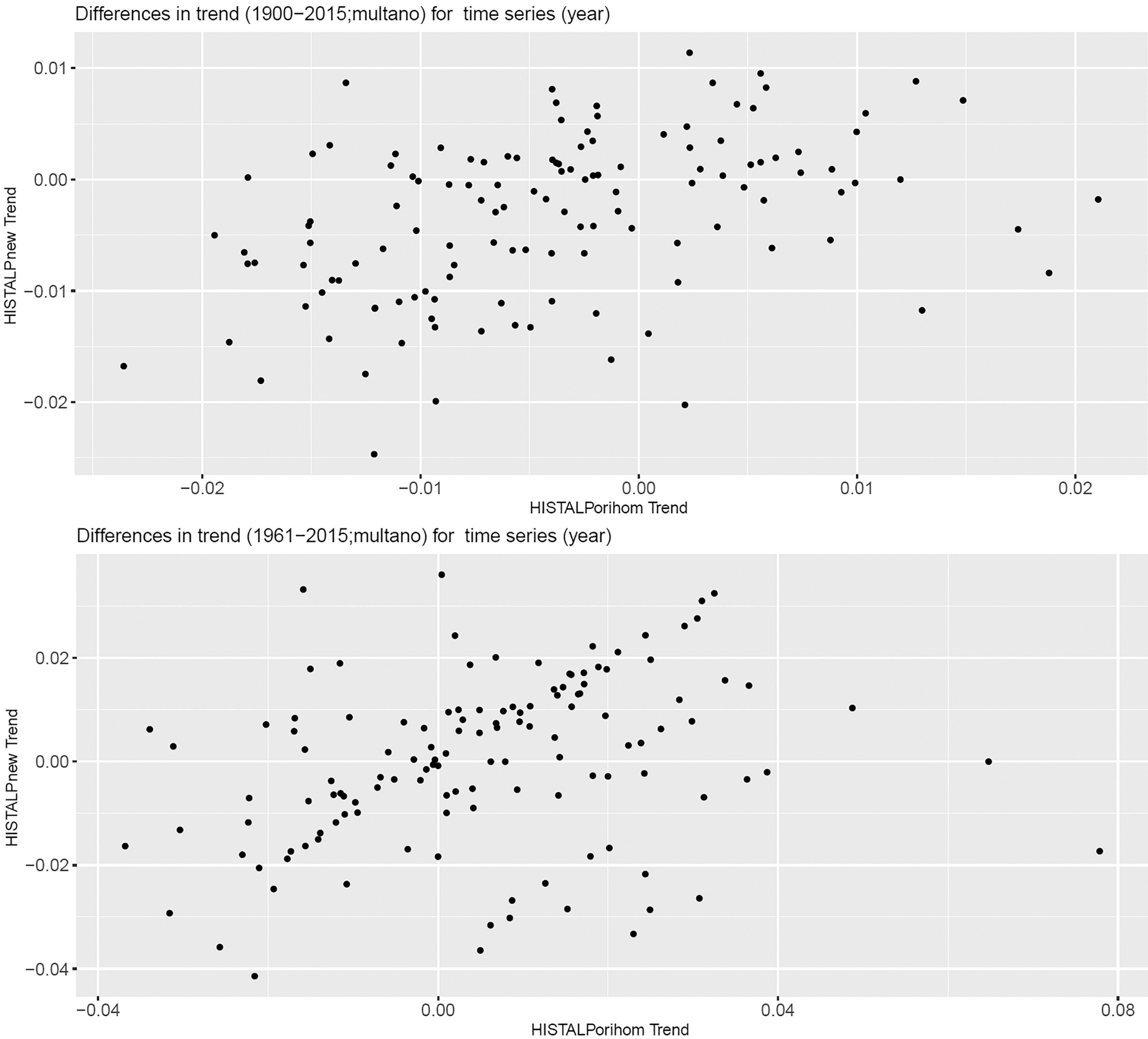

FIGURE 7 Differences in annual trends (relative anomalies per decade) for 1961–2015 between HISTALPorihom (x-axis) and HISTALPnew (y-axis) homogenization based on relative anomaly (to 1971–2000) time series.

spatial structure of trends was similar to that found in the previous homogenization (not shown).

Absolute trends range from −26 to 13 mm/decade (−56 to 31 mm/decade) for annual precipitation sums ranging from about 460 to 1760 mm/year (460 to 1830 mm/year) for the period 1900–2015 (1961–2015), with a similar spread of trends independent of the annual precipitation sum. Trend analyses based on the anomaly time series showed changes, positive as well as negative, among the HISTALPorihom and HISTALPnew results. Trends were calculated for the period 1900–2015 and for the period from 1961 to 2015. The differences in the trend were stronger for the period starting in 1961 as are the trends themselves (Figure 7). The biggest trend differences in the 1961–2015 period, occur at stations with changed unhomogenized data used for the homogenization of HISTALPorihom and HISTALPnew.

4.2 | Comparison to national datasets

4.2.1 | Comparison to the Austrian dataset

The comparison was done for 41 stations. For 13 stations, both homogenization methods found inhomogeneities.

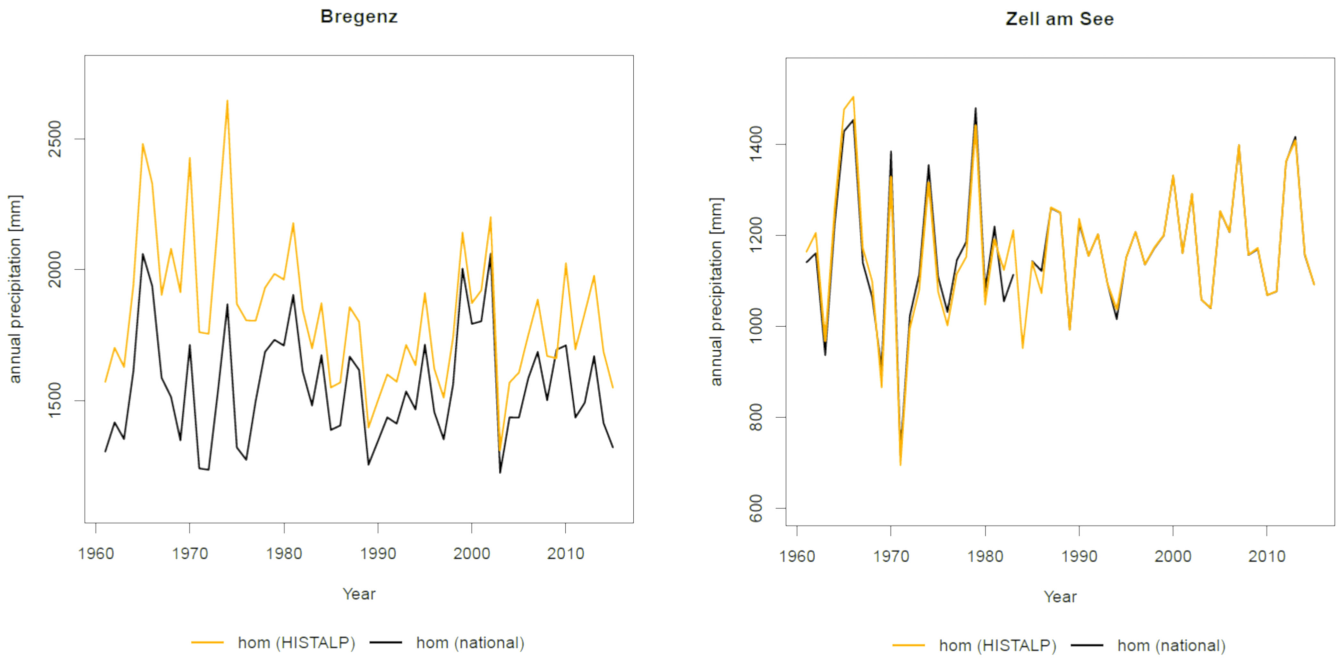

FIGURE 8 Homogenized annual time series of Bregenz (left) and Zell am See (right) from the HISTALPnew dataset and the national dataset. [Colour figure can be viewed at wileyonlinelibrary.com]

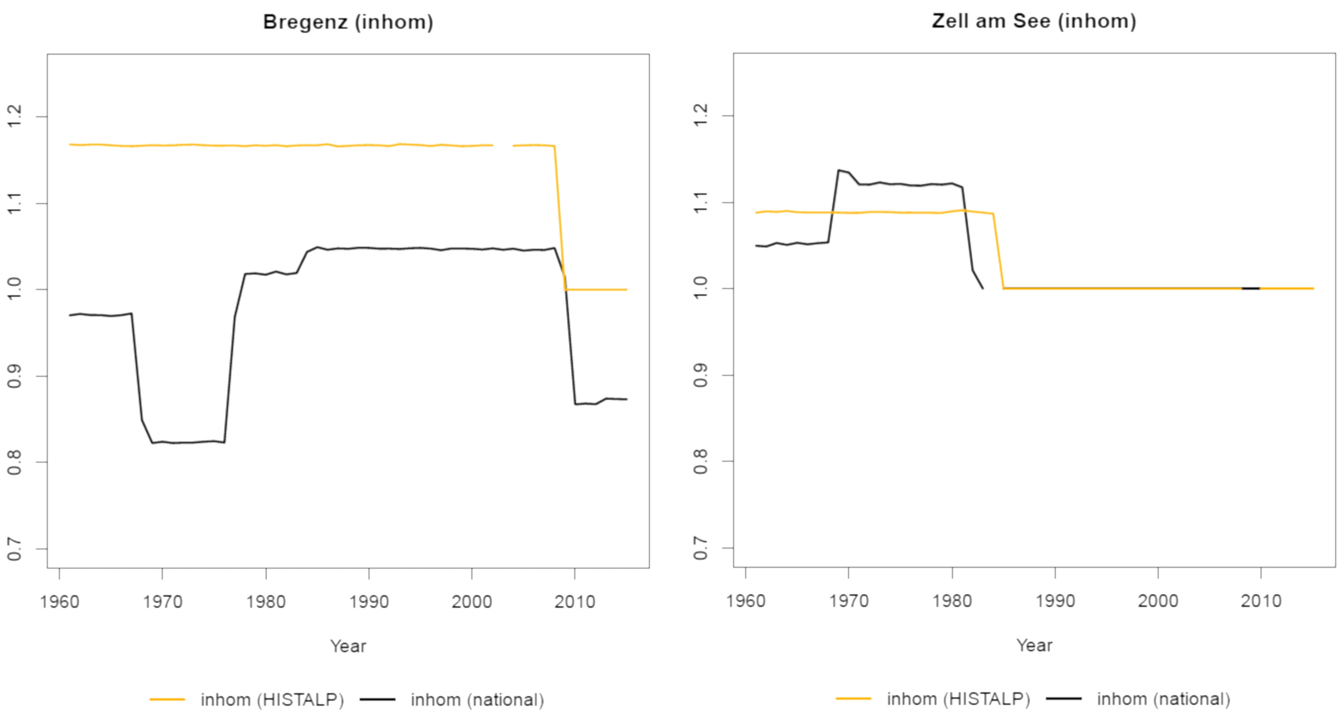

FIGURE 9 Adjustments applied to the annual precipitation sum measurements in the HISTALPnew homogenization and the national homogenization for Bregenz (left) and Zell am See (right). [Colour figure can be viewed at wileyonlinelibrary.com]

For 23 stations, within the HISTALPnew dataset no break was detected, while ACMANT detected some. For three stations, both homogenizations did not detect any break. For two stations a break was detected in the HISTALP homogenization, but not in the ACMANT one. Since during the homogenization of daily series the gap filling was not used, for the comparison of the two homogenization procedures the values missing in the national dataset were set missing in the HISTALPnew dataset as well.

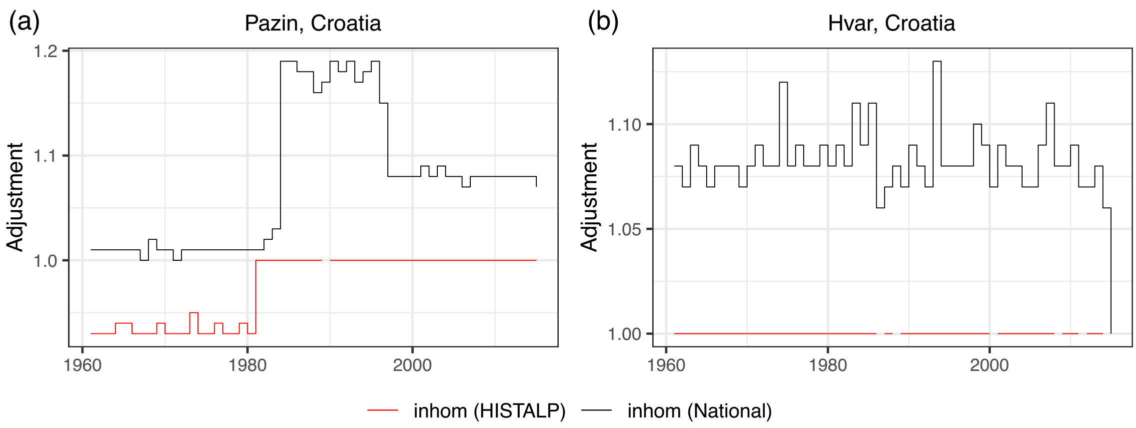

FIGURE 10 As Figure 8 but for Pazin(left) and Hvar (right) for 1961–2015. [Colour figure can be viewed at wileyonlinelibrary.com]

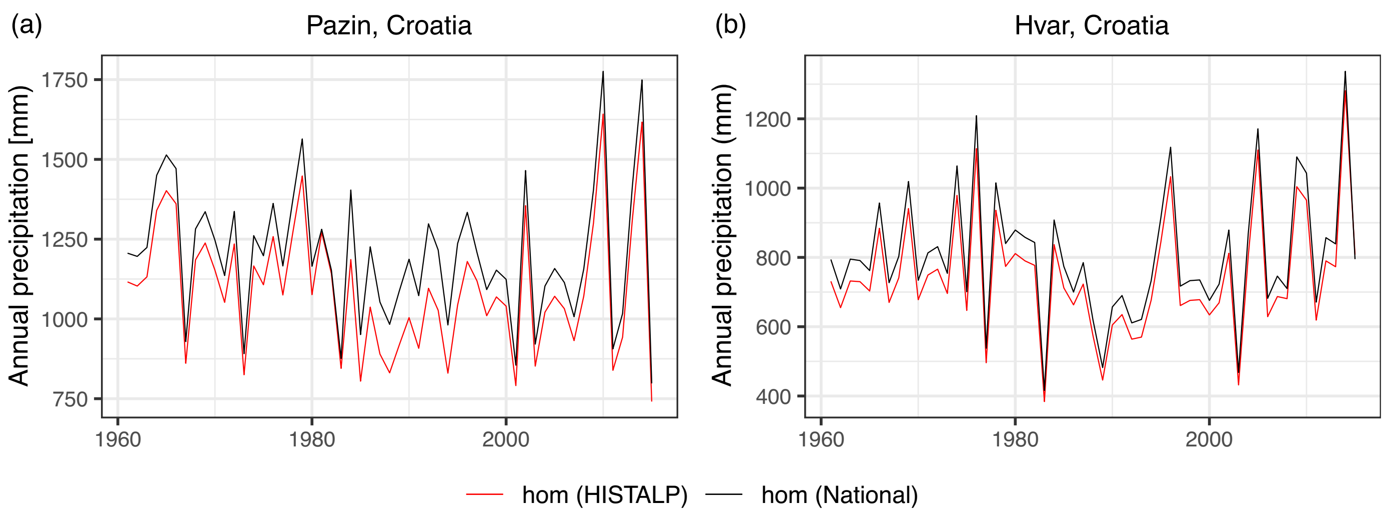

FIGURE 11 As Figure 9 but for Pazin (left) and Hvar (right) for HISTALP and national dataset. 1961–2015, not-normalized to common period. [Colour figure can be viewed at wileyonlinelibrary.com]

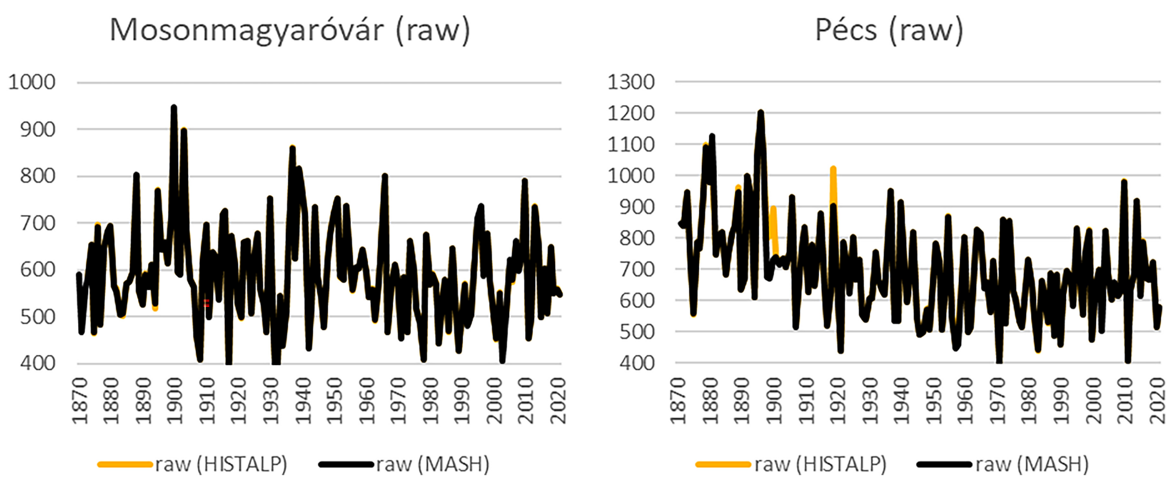

FIGURE 12 Comparison of measurement data before homogenization in the HISTALP and national databases for Mosonmagyaróvár (left) and Pécs (right). [Colour figure can be viewed at wileyonlinelibrary.com]

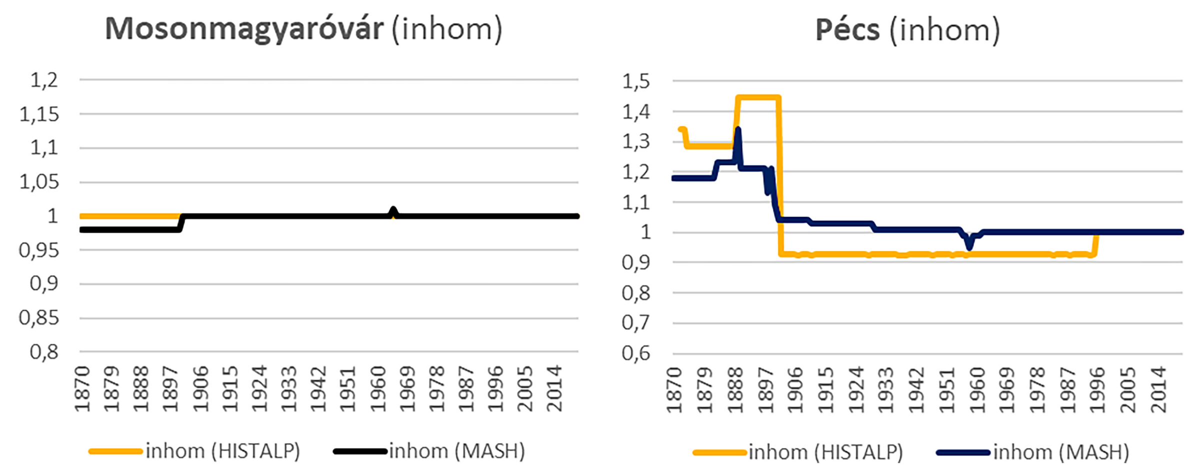

FIGURE 13 As Figure 9 but for Mosonmagyaróvár (left) and Pécs (right). [Colour figure can be viewed at wileyonlinelibrary.com]

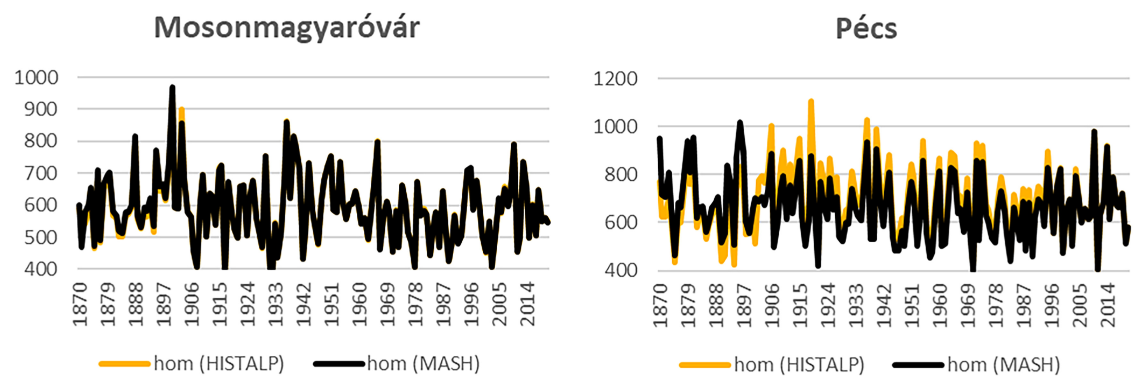

FIGURE 14 As Figure 8 but for Mosonmagyaróvár (left) and Pécs (right). [Colour figure can be viewed at wileyonlinelibrary.com]

Looking at the distribution of trend values, it turns out that the spread between the stations is less in the results from the daily homogenization. With an identical median and nearly no difference in the second quantile (3.9 mm/decade for national homogenization and 3.3 mm/decade for HISTALPnew), the causes of this are mainly in three stations with a more negative trend in HISTALPnew than in the national dataset. For eight stations, the sign of the trend is different in the two homogenizations, however, for none of those the trend is statistically significant in any of the two datasets. The annual mean precipitation sums are quite similar for all the stations in both datasets, with a median of 1 mm, and most of them below 1% of the annual precipitation. In the most extreme case the difference in the annual mean is 101 mm (about 7%) of the annual precipitation amount. The RMSE calculated between the national homogenized dataset and HISTALPnew and the annual precipitation amounts range between 5 and 171 mm with a median of 38 and three quarters of the stations having an RMSE below 50 mm. The standard deviation of annual precipitation amounts for the single stations is quite similar in both datasets most values between −2 (second quantile) and +3 (fourth quantile).

The selection of stations shown in Table 3 provides information on stations with a longer time period of different data due to homogenization effects (breaks in most cases around 1999), covering the range of more or less agreeing series between the time series. The comparison was done for the period 1961 (start of the daily homogenization) to 2015 (in accordance with the comparison between the HISTALP versions). For Bregenz the first break in the daily homogenization was outside this time range, while it was in 2008 in the HISTALPnew homogenization. Therefore, there was an offset between the daily and the monthly homogenization throughout the whole timespan. The difference was increased by additional breaks detected and corrected in the daily time series before 1980 (see Figures 8 and 9). The other selected station having a break before 1990 is Zell am See, showing a good agreement between the different homogenization procedures, which detected a break at a similar temporal point. Hardly any of the trends in any of the compared

FIGURE 15 As Figure 9 but for Belluno (upper) and Balme (lower). [Colour figure can be viewed at wileyonlinelibrary.com]

stations and homogenization methods was significant for the period 1961–2015 on a 95% confidence level (i.e., p-value ≤ 0.05).

4.2.2 | Comparison to the Croatian dataset

Out of 406 stations homogenized in a new national study, 15 were included in the comparison of the homogenized national and HISTALPnew precipitation records for the common period 1961–2015. Six of those had complete data records, eight had up to 2% missing data, and station Požega (eastern Croatia) had 13% missing data. Missing data were filled during the homogenization process, being one of the reasons for the differences in comparing HISTALPnew to national homogenized data. A break in homogeneity was detected in the series from the station Gospić (mountainous region), three breaks were detected in the series from Pazin (Istrian inland), one in Pula (Istrian coast), and one on station Hvar (southern Adriatic): see Table 4 for more details. Those four stations, together with Požega, where no homogeneity break was detected, were analysed in more details. While three breaks were detected for Pazin with Climatol (Figure 10), only one, in 1980, was detected with HOMER. Zahradníček et al. (2014) did not detect breaks on the rest of the stations where the breaks were detected in recent study.

Among the 15 analysed stations, annual RMSEs were up to 3.2 mm over those stations for which no homogenization method detected breaks, even though zero is expected, and MSESSs were equal one. RMSEs different from zero could be attributed to small differences between the measurements included in HISTALP and the current national database. This can be a consequence of either rounding errors, or errors in old data provided to HISTALP, or to later corrections in the national dataset used for national homogenization. Larger RMSEs of 1.6–21.6 were found on homogenous stations with missing data, due to different methods for filling the missing data in Climatol and HOMER. For four stations with the breaks in homogeneity, RMSEs were 16.0–43.1 mm and MSESSs were 0.95–1.00 due to break detection with Climatol compared to no breaks detected with HOMER, or due to three breaks detected with Climatol compared to one with detected with HOMER in Pazin, and consequently, different homogenized series.

Seasonal and annual RMSEs and MSESSs are presented for selected stations in Table 3. For those selected

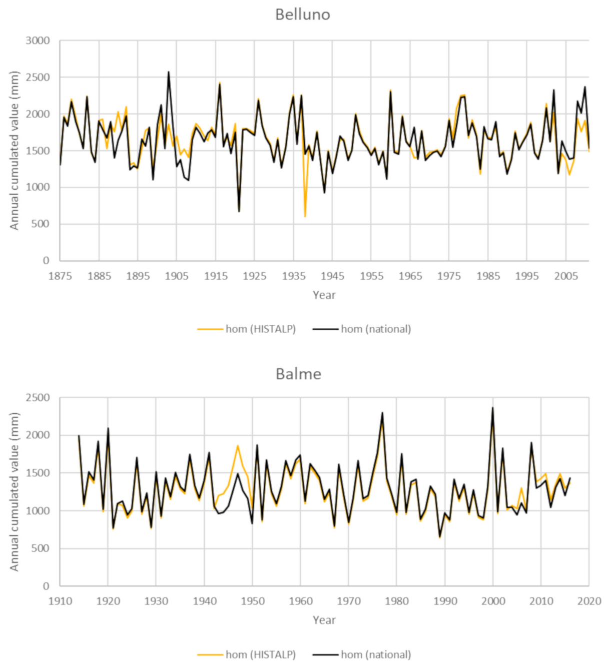

FIGURE 16 As Figure 8 but for Belluno (upper) and Balme (lower). [Colour figure can be viewed at wileyonlinelibrary.com]

stations annual RMSEs were in the range 12.5–43.1 mm, the lowest being in Hvar, and the highest in Pazin, due to differences in homogenization performed with both, Climatol and HOMER. Figure 11 shows annual precipitation for those two stations. Annual MSESS were the worst in Pazin (0.95). RMSEs were in the range 1.5–12.7 mm in spring, 3.2–11.1 mm in summer, 5.9–15.0 mm in autumn and 4.5–10.8 mm in winter. MSESS showed the largest range in spring (0.95–1) and the lowest in summer (0.98–1). Požega and Pazin showed the biggest difference with HISTALP series in all seasons.

Seasonal and annual trends were calculated for the relative (multiplicative) anomalies of the HISTALPnew and national homogenized series with respect to 1971–2000 period. Fifteen Croatian stations were checked for seasonal and annual precipitation trends and those are comparable to the corresponding HISTALPnew homogenized series, both in slopes and significance. No significant annual trends were observed, neither on HISTAL Pnew nor in the Croatian homogenized series, even though there was an indication of no or negative annual trends, up to 3% per decade, on all but two stations, namely Osijek and Crikvenica, which exhibited positive, although non-significant trends. Spring exhibits non-significant negative precipitation trends up to −5%, while at Pula (Table 3) the trend of −6% was significant. In summer, there was also an indication of negative precipitation trends that were mostly non-significant and up to −7%. There were significant negative trends of 6%–9% on four stations during summer (Bjelovar, Gospić, Rijeka and Zadar). There was an indication of prevailing increasing precipitation during autumn, mostly non-significant up to 5%, except at continental station Osijek that showed significant increasing precipitation of 7%. The exception with non-significant negative autumn trends were two stations, Pazin and Zadar in the maritime region. At all stations winter trends were non-significant, in the range −2% to 5% without clear positive or negative regional signal.

4.2.3 | Comparison to the Hungarian dataset

Before the comparison of the HISTALPnew data series with the corresponding homogenized national data series for Hungary, the discussion of the differences of the unhomogenized series was necessary (Figure 12). First, the rounding of monthly precipitation sum to integer values of mm in HISTALP can cause small differences, as the national dataset allows decimals. According to our analysis the size of the differences in descending order were the following: 36.2% for Keszthely, 16.7% for Sopron, 9.3% for Pécs, 7.6% for Szombathely and 6.6% for Mosonmagyaróvár, considering the years with differences larger than 5 mm. The average differences (National—HISTALP) were computed for the part of the series without missing data. The unhomogenized HISTALP dataset contained more precipitation for Pécs (43.4 mm), Szombathely (45.1 mm) and Keszthely (11.4 mm) stations and less for Mosonmagyaróvár (−12.7 mm) and Sopron (−6.4 mm) stations.

The other important point was that the MASH homogenization method allowed handling up to 500 stations at the same time, thus significantly more stations were used during the implementation of the national homogenization (Izsák, Szentimrey, Lakatos, Pongrácz, & Szentes, 2022; Szentimrey & Izsák, 2022).

The detected annual multiplicative inhomogeneities are shown in Figure 13 for two selected stations. The largest difference can be observed at Pécs and Keszthely from the five analysed stations. On the rest of the stations the detected inhomogeneities and breakpoints were similar. The adjusted series can be seen in Figure 14, again for the two selected stations. The effect of the detected breaks and related inhomogeneities for Pécs is clear. The largest difference (about 10 mm in each season) can be found at Keszthely station in the beginning of the period, while the series of Mosonmagyaróvár and Szombathely are almost identical when averaged over the whole period (Table 3). Higher discrepancies in the annual averages could come from different reasons: in the case of Pécs, the seasons differ slightly, but adding up generates

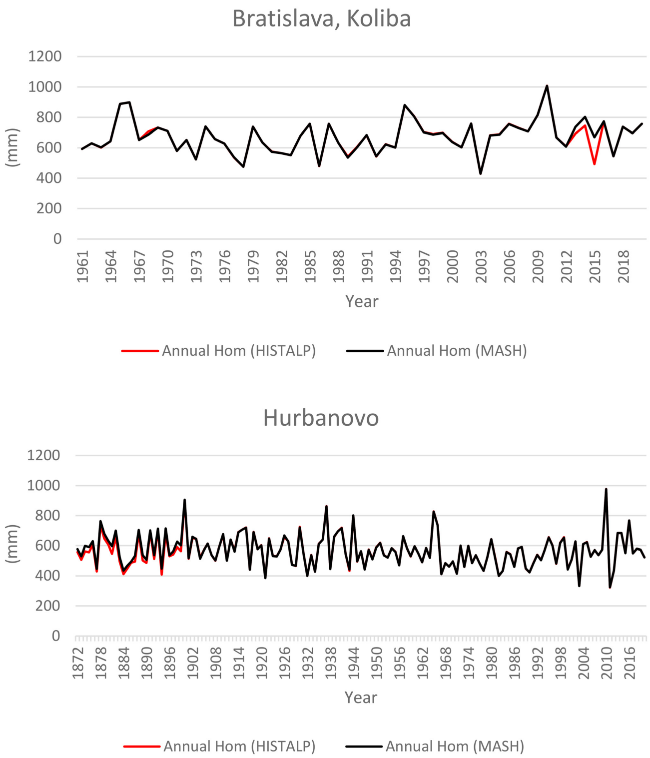

FIGURE 17 As Figure 8 but for Bratislava (upper) and Hurbanovo (lower). [Colour figure can be viewed at wileyonlinelibrary.com]

a remarkable difference, while in the case of Sopron the winter averages make the large part of the annual differences.

As most of the breakpoints were not detected in the years when the series differ, the differences are not seen as causes for the differences in the break detection result. The major breaks in the beginning of the 20th century were caused by the changeover from the earlier Austrian-type rain gauge to the Hellmann system with a few years shifting in the HISTALP and in the national dataset. We note that information on the instrument change was used as metadata during the national homogenization process. Interestingly, the inhomogeneity at Pécs was unexpectedly high in HISTALPnew even though the old type instruments registered only about 5%–15% more. The other anomaly to consider at Pécs in the HISTALPnew dataset was around the break detected in the 1990s possibly caused by switching to the automatic tipping bucket system, which tends to measure a bit less precipitation during winter and intense rainfall than traditional instruments. The increased rainfall in HISTALPnew is not consistent with this experience.

Looking at the temporal standard deviation, a big difference was indicated in Pécs, Sopron and Keszthely, which was most pronounced in winter and in the annual variance (Table 3). In terms of RMSE, Pécs annual value showed the largest differences (see also Figure 14). Relatively high RMSE values were associated with Keszthely station. The smallest RMSE was linked to Mosonmagyaróvár in winter. This is obvious, because the data series show quite good agreement and beside this winter is the driest season in Hungary (Izsák, Szentimrey, Lakatos, & Pongrácz, 2022; Lakatos et al., 2020). The closeness of the series was indicated by the MSESS value, which was around 0.99 for Mosonmagyaróvár in all seasons and for the annual record. As we expected from the different results of break detection, the lowest MSESS values appeared for Pécs (0.64 for Spring) and Keszthely.

The slope of the trend and its significance were computed for five stations for 1871–2021 and 1961–2021. Regarding the period 1871–2021, there was a good agreement in the signal although most of the changes are not significant. Nevertheless, some pronounced differences can be observed: annual sum for Sopron decreased significantly but to a quite different extent (HISTAPnew: −1.2% per decade; national dataset: −0.7% per decade). In general, the trends in HISTALPnew were steeper for all seasons, except summer. The summer precipitation decreased significantly and equally (−1.4% per decade) for Sopron. The spring precipitation exhibited a decline for all stations in both datasets, although the trends for Mosonmagyaróvár (−1.8%), Sopron (−1.3%) and Keszthely (−2.5%) were statistically significant in HISTALPnew, while significant change emerged at Pécs (−2.7%) and Szombathely (−1.6%) beside Mosonmagyaróvár (−1.8) in the national homogenized dataset. Trends for Szombathely were generally weaker in HISTALPnew, and there were some differences of the significance too. Considering the shorter period (1961–2021), no significant yearly or seasonal change emerged in neither of the two datasets.

4.2.4 | Comparison to the Italian dataset

The homogenization of the HISTALPnew and the national homogenized dataset was compared taking into account that in a few cases different versions of the raw series were used and in a greater number of cases different data sources were used for updating after the 2000s. The comparison was performed considering for each station both the entire period of common data availability and the period starting in 1961. Focusing on the former period, for six of the thirty-six series no breaks were detected in both data sets. Twelve series were homogenized in only one dataset: in most cases, however, the homogenization was applied to rather short periods (see e.g., Figure 15). The other series were homogenized in both datasets. In most

TABLE 3 Mean and standard deviation for selected national homogenized series.

Country	Station + period	Season	Mean (HISTALP)	Mean (national dataset)	Standard deviation (HISTALP)	Standard deviation (national dataset)	RMSE	MSESS	Trend slope (HISTALP)	*p*-value (HISTALP)	Trend slope (national dataset)	*p*-value (national dataset)
AT	Bad Gastein (1961–2015)	Spring	262.2	278.8	65.6	70.1	12.2	1.0	−0.013	0.46	−0.002	0.87
		Summer	483.7	513.3	81.3	84.1	22.8	0.9	0.009	0.51	0.020	0.10
		Autumn	296.3	314.3	87.1	90.2	14.2	1.0	0.024	0.38	0.040	0.11
		Winter	156.6	166.9	53.1	57.2	7.8	1.0	−0.021	0.54	−0.006	0.80
		Year	1196.9	1269.8	136.4	136.4	54.1	0.8	0.001	0.96	0.016	0.12
	Bregenz (1961–2015)	Spring	441.4	376.8	128.4	113.2	40.0	0.9	−0.021	0.37	−0.041	0.09
		Summer	668.9	566.5	144.9	107.4	67.5	0.7	0.016	0.39	−0.007	0.77
		Autumn	407.7	346.9	127.8	112.1	39.9	0.9	0.032	0.18	0.026	0.29
		Winter	312.5	265.5	109.0	88.9	32.3	0.9	−0.032	0.35	−0.038	0.32
		Year	1829.3	1554.5	268.1	213.2	171.4	0.5	0.005	0.77	−0.007	0.56
	Graz University (1961–2015)	Spring	185.7	188.6	60.9	62.3	3.1	1.0	0.000	0.97	0.006	0.86
		Summer	370.7	377.3	93.2	94.6	7.1	1.0	0.002	0.91	0.007	0.77
		Autumn	199.3	202.7	55.3	56.4	4.6	1.0	0.017	0.50	0.021	0.37
		Winter	91.6	93.0	39.6	40.3	1.3	1.0	−0.010	0.74	−0.003	0.92
		Year	846.4	860.6	136.0	137.9	12.8	1.0	0.000	1.00	0.005	0.74
	Wr.Neustadt (1961–2015)	Spring	148.2	140.6	56.3	52.2	7.5	1.0	0.021	0.51	0.003	0.89
		Summer	251.1	236.8	76.9	74.1	18.5	0.9	0.019	0.48	−0.001	0.95
		Autumn	138.7	129.8	47.2	41.0	16.6	0.9	**0.053**	0.04	0.037	0.16
		Winter	82.4	76.8	30.4	28.3	10.8	0.9	0.000	0.96	−0.021	0.56
		Year	620.2	583.6	113.4	101.2	49.1	0.8	0.020	0.25	−0.002	0.94
	Zell am See (1961–2015)	Spring	253.3	252.6	66.4	64.4	7.2	1.0	0.028	0.32	0.044	0.09
		Summer	471.6	472.6	80.5	78.6	15.3	1.0	0.015	0.24	**0.038**	0.02
		Autumn	250.7	250.0	78.4	78.9	7.5	1.0	0.050	0.06	**0.066**	0.00
		Winter	191.2	191.1	78.9	77.7	5.7	1.0	−0.012	0.78	0.006	0.91
		Year	1166.9	1166.5	146.4	143.1	30.8	1.0	0.010	0.30	**0.033**	0.01
HR	Požega (1961–2015)	Spring	180.4	182.5	54.1	57.1	12.7	1.0	−0.01	0.79	−0.01	0.84
		Summer	241.0	240.1	77.6	79.4	11.0	1.0	−0.04	0.14	−0.04	0.15
		Autumn	206.1	206.3	66.4	69.4	14.7	1.0	0.05	0.09	0.05	0.1
		Winter	151.5	153.4	58.2	59.0	10.8	1.0	−0.02	0.53	−0.02	0.6

TABLE 3 (Continued)

Country	Station + period	Season	Mean (HISTALP)	Mean (national dataset)	Standard deviation (HISTALP)	Standard deviation (national dataset)	RMSE	MSESS	Trend slope (HISTALP)	*p*-value (HISTALP)	Trend slope (national dataset)	*p*-value (national dataset)
		Year	778.2	781.5	136.8	137.9	16.1	1.0	−0.02	0.38	−0.01	0.44
	Gospić (1961–2015)	Spring	304.9	300.5	77.4	75.6	3.5	1.0	−0.03	0.27	−0.02	0.4
		Summer	238.4	234.8	89.0	87.5	3.2	1.0	**−0.09**	0.02	**−0.08**	0.03
		Autumn	474.5	468.3	158.2	157.1	5.9	1.0	0.03	0.33	0.03	0.26
		Winter	361.2	356.3	130.3	129.1	4.5	1.0	0	0.98	0.01	0.87
		Year	1374.4	1355.2	226.0	224.1	16.0	1.0	−0.01	0.73	0	0.98
	Pazin (1961–2015)	Spring	243.9	267.6	68.5	73.4	10.4	1.0	−0.04	0.17	−0.04	0.2
		Summer	252.6	278.3	86.0	95.2	11.1	1.0	−0.04	0.18	−0.04	0.2
		Autumn	354.6	388.7	128.3	140.5	15.0	1.0	−0.01	0.71	−0.01	0.7
		Winter	246.1	269.9	108.0	116.6	10.2	1.0	−0.02	0.59	−0.02	0.56
		Year	1094.0	1201.2	201.8	210.2	43.1	1.0	−0.03	0.07	−0.03	0.09
	Pula (1961–2015)	Spring	177.7	188.5	52.9	56.3	4.2	1.0	**−0.06**	0.04	**−0.06**	0.02
		Summer	166.9	177.0	76.6	80.7	4.3	1.0	−0.07	0.09	−0.07	0.07
		Autumn	287.2	303.5	115.6	120.5	8.3	1.0	0.03	0.49	0.02	0.56
		Winter	214.7	227.9	102.9	108.4	6.2	1.0	−0.02	0.75	−0.02	0.67
		Year	844.7	895.0	211.9	217.2	20.0	1.0	−0.02	0.31	−0.03	0.27
	Hvar (1961–2015)	Spring	164.0	177.5	65.9	71.6	1.5	1.0	0.01	0.78	0.01	0.79
		Summer	110.1	117.9	60.6	65.7	5.4	1.0	0	0.98	0	1
		Autumn	239.1	257.7	89.8	94.5	5.9	1.0	0.03	0.36	0.02	0.43
		Winter	233.7	252.7	111.2	118.5	5.3	1.0	−0.02	0.71	−0.02	0.73
		Year	745.1	803.8	170.3	180.8	12.5	1.0	0	0.85	0	0.98
HU	Mosonmagyaróvár (1871–2021)	Spring	140.4	140,8	50,9	51.2	3,9	1	**−0.018**	0.02	**−0.018**	0.02
		Summer	190.3	189.8	64,7	63,7	5,7	1.0	0.002	0.75	0.003	0.68
		Autumn	148.9	150,4	50,5	51,9	8,1	1.0	−0.006	0.41	−0.011	0.12
		Winter	111,1	111,1	41,7	42,1	3,5	1.0	−0.004	0.59	−0.004	0.64
		Year	590,7	592,1	102,5	103,7	10,2	1.0	−0.005	0.12	−0.006	0.07
	Pécs (1871–2021)	Spring	176,3	172.8	63,2	62,0	27.7	0.6	−0.015	0.06	**−0.027**	0.00
		Summer	208,7	204,4	70,0	68,5	23,7	0.9	0.011	0.07	0.004	0.53
		Autumn	180,9	172,4	72,4	68,8	16,7	0.9	−0.009	0.26	−0.011	0.15

(Continues)

TABLE 3 (Continued)

Country	Station + period	Season	Mean (HISTALP)	Mean (national dataset)	Standard deviation (HISTALP)	Standard deviation (national dataset)	RMSE	MSESS	Trend slope (HISTALP)	*p*-value (HISTALP)	Trend slope (national dataset)	*p*-value (national dataset)
		Winter	120,7	114.1	45,3	40.9	14,7	0.9	0.012	0.09	0.009	0.24
		Year	686,7	664,2	135,7	129,9	70,2	0.7	−0.001	0.89	−0.007	0.06
	Sopron (1871–2021)	Spring	166.8	164,6	55,5	54.4	7,7	1,0	**−0.013**	0.04	−0.009	0.16
		Summer	247.5	247.6	75.5	75,4	9,2	1.0	**−0.014**	0.04	**−0.014**	0.04
		Autumn	172,3	168.4	63,6	61,3	13,2	0.9	−0.009	0.22	−0.003	0.58
		Winter	107.8	98.0	47,7	42,3	13,2	0.9	−0.013	0.14	0.004	0.66
		Year	694.4	678,4	121,7	113,7	27,6	1.0	**−0.012**	0.00	**−0.007**	0.03
	Szombathely (1871–2021)	Spring	143,5	147,5	49.0	49,6	14.0	0.9	−0.006	0.32	**−0.016**	0.01
		Summer	234.8	239,2	67.7	69,6	13,9	0.9	−0.006	0.34	**−0.013**	0.05
		Autumn	157,4	158,8	53,4	54,2	9,4	1.0	−0.003	0.70	−0.006	0.39
		Winter	88,0	87,2	38,8	39,6	10,1	0.9	0.005	0.55	0.013	0.13
		Year	623,7	632.5	99.8	101,5	29,5	0.9	−0.004	0.24	**−0.008**	0.01
	Keszthely (1871–2021)	Spring	159,2	149,9	54,1	49,4	15,4	0.9	**−0.025**	0.00	−0.013	0.06
		Summer	223,6	212,1	77,0	74,8	19,2	0.9	−0.003	0.66	0.006	0.32
		Autumn	178.1	168,5	67,0	62,8	19,7	0.9	−0.013	0.08	−0.001	0.83
		Winter	111,6	102,9	46.6	42,4	14,1	0.9	0.012	0.13	0.014	0.07
		Year	672,5	633,1	137,3	128,1	55,9	0.7	−0.007	0.07	0.003	0.50
IT	Bressanone (1878–2016)	Spring	140.5	140.2	41.9	42.2	5.2	1.0	−0.002	0.79	−0.001	0.89
		Summer	297.0	296.9	70.2	70.1	11.3	0.9	0.005	0.26	0.006	0.23
		Autumn	178.4	177.8	71.8	72.1	5.1	1.0	−0.009	0.33	−0.009	0.30
		Winter	67.4	66.8	118.6	119.2	4.4	1.0	0.000	0.92	0.003	0.81
		Year	682.9	681.3	118.6	119.2	14.2	1.0	−0.002	0.61	−0.001	0.75
	Imperia (1876–2011)	Spring	192.2	193.7	103.7	107.3	8.5	1.0	**−0.021**	0.04	**−0.027**	0.01
		Summer	74.0	74.7	48.7	48.6	4.5	1.0	−0.002	0.84	−0.002	0.89
		Autumn	272.9	274.8	135.8	137.1	15.1	1.0	−0.001	0.93	−0.006	0.57
		Winter	207.7	208.3	120.8	118.3	14.0	1.0	0.016	0.22	0.014	0.29
		Year	746.0	750.6	219.7	222.9	29.9	1.0	−0.006	0.30	−0.012	0.09

TABLE 3 (Continued)

Country	Station + period	Season	Mean (HISTALP)	Mean (national dataset)	Standard deviation (HISTALP)	Standard deviation (national dataset)	RMSE	MSESS	Trend slope (HISTALP)	*p*-value (HISTALP)	Trend slope (national dataset)	*p*-value (national dataset)
	Monte Maria (1858–2016)	Spring	140.4	139.6	58.7	58.6	9.1	1.0	−0.004	0.47	−0.004	0.49
		Summer	243.3	244.7	64.8	63.9	8.5	1.0	0.004	0.44	0.005	0.33
		Autumn	196.3	197.6	87.9	87.3	6.2	1.0	−0.008	0.29	−0.008	0.29
		Winter	105.8	106.0	50.8	51.5	9.2	1.0	−0.004	0.60	−0.003	0.71
		Year	685.2	687.4	133.4	131.9	15.6	1.0	−0.004	0.31	−0.003	0.38
	Torino (1802–2016)	Spring	310.7	285.9	129.0	130.2	19.3	1.0	−0.001	0.75	−0.006	0.17
		Summer	257.6	237.8	110.3	111.9	18.4	1.0	0.000	0.91	−0.003	0.54
		Autumn	266.6	245.9	134.1	136.9	19.0	1.0	−0.004	0.48	−0.009	0.15
		Winter	140.4	129.4	88.9	89.1	11.0	1.0	−0.001	0.89	−0.004	0.55
		Year	975.3	899.0	236.4	246.8	58.0	0.9	−0.003	0.26	**−0.008**	0.01
	Udine (1803–2015)	Spring	386.7	359.0	134.6	136.0	22.9	1.0	−0.002	0.58	−0.002	0.61
		Summer	434.0	407.0	130.4	127.4	33.8	0.9	**−0.010**	0.01	**−0.012**	0.00
		Autumn	489.9	451.5	178.4	180.2	32.2	1.0	**−0.012**	0.00	**−0.012**	0.00
		Winter	296.6	268.5	152.7	157.2	34.5	1.0	−0.003	0.56	0.000	0.95
		Year	1606.7	1485.5	309.3	322.5	65.8	1.0	**−0.008**	0.00	**−0.007**	0.00
SK	Bratislava, Koliba (1961–2017)	Spring	153.6	155.2	50.6	50.4	7.4	1.0	−0.019	0.50	−0.005	0.83
		Summer	208.8	207.5	75.3	74.3	11.2	1.0	0.019	0.55	0.012	0.69
		Autumn	166.1	167.7	55.1	55.7	7.8	1.0	0.021	0.37	0.03	0.25
		Winter	136.5	139.0	44.7	48.4	12.9	0.9	0.006	0.86	0.02	0.59
		Year	666.5	669.9	110.8	109.6	25.7	1.0	0.016	0.26	0.022	0.11
	Hurbanovo (1961–2017)	Spring	125.9	125.7	51.3	51.2	0.8	1.0	0.016	0.57	0.016	0.56
		Summer	177.1	177.1	59.2	59.2	0.5	1.0	0.023	0.41	0.024	0.43
		Autumn	136.4	136.4	50.7	50.7	0.4	1.0	0.029	0.34	0.03	0.34
		Winter	107.1	107.0	43.2	43.2	0.4	1.0	−0.004	0.93	−0.003	0.93
		Year	546.7	546.2	114.0	113.8	1.0	1.0	0.03	0.08	0.03	0.09

Note: RMSE and MSESS for HISTALP and national normalized series. Trends (slope in relative anomalies per decade) and significance of trends (*p*-value) for selected HISTALP and national homogenized anomalies relative to the common 1961–2000 period or to the entire period of common data availability. Significant trends are given in bold on grey background.

Station_name	IN	HO	brk1	brk2	brk3
Požega	13	NA	NA	NA	NA
Gospić	NA	54	1993–04 (17.8)	NA	NA
Pazin	2	90	1983–11 (39.8)	1996–09 (15.4)	2016–05 (18.4)
Pula	2	78	2009–08 (18.4)	NA	NA
Hvar	NA	88	2014–09 (15.1)	NA	NA

Abbreviation: NA, no detected breaks.

TABLE 4 Selected Croatian stations, percentage of filled missing data (IN) and percentage of homogenized data (HO) for 1960–2020 and year and month of the detected breaks (brk1–brk3) with the SNHT T value in brackets.

cases, the homogenized periods and the applied adjustments were rather similar, whereas in a limited number of cases (four series) the homogenized periods and the adjustments highlighted stronger differences.

At monthly level the median of the MSESS values between the records of the two datasets was 0.96 (first quartile: 0.94; third quartile: 0.98) and only five records showed MSESS lower than 0.90. Considering the period since 1961 the values were slightly lower showing a median equal to 0.96 (first quartile: 0.92; third quartile: 0.97). The median of the absolute differences between the monthly records of the two datasets was 4.9 mm (first quartile: 3.1 mm; third quartile: 6.6 mm), whereas the corresponding value for RMSE was 10.2 mm (first quartile: 8.2 mm; third quartile: 15.4 mm). Considering the series starting from 1961 the median of the absolute differences between the monthly records of the two datasets was 5.2 mm (first quartile: 3.4 mm; third quartile: 8.3 mm), whereas the corresponding value for RMSE was 11.3 mm (first quartile: 8.3 mm; third quartile: 18.0 mm). Two examples for annual homogenized time series are provided in Figure 16.

The obtained results underlined a rather good agreement between the HISTALPnew and the national homogenized dataset. As expected, the results obtained since 1961 showed a slightly lower agreement, due to the fact that in some cases different data sources were used for updating the series after the 2000s. The agreement between the two datasets was also rather good, as far as long-term trends are concerned: the trend signal was rather weak and for both datasets more than half of the records did not show any significant trend (p-value $\leq$0.05). Moreover, for both datasets all records with significant trend (15 records for the national dataset, seven records for the HISTALPnew one) had negative slope values (the average values for the annual series are −1.2% per decade for the national dataset and −1.0% per decade for the HISTALPnew one). This signal became even weaker if the series since 1961 were considered: no series for the national dataset showed a significant trend, while only two series for the HISTALPnew dataset showed a significant negative trend.

4.2.5 | Comparison Slovakia

The homogenized HISTALPnew series were compared with the corresponding series of the national homogenized dataset for the common period 1961–2017. At monthly level the median of the MSESS values between the records of the two datasets was 0.99 (first quartile: 0.99; third quartile: 1): at seasonal level (Table 3) in spring 0.98–1.00, in summer 0.98–1.00, in autumn 0.98–1.00, in winter 0.93–1.00 and in year 0.95–1.00.

The median of the absolute differences between the monthly records of the two datasets was 0.1 mm (first quartile: 0.0 mm; third quartile: 0.3 mm), whereas the corresponding value for RMSE was 2 mm (first quartile: 0.9 mm; third quartile: 4.2 mm):at seasonal level in spring 0.0–7.4 mm, in summer 0.0–11.2 mm, in autumn 0.0–7.8 mm, in winter 0.0–12.9 mm and year 0.2–26.7 mm.

The obtained results underline a rather good agreement between the HISTALPnew and the national homogenized datasets except for the values of the period 2013–2015 from Bratislava-Koliba, which differed considerably in the two datasets (Figure 17). This is caused by the fact that in HISTALPnew the data of Bratislava airport are used for those 2 years, while the national dataset replaced the former station with the airport station only in 2016.

The summary of the trends is presented in Table 3. In both datasets there was no significant trend signal in seasonal or annual values. There was a good agreement in the direction of all analysed trends as well. The agreement was higher in Bratislava Koliba than in Hurbanovo. Especially strong differences occurred in autumn at both stations.

Taking HISTALPnew data into account, small precipitation changes between −0.4% and 0.6% per decade could be observed during winter for 1961–2017 period. Results showed higher changes from −1.9% to 1.6% for spring period. Summer and autumn showed more significant increase with 1.9%–2.9% per decade. The same could be stated for annual characteristics with increases between 1.6% and 3% per decade. Comparison between HISTALPnew and national data showed higher slope values of national data for Bratislava-Koliba except summer. HISTALPnew and homogenized national trends fit well for 1961–2017 period in Hurbanovo.

5 | CONCLUSIONS

Results of an updated homogenization of the HISTALP precipitation dataset (HISTALPnew) have been presented. Such an update was essential due to the long number of years, which was added after the last homogenization activity. Changes in data providers (especially for Italy) and relocation of stations had to be considered properly. The difficulty in the homogenization of this pan-Alpine dataset is the sparse stations network. Use of smaller networks for particularly critical stations, in connection with strongly correlated reference stations, proved to be a fruitful approach. For some of the stations (Montmorod, Nancy-Essey Tomblaine and Hohenpeißenberg), in contrast to the former HISTALP homogenization, the applied methodology did not allow to obtain homogenized records.

The fraction of detected breaks in the HISTALP dataset might seem low. This is a consequence of the number of available reference stations, which is also decreasing the further back in time the time series reaches. The spatial distribution of trends and range of the monthly precipitation data support the idea of a generally good quality of the homogenization.

For further quality check, the newly homogenized HISTALP dataset was compared to national homogenized datasets. It is known from the literature that different homogenization procedures do not necessarily give the same results (Izsák & Szentimrey, 2020; Venema et al., 2012; WMO, 2020). Break detection and corrections resulting from homogenization depend largely on the mathematical background of the software used. Moreover, additional factors can affect the differences: timing of the homogenization, selection of reference series, selection of homogenization methods. Additionally for interactive methods, the experience of the homogenizer plays an important role. In this case, knowledge of metadata is also an important factor. Especially when handling a large number of stations, a fully automatic version is often preferred to an interactive one due to the required personnel resources and good reproducibility of the homogenization.

The results of this article show the combined influences of all those factors (methods, available reference stations, timing of the homogenization process, …) by means of the comparison of the newly homogenized HISTALP records with corresponding records from national homogenization activities performed in Austria, Croatia, Hungary, Italy and Slovakia. In all of the national activities another homogenization method was used and the network of reference stations was denser. In addition to the above-mentioned factors, despite a check with the data providers before the start of the homogenization, differences in the available original data became obvious during the comparison. Differences in the original measurement data can be caused by, for example, changes in the original data due to data quality control, data filling methods, data rescue activities or different data sources. Moreover, some time series might have been provided as pre-homogenized data to HISTALP when the database was created. The last cause can be easily eliminated by a further exchange on the data with the data providers, especially for other parameters, for which no new homogenization has been done so far. However, the others are harder to keep track of in a secondary database, based on data provided by different data providers. In Italy, the situation is further complicated by the diversity of data providers caused by a radical change in the management of the rain gauge network in the 1990s when the National Hydrographic Service was closed and its competences were transferred to the regions. Issues with measurement data from Hungary and Slovakia will be addressed in a future step.

The results of the comparison show that in the national homogenizations more breaks were detected than in the newly homogenized HISTALP one, as was to be expected due to the higher number of highly correlated reference series. Nevertheless, the comparison gives some confidence in the new HISTALP dataset and its homogenization. Most of the stations, both in newly homogenized HISTALP and in the homogenized national datasets, showed only weak trend signals and only the minority of them is statistically significant on the 95%-confidence level. The geographical distribution of the trends after homogenization follows a realistic pattern. Differences in the break detection partly result in higher differences of the final time series regarding RMSE and MSESS. Nevertheless, excluding from the comparison those stations with strong differences in the original data, results in rather small RMSE values in most cases and MSESS values close to 1. However, for a few of the stations the new homogenization result of HISTALP seems in contrast to the homogenization of the national dataset (e.g., Pécs and Bregenz). For those cases a further analysis and some further homogenization assessment is planned for the future.

The advantage of a common homogenization for a dataset is, nevertheless, the consistency of the dataset in itself. The identical timing of homogenization effort and the use of the identical method are responsible for some of the differences we experienced in the comparison of the national and pan-Alpine datasets. Nevertheless, an increased exchange on national results might help in the future for identifying or setting breaks in the pan-Alpine dataset.

The HISTALP homogenized dataset presented in this article is used in the Copernicus LAPrec-Dataset and will be provided for academic use as well as for information via the HISTALP-webpage (www.zamg.ac.at/histalp), taking into account national restrictions regarding the Swiss and French stations.

AUTHOR CONTRIBUTIONS

Barbara Chimani: Conceptualization; methodology; validation; visualization; software; data curation; writing – original draft; writing – review and editing. **Oliver Bochníček:** Validation; visualization; software; writing – original draft; methodology. **Michele Brunetti:** Conceptualization; data curation; methodology; software; validation; visualization; writing – original draft; writing – review and editing. **Manfred Ganekind:** Data curation; writing – review and editing. **Juraj Holec:** Methodology; validation; visualization; software; writing – original draft. **Beatrix Izsák:** Methodology; validation; visualization; software; writing – original draft. **Mónika Lakatos:** Conceptualization; data curation; methodology; validation; visualization; software; writing – original draft; writing – review and editing. **Melita Perčec Tadić:** Conceptualization; data curation; methodology; validation; visualization; software; writing – original draft; writing – review and editing. **Veronica Manara:** Conceptualization; data curation; methodology; validation; visualization; software; writing – original draft. **Maurizio Maugeri:** Conceptualization; writing – original draft; methodology; validation; visualization; software; data curation. **Pavel Šťastný:** Methodology; validation; visualization; software; writing – original draft. **Olivér Szentes:** Methodology; validation; visualization; software; data curation; writing – original draft. **Dino Zardi:** Writing – original draft; writing – review and editing.

ACKNOWLEDGEMENTS

The authors would like to thank all HISTALP data providers for their ongoing commitment to and support for this database (http://zamg.ac.at/histalp/support/recent_prov.php). Furthermore, they thank Copernicus Climate Change Service for the interest in the Alpine climate dataset and their support via the contract C3S_311a_Lot4.

Veronica Manara was supported by the 'Ministero dell'Università e della Ricerca' of Italy (grant FSE-REACT, DM 10/08/2021 – n. 1062).

The Hungarian contribution to this article was supported by the Sustainable Development and Technologies National Programme of the Hungarian Academy of Sciences and RRF-2.3.1-21-2022-00014 National Multidisciplinary Laboratory for Climate Change.

ORCID

Barbara Chimani https://orcid.org/0000-0003-0298-4181
Beatrix Izsák https://orcid.org/0000-0003-1323-5389
Olivér Szentes https://orcid.org/0000-0003-3537-0397

REFERENCES

Alexandersson, H. (1986) A homogeneity test applied to precipitation data. *Journal of Climate*, 6, 661–675.

Alexandersson, H. & Moberg, A. (1997) Homogenisation of Swedish temperature data, part I: a homogeneity test for linear trends. *International Journal of Climatology*, 7, 1001–1013.

Aschwanden, A., Beck, M., Häberli, C., Haller, G., Kiene, M., Roesch, A. et al. (1996) Klimatologie der Schweiz, Heft 2: Bereinigte Zeitreihen. Die Ergebnisse des Projekts KLIMA90, Band 1–4. Schweizerische Meteorologische Anstalt: Zürich.

Auer, I. (1993) Niederschlagsschwankungen in Österreich seit Beginn der instrumentellen Beobachtungen durch die Zentralanstalt für Meteorologie und Geodynamik. Österreichische Beiträge zu Meteorologie und Geophysik, Vol. 7. Zentralanstalt für Meteorologie und Geodynamik: Wien.

Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R. et al. (2007) HISTALP—historical instrumental climatological surface time series of the greater Alpine region 1760-2003. *International Journal of Climatology*, 27, 17–46.

Auer, I., Böhm, R., Jurkovic, A., Orlik, A., Potzmann, R., Schöner, W. et al. (2005) A new instrumental precipitation dataset for the greater Alpine region for the period 1800-2002. *International Journal of Climatology*, 25, 139–166.

Auer, I., Böhm, R. & Schöner, W. (2001a) Long climatic time series from Austria. In: Jones, P.D., Ogilvie, A.E.J., Davies, T.D. & Briffa, K.R. (Eds.) *History and climate—memories of the future?*. New York, NY: Kluver Academic/Plenum Publishers, pp. 125–152.

Auer, I., Böhm, R. & Schöner, W. (2001b) Austrian long-term climate 1767–2000—Multiple instrumental climate time series from Central Europe. Österreichische Beiträge zu Meteorologie und Geophysik, 25: 147 pages plus Data- and Metadata-CD.

Auer, I., Böhm, R. & Schöner, W. (2001c) Final report of EU-project ALPCLIM. Chapter 3: Instrumental Climate.

Auer, I., Nemec, J., Gruber, C., Chimani, B. & Türk, K. (2010) HOM-START Homogenisation of climate series on a daily basis, an application to the StartClim dataset, Vienna: Klima- und Energiefonds, project report, 34 pages. Available from: https://www.zamg.ac.at/cms/de/dokumente/klima/dok_projekte/homstart/homstart-endbericht [Accessed 28th November 2022]

Barry, R. (2008) *Mountain weather and climate*, 3rd edition. Cambridge: Cambridge University Press. Available from: https://doi.org/10.1017/CBO9780511754753

Begert, M., Schlegel, T. & Kirchhofer, W. (2005) Homogeneous temperature and precipitation series of Switzerland from 1864 to 2000. *International Journal of Climatology*, 25, 65–80.

Beniston, M. (2003) Climatic change in mountain regions: a review of possible impacts. In: Diaz, H.F. (Ed.) *Climate variability and change in high elevation regions: past, present & future*. Advances in Global Change Research, Vol. 15. Dordrecht: Springer. Available from: https://doi.org/10.1007/978-94-015-1252-7_2

Beniston, M. & Jungo, P. (2002) Shifts in the distributions of pressure, temperature and moisture and changes in the typical weather patterns in the Alpine region in response to the behavior of the North Atlantic Oscillation. *Theoretical and Applied Climatology*, 71, 29–42. Available from: https://doi.org/10.1007/s704-002-8206-7

Böhm, R., Auer, I., Brunetti, M., Maugeri, M., Nanni, T., & Schöner, W. (2001) Regional temperature variability in the European Alps: 1760-1998 from homogenized instrumental time series. *International Journal of Climatology*, 21(14), 1779–1801. https://doi.org/10.1002/joc.689

Böhm, R. (1992) Lufttemperaturschwankungen in Österreich seit 1775. Österreichische Beiträge Zu Meteorologie Und Geophysik, Vol. 5. Zentralanstalt für Meteorologie und Geodynamik: Wien. 1–96.

Brunetti, M., Buffoni, L., Maugeri, M. & Nanni, T. (2000) Trends of minimum and maximum daily temperatures in Italy from 1865 to 1996. *Theoretical and Applied Climatology*, 66, 49–60.

Brunetti, M., Lentini, G., Maugeri, M., Nanni, T., Auer, I., Böhm, R. et al. (2009) Climate variability and change in the greater Alpine region over the last two centuries based on multi-variable analysis. *International Journal of Climatology*, 29, 2197–2225.

Brunetti, M., Maugeri, M., Monti, F. & Nanni, T. (2006) Temperature and precipitation variability in Italy in the last two centuries from homogenised instrumental time series. *International Journal of Climatology*, 26(3), 345–381. Available from: https://doi.org/10.1002/joc.1251

Brunetti, M., Maugeri, M., Nanni, T., Auer, I., Böhm, R. & Schöner, W. (2006) Precipitation variability and changes in the greater Alpine region over the 1800–2003 period. *Journal of Geophysical Research*, 111, D11107. Available from: https://doi.org/10.1029/2005JD006674

Buffoni, L., Maugeri, M. & Nanni, T. (1999) Precipitation in Italy from 1833 to 1996. *Theoretical and Applied Climatology*, 63, 33–40.

Caussinus, H. & Lyazrhi, F. (1997) Choosing a linear model with a random number of change-points and outliers. *Annals of the Institute of Statistical Mathematics*, 49(4), 761–775.

Caussinus, H. & Mestre, O. (2004) Detection and correction ofartificial shifts in climate series. *Journal of the Royal Statistical Society, Series C (Applied Statistics)*, 53, 405–425.

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

Crespi, A., Brunetti, M., Ranzi, R., Tomirotti, M. & Maugeri, M. (2020) A multi-century meteo-hydrological analysis for the Adda river basin (Central Alps). Part I: gridded monthly precipitation (1800-2016) records. *International Journal of Climatology*, 41(1), 162–180. Available from: https://doi.org/10.1002/joc.6614

Domonkos, P. (2011) Efficiency evaluation for detecting inhomogeneities by objective homogenisation methods. *Theoretical and Applied Climatology*, 105, 455–467. Available from: https://doi.org/10.1007/s00704-011-0399-7

Domonkos, P. (2021) ACMANT v4: Scientific content and operation of the software. Available from: https://github.com/dpeterfree/ACMANT/tree/ACMANTv4.4 [Accessed 19th December 2022]

Domonkos, P. & Coll, J. (2017) Homogenisation of temperature and precipitation time series with ACMANT3: method description and efficiency tests. *International Journal of Climatology*, 37, 1910–1921. Available from: https://doi.org/10.1002/joc.4822

Domonkos, P., Venema, V., Auer, I., Mestre, O. & Brunetti, M. (2012) The histroical pathway towards more accurate homogenisation. *Advances in Science and Research*, 8, 45–52.

Gajić-Čapka, M. & Zaninović, K. (1997) Changes in temperature extremes and their possible causes at the SE boundary of the Alps. *Theoretical and Applied Climatology*, 57(1–2), 89–94.

Giorgi, F., Torma, C., Coppola, E., Ban, N., Schär, C. & Somot, S. (2016) Enhanced summer convective rainfall at Alpine high elevations in response to climate warming. *Nature Geoscience*, 9(8), 584–589. Available from: https://doi.org/10.1038/ngeo2761

Gisler, O., Baudenbacher, M. & Bosshard, W. (1997) Homogenisierung schweizersicher klimatologischer Messreihen des 19. und 20. Jahrhunderts. Projektschlussbericht im Rahmen des nationalen Forschungsprogrammes, Klimaänderung und Naturkatastrophen"NFF31.vdf Hochschulverlag an der ETH.

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J. & Stoffel, M. (2014) 21st century climate change in the European Alps—a review. *Science of the Total Environment*, 493, 1138–1151.

Guijarro, J.A. (2019) Package 'climatol' Version 3.1.2. Available from: https://cran.r-project.org/web/packages/climatol/climatol.pdf

Guijarro, J.A. (2021) Homogenization of climatic series with Climatol Version 3.1.1. Available from: http://www.climatol.eu/homog_climatol-en.pdf. [Accessed 28th November 2022]

Haeberli, W. & Beniston, M. (1998) Climate change and its impact on glaciers and permafrost in the Alps. *Ambio*, 27, 258–265.

Haslinger, K. & Mayer, K. (2022) Early spring droughts in Central Europe: indications for atmospheric and aceanic drivers. *Atmospheric Science Letters*, 24, e1136. Available from: https://doi.org/10.1002/asl.1136

Hawkins, D.M. (2001) Fitting multiple change-points to data. *Computational Statistics & Data Analysis*, 37, 323–341.

Herzog, J. & Müller-Westermeier, G. (1998) Homogenitätsprüfung und Homogenisierung klimatologischer Meßreihen im deutschen Wetterdienst. Berichte des Deutschen Wetterdienstes, Vol. 202. Selbstverlagdes Deutschen Wetterdienstes: Offenbach am Main.

Hiebl, J., Auer, I., Böhm, R., Schöner, W., Maugeri, M., Lentini, G. et al. (2009) A high-resolution 1961-1990 monthly temperature climatology for the greater Alpine region. *Meteorologische Zeitschrift*, 18(5), 507–530. Available from: https://doi.org/10.1127/0941-2948/2009/0403

IPCC. (2021) Climate change 2021: the physical science basis. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (Eds.) *Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge, UK and New York, NY: Cambridge University Press. Available from: https://doi.org/10.1017/9781009157896

Isotta, F.A., Frei, C., Weilguni, V., Perčec Tadić, M., Lassègues, P., Rudolf, B. et al. (2014) The climate of daily precipitation in the Alps: development and analysis of a high-resolution grid dataset from pan-Alpine rain-gauge data. *International Journal of Climatology*, 34, 1657–1675. Available from: https://doi.org/10.1002/joc.3794

Izsák, B. & Szentimrey, T. (2020) To what extent does the detection of climate change in Hungary depend on the choice of statistical methods? *International Journal on Geomathematics*, 11, 17. Available from: https://doi.org/10.1007/s13137-020-00154-y

Izsák, B., Szentimrey, T., Lakatos, M. & Pongrácz, R. (2022) Extreme months: multidimensional studies in the Carpathian Basin. *Atmosphere*, 13, 1908. Available from: https://doi.org/10.3390/atmos13111908

Izsák, B., Szentimrey, T., Lakatos, M., Pongrácz, R. & Szentes, O. (2022) Creation of a representative climatological database for Hungary from 1870 to 2020. *Időjárás*, 126, 1–26. Available from: https://doi.org/10.28974/idojaras.2022.1.1

Laimighofer, J. & Laaha, G. (2022) How standard are standardized drought indices? Uncertainty components for the SPI & SPEI case. *Journal of Jydrology*, 613 (A), 128385. Available from: https://doi.org/10.1016/j.jhydrol.2022.128385

Lakatos, M., Izsák, B., Szentes, O., Hoffmann, L., Kircsi, A. & Bihari, Z. (2020) Return values of 60-minute extreme rainfall for Hungary. *Időjárás*, 124, 143–156. Available from: https://doi.org/10.28974/idojaras.2020.2.1

Likso, T. (2004) Inhomogeneities in temperature time series in Croatia. *Hrvatski meteorološki časopis (Croatian Meteorological Journal)*, 38, 3–9.

Lindau, R. & Venema, V. (2018) On the reduction of trend errors by the anova joint correction scheme used in homogenization of climate station records. *International Journal of Climatology*, 38, 5255–5271.

Manara, V., Brunetti, M., Gilardoni, S., Landi, T.C. & Maugeri, M. (2019) 1951-2017 changes in the frequency of days with visibility higher than 10 km and 20 km in Italy. *Atmospheric Environment*, 214, 1. Available from: https://doi.org/10.1016/j.atmosenv.2019.116861

Marcolini, G., Koch, R., Chimani, B., Schöner, W., Bellin, A., Disse, M. et al. (2019) Evaluation of homogenization methods for seasonal snow depth data in the Austrian Alps, 1930-2010. *International Journal of Climatology*, 39(11), 4514–4530. Available from: https://doi.org/10.1002/joc.6095

Marty, C., Tilg, A.-M. & Jonas, T. (2017) Recent evidence of large-scale receding snow water equivalents in the European Alps. *Journal of Hydrometeorology*, 18(4), 1021–1031. Available from: https://doi.org/10.1175/jhm-d-16-0188.1

Matiu, M., Crespi, A., Bertoldi, G., Carmagnola, C.M., Marty, C., Morin, S. et al. (2021) Observed snow depth trends in the European Alps: 1971 to 2019. *The Cryosphere*, 15(3), 1343–1382. Available from: https://doi.org/10.5194/tc-15-1343-2021

Maugeri, M. & Nanni, T. (1998) Surface air temperature variations in Italy: recent trends and an update to 1993. *Theoretical and Applied Climatology*, 61, 191–196.

Mestre, O., Domonkos, P., Picard, F., Auer, I., Robin, S., Lebarbier, E. et al. (2013) HOMER: a homogenization software—methods and applications. *Időjárás*, 117(1), 47–67.

Nemec, J., Gruber, C., Chimani, B. & Auer, I. (2012) Trends in extreme temperature indices in Austria based on a new homogenised dataset. *International Journal of Climatology*, 33, 1538–1550. Available from: https://doi.org/10.1002/joc.3532

Perčec Tadić, M., Pasarić, Z. & Guijarro, J.A. (2022) Croatian high-resolution monthly gridded dataset of homogenised surface air temperature. *Theoretical and Applied Climatology*, 151, 227–251. Available from: https://doi.org/10.1007/s00704-022-04241-y

Peterson, T. C., Easterling, D. R., Karl, T. R., Groisman, P., Nicholls, N., Plummer, N. et al. (1998) Homogeneity adjustments of in situ atmospheric climate data: a review. *International Journal of Climatology*, 18(13), 1493–1517. https://doi.org/10.1002/(SICI)1097-0088(19981115)18:13<1493::AID-JOC329>3.0.CO;2-T

Picard, F., Lebarbier, E., Hoebeke, M., Rigaill, G., Thiam, B. & Robin, S. (2011) Joint segmentation, calling, and normalization of multiple CGH profiles. *Biostatistics*, 12(3), 413–428. Available from: https://doi.org/10.1093/biostatistics/kxq076

Ribeiro, S., Caineta, J. & Coasta, A.C. (2016) Review and discussion of homogenisation methods for climate data. *Physics and Chemistry of the Earth, Parts A/B/C*, 94, 167–179. Available from: https://doi.org/10.1016/j.pce.2015.08.007

Schär, C., Davies, T.D., Frei, C., Wanner, H., Widmann, M., Wild, M. et al. (1998) Current Alpine climate. In: Cebon, P., Dahinden, U., Davies, H.C., Imboden, D.M. & Jäger, C. (Eds.) *Views from the Alps: regional perspectives on climate change*. Boston: MIT Press, pp. 21–72.

Scherrer, S.C. (2020) Temperature monitoring in mountain regions using reanalyses: lessons from the Alps. *Environmental Research Letters*, 15(4), 044005. Available from: https://doi.org/10.1088/1748-9326/ab702d

Sen, P.K. (1968) Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, 63, 1379–1389. Available from: https://doi.org/10.1080/01621459.1968.10480934

Serra, E., Magrani, F., Valla, P.G., Gribenski, N., Carcaillet, J. & Egholm, D.L. (2022) Lateglacial paleoglacier and paleoclimate reconstructions in the north-western Italian Alps. *Quaternary Science Reviews*, 298, 107822. Available from: https://doi.org/10.1016/j.quascirev.2022.107822

Sneyers, R. (1992) On the use of statistical analysis for the objective determination of climate change. *Meteorologische Zeitschrift*, 1, 247–256.

Szentimrey, T. (1997) Statistical procedure for joint homogenisation of climate time series. In *Proceedings of the First seminar for Homogenisation of Surface Climatological Data, Budapest, 6–12 October 1996*. Hungarian Meteorological Service, K´eszült a MET-DRUCK nyomd´aban, Budapest, pp. 47-62.

Szentimrey, T. (1999) Multiple Analysis of Series for Homogenization (MASH). *Proceedings of the Second Seminar for Homogenization of Surface Climatological Data, Budapest, Hungary*; WMO, WCDMP-No. 41, pp. 27-46.

Szentimrey, T. (2001) Multiple analysis of series for homogenization (MASH), seasonal application of MASH (SAM), automatic using of meta data. In *Proceedings of the Third Seminar for Homogenization and Quality Control in Climatological Databases, Budapest, Hungary, 25–29 September, 2000*.

Szentimrey, T. (2017) *Manual of homogenization software MASHv3.03. Hungarian Meteorological Service, Budapest, Hungary, 2017*.

Szentimrey, T., Bihari, Z. & Lakatos, M. (2010) Quality control procedures in MISH-MASH systems. *10th EMS Annual Meeting, 10th European Conference on Applications of Meteorology (ECAM) Abstracts, held Sept. 13-17, 2010 in Zürich, Switzerland*.

Szentimrey, T. & Izsák, B. (2022) Joint examination of climate time series based on a statistical definition of multidimensional extreme. *Időjárás*, 126, 159–184. Available from: https://doi.org/10.28974/idojaras.2022.2.1

Theil, H. (1950) A rank-invariant method of linear and polynomial regression analysis. I, II, III, Nederl. Akad. Wetensch., Proceedings, Vol. 53, pp. 386-392, 521-525, 1397-1412.

Valler, V., Franke, J., Brugnara, Y. & Brönnimann, S. (2021) An updated global atmopsheric paleo-reanalysis covering the last 400 years. *Geoscience Data Journal*, 9, 89–107. Available from: https://doi.org/10.1002/gdj3.121

Van Malderen, R., Pottiaux, E., Klos, A., Domonkos, P., Elias, M., Ning, T. et al. (2020) Homogenizing GPS integrated water vapor time series; benchmarking break detection methods on synthetic data sets. *Earth and Space Science*, 7, 5. Available from: https://doi.org/10.1029/2020EA001121

Venema, V., Mestre, O., Aguilar, E., Auer, I., Guijarro, J.A., Domonkos, P. et al. (2012) Benchmarking monthly homogenization algorithms. *Climate of the Past*, 8, 89–115.

Volkert, H. (2009) The International Conferences on Alpine Meteorology: characteristics and trends from a 57-year-series of scientific communication. *Meteorology and Atmospheric Physics*, 103, 5–12. Available from: https://doi.org/10.1007/s00703-008-0312-9

Ward, J.H. (1963) Hierarchical grouping to optimize an objective function. *Journal of the American Statistical Association*, 58, 236–244. Available from: https://doi.org/10.1080/01621459.1963.10500845

World Meteorological Organization (WMO). (2020) Guidelines on Homogenization, WMO-No. 1245.

Zahradníček, P., Rasol, D., Cindrić, K. & Štěpánek, P. (2014) Homogenization of monthly precipitation time series in Croatia. *International Journal of Climatology*, 3682, 3671–3682. Available from: https://doi.org/10.1002/joc.3934

Zaninović, K. & Gajić-Čapka, M. (2000) Changes in components of the water balance in the Croatian lowlands. *Theoretical and Applied Climatology*, 65(1–2), 111–117.

How to cite this article: Chimani, B., Bochníček, O., Brunetti, M., Ganekind, M., Holec, J., Izsák, B., Lakatos, M., Tadić, M. P., Manara, V., Maugeri, M., Šťastný, P., Szentes, O., & Zardi, D. (2023). Revisiting HISTALP precipitation dataset. *International Journal of Climatology*, *43*(15), 7381–7411. https://doi.org/10.1002/joc.8270