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Homogeneity Assessment and Correction Methodology for the 1980–2022 Daily Temperature Series in Padua, Italy

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Abstract: Meteorological observations over the last four decades are of paramount importance to investigating ongoing climate change. An important issue is the quality and reliability of the climatic series, which are fundamental prerequisites to drawing the correct conclusions. Homogeneity tests are used to detect discontinuities whose interpretation is facilitated by metadata availability. In this work, daily minimum and maximum temperature measurements collected in Padua, Italy, between 1980 and 2022 are examined. During this period, the weather station of Padua center underwent many changes in location or instruments; therefore, some tests have been used to identify and remove their effects and obtain homogeneous series. Some well-known absolute tests have been applied to investigate the shift in the mean value: Standard Normal Homogeneity test (SNH), Buishand U and range tests, Pettitt test, F-test, and STARS. Relative tests have been applied too, using several stations nearby Padua and two reanalysis datasets (ERA5 and MERIDA) as reference series to enhance the picture of the local situation and provide more robust conclusions. The applied tests identify change-points in the years in which a change in instrument or the location of the station has occurred, confirming that these changes have compromised the homogeneity of the series. The sub-series obtained, splitting the observations in correspondence with these change-points, have been homogenized with respect to a selected period. The corrected series of the minimum and maximum temperatures are more coherent with the modern warming trend. The transfer functions to be applied to future measurements of minimum temperature have been calculated, while the series of maximum temperature measurements can be directly extended.

Keywords: homogeneity tests; daily temperature series; correction methodology; climate change

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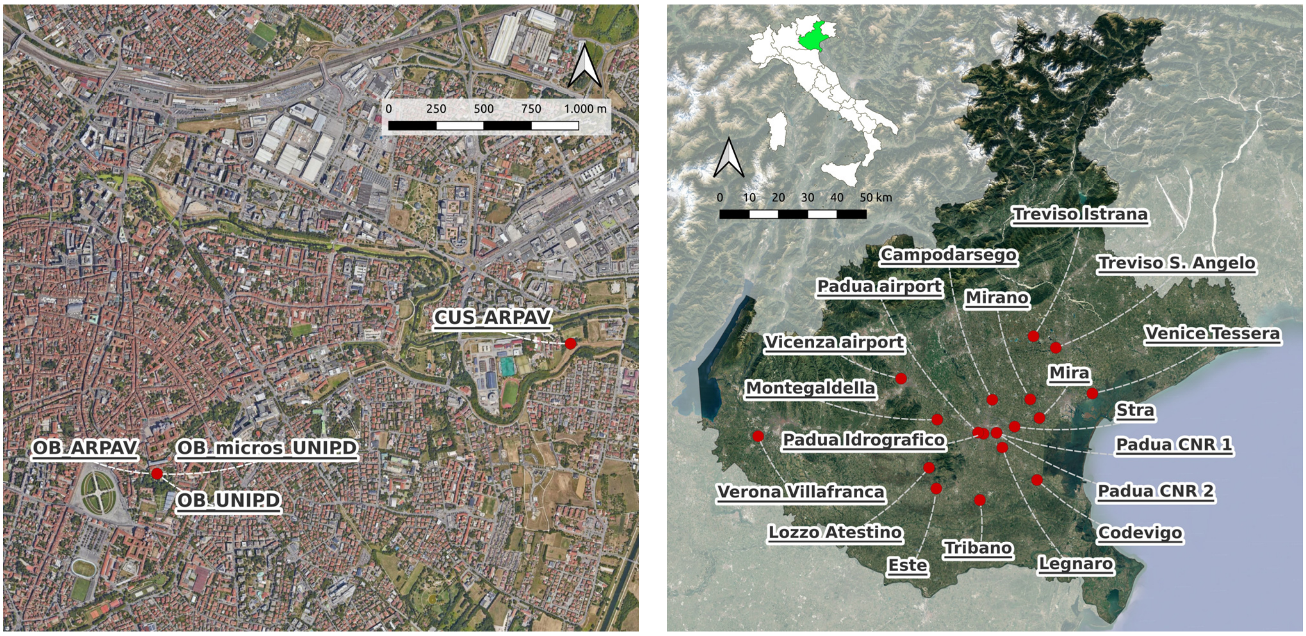
1. Introduction

Temperature observations in Padua have a very long history, being one of the oldest continuous series in the world, with regular measurements starting in 1725 [1] and some sporadic records being taken even before [2]. The modern observations in the city center, from 1980 to present day, were started by the University of Padua at the historical Botanical Garden. In 1993, the original weather station was substituted, and since 2000, when the weather station was changed again and moved of some meters in the Botanical Garden, measurements have been under the control of ARPAV (Regional Agency for Environmental Protection of Veneto). In 2019, the station was relocated ~2 km away to a less urban environment (see Figure 1a).



(**a**) (**b**)

Figure 1. Locations of the meteorological stations considered in this study: (**a**) Padua city center; (**b**) Veneto region.

Hence, over the 1980–2022 period, some inhomogeneities in the temperature records could arise because of the changes of instrument and location. The availability of the metadata in combination with statistical methods provides the most complete and effective way to identify inhomogeneities, with the final aim being to identify the climate signal from human interventions.

The statistical methods used for this scope are commonly known as homogeneity tests, which are widely described in the literature, e.g., [3,4]. A possible classification divides absolute from relative tests; the former use the series itself, while the latter use the information from neighboring stations, called reference stations, which are supposedly homogeneous. The most common type of shifts, i.e., in the mean, was considered in this study, defined as "differing average climatic levels over a multi-annual duration" [5]. Several studies, e.g., [6], recommend applying relative homogeneity tests when one or more reliable reference stations are available with a high level of correlation with the test station. Relative tests are generally more powerful and reliable than absolute ones [3], but their results highly depend on the quality of the reference series; consequently, they have to be used with at least one absolute test in order to detect possible inhomogeneities in the reference series. On the other hand, relative tests cannot deal with concurrent changes in both the test and the reference stations, as happens when climate variations occur. However, if the aim is to assess the presence of artificial change-points in the series because of changes in the instrument and/or location, then relative tests can indubitably help.

The evaluation of the reliability of the temperature series of Padua is essential to investigating climate change in the last decades in the Mediterranean region, a hotspot due to the enhanced warming trend [7]. Therefore, the aim of this study is to assess the presence of change-points (CPs) in the modern Padua daily temperature series, obtained by composing different records over the last forty years.

The homogenization of the observations will allow for the extension of the series in the future once the procedure to blend new observations into the adjusted series is known. Moreover, as homogeneity tests sometimes fail to provide unique results or have limited reliability, this analysis offers the possibility to evaluate them in the presence of clear knowledge of the metadata.

2. Materials and Methods

In this study, daily minimum and maximum temperatures collected in the station located in the Padua center over the period January 1980–December 2022 are considered. Four sub-periods can be distinguished:

1. January 1980–December 1993: observations collected at the Botanical Garden by the University of Padua (shortened to *OB_UNIPD*) using a SPIGE mechanical thermo-hygrograph (measurements were copied from the strip chart into a log), and, from 1984 to 1990, two SPIGE minima and maxima glass thermometers. On 24 October 1990, modern electronic instruments were installed, and observations were sampled automatically at unknown intervals [1].
2. October 1993–November 2001: hourly sampling (it is unknown whether instantaneous or mean values) with a new instrument, same location, again by the University of Padua (*OB_micros_UNIPD*).
3. May 2000–10 March 2019: 15 min sampling (instantaneous values) with a new instrument some tens of meters away with respect to the previous location by ARPAV (*OB_ARPAV*).
4. 11 March 2019 up to present: the station was relocated ~2 km east, in the University Sports Center (*CUS_ARPAV*), where it is currently.

Data quality checks were not applied as the measurements had already been validated with automatic and manual procedures by ARPAV. In Table 1, the record availability for each station is reported.

Table 1. Daily temperature datasets for the center of Padua in the period 1980–2022.

Station Shortname	Longitude	Latitude	Elevation	Data Availability
OB_UNIPD	11.8805	45.3993	12 m	1 January 1980–31 December 1993 (99.6%)
OB_micros_UNIPD	11.8805	45.3993	12 m	1 October 1993–30 November 2001 (91.0%)
OB_ARPAV	11.8805	45.3993	12 m	1 May 2000–10 March 2019 (100.0%)
CUS_ARPAV	11.9085	45.4050	12 m	11 March 2019–31 December 2022 (99.9%)

It is not possible to find transfer functions between the different datasets because the overlapping periods are too short or even absent. Therefore, a new series was composed simply by merging the datasets one after the other (*OB_UNIPD* from 1 January 1980 to 30 September 1993, *OB_micros_UNIPD* from 1 October 1993 to 30 April 2000, *OB_ARPAV* from 1 May 2000 to 10 March 2019, and *CUS_ARPAV* from 11 March 2019), and the presence of CPs was investigated by means of homogeneity tests.

The selected tests are listed in Table 2 with their main features, i.e., their typology (absolute or relative); their ability to detect one or more CPs; in which part of the series they show greater sensitivity; and their ability to work in the presence of a trend in the series. Further details are available in the literature (see hereafter).

Table 2. Homogeneity tests and their R implementations used in this study. The main features of each test are reported.

Test	R Package	Abs./Rel.	Single/Multiple Change-Points	Major Sensitivity	Trend
SNH	trend 1.1.5	Abs.	Single	Beginning/End	N
Pettitt		Abs.	Single	Middle	N
BU BR		Abs.	Single	Single	N
VN	DescTools 0.99.47	Abs.	Single	-	N
F-test	strucchange 1.5–3	Both	Single	-	Y
cpt.mean	changepoint 2.2.4	Both	Multiple	-	Y
STARS	rshift 2.2.2	Both	Multiple	-	Y
Climatol	climatol 4.0.0	Rel.	Multiple	-	N

The following absolute tests were applied: the standard normal homogeneity test (SNH) [8], the Buishand U (BU) and range (BR) tests [9,10], the Pettitt test [10,11], the F-test [3,4,12], the STARS (Sequential T-test Analysis of Regime Shifts) [13], the cpt.mean [14,15], and the Von Neumann ratio (VN) test [16]. All tests, except VN, give information on the timing of the CP. The STARS method requires the setting of certain parameters and their optimization after several trials. It finds the most significant CPs (based on a *t*-test), splits the series at that point, and searches for further changes in each segment, repeating the procedure iteratively until no more CPs are detected or the sub-series become smaller than the minimum cutoff length [13].

As some tests may not work properly if there is a trend in the series, it is important to check if it is statistically significant and, in such cases, to interpret the results of the homogenization tests critically. Therefore, the non-parametric Mann–Kendall trend test was used, which does not require any underlying assumption about the normality of the data [17–19].

Over the whole period, relative tests have been performed using two reanalysis datasets, i.e., ERA5 and MERIDA, as a reference. The ERA5 reanalysis, produced by the Copernicus Climate Change Service (C3S) at ECMWF [20], represents the state of the art in the field of global meteorological reanalysis. It has a horizontal resolution of 31 km, so the pixel selected to extract the series has to be the closest to Padua and at the same altitude, not containing the near Euganean Hills, southwest of the city center. The ERA5 synthetic station is reliable, complete, and able to capture the mean and extreme temperatures in plain regions of Italy [21].

The Meteorological Reanalysis Italian Dataset (MERIDA) is a reanalysis product developed for Italy and the surrounding areas. It uses ERA5 as initial and boundary conditions for the numerical simulations with the advanced research core of the weather research and forecasting (WRF-ARW) mesoscale model [22]. Simulated data are provided on a 7 km horizontal resolution grid at hourly steps and exploit observations (temperature and precipitation) from the meteorological stations of the Regional Agencies for Environmental Protection (ARPA). These stations meet the WMO guidelines and are distributed throughout the national territory, but they are not assimilated by ERA. Data are validated by ARPA and cross-validated again through spatial and temporal consistency criteria [22]. MERIDA datasets start in 1990, but only the 1993–2022 period was used because the unbroken observations performed by most of the ARPAV stations located in the area of interest and assimilated by the model started in 1993.

Among the relative tests, the R package Climatol [23] was also applied, developed by the Spanish State Meteorological Agency (AEMET). Climatol performs quality control, homogenization, and infilling of missing data in a set of daily series of any climatic variable. The homogenization is based on the SNH test [8], considering reference stations to detect inhomogeneities in the test series; when the SNH test statistics are greater than a prescribed threshold, the series is split at the point of maximum SNH, moving all data before the break to a new series that is incorporated into the data pool. This procedure is performed iteratively, splitting only the series with the higher SNH values at every cycle, until no inhomogeneous series is found. As the core test, the SNH test was originally designed to detect no more than a single CP in a series. To overcome this problem, the test was first applied to stepped overlapping temporal windows and then to the complete series. Finally, the method infills missing data in all homogeneous series and sub-series. As reference stations to be used by the algorithm, fourteen stations within a 25 km radius from Padua were selected (top of Table 3). The farther five stations of the Aeronautica Militare (Italian Air Force) were also included because of their longer available series (last five rows of Table 3) (Figure 1b). At this step, the ERA5 series was added, but not MERIDA because it is a derived product obtained from ERA5 and the stations themselves. To infill the missing data and compute the homogeneity tests, the algorithm does not use the proximity criterion but evaluates the correlation between datasets. The stations selected are all located on a plain terrain, but the algorithm was also successfully applied to orographically complex areas, e.g., Spain and southern Italy [23,24].

Table 3. Daily temperature availability for the reference stations.

Station Shortname	Longitude	Latitude	Elevation	Data Availability
Padua Idrografico	11.8716	45.3912	13 m	1 January 1986–31 December 1996 (50.9%)
Padua airport	11.8483	45.3953	13 m	1 January 1980–29 December 1990 (98.8%)
Padua CNR 1	11.9290	45.3931	10 m	10 April 1984–31 December 1986 (51.4%)
Padua CNR 2	11.9290	45.3931	10 m	29 October 1993–29 December 2008 (78.3%)
Codevigo	12.1000	45.2430	0 m	18 February 1992–31 December 2022 (99.6%)
Tribano	11.8490	45.1860	4 m	1 January 1996–31 December 2022 (100.0%)
Mira	12.1177	45.4353	5 m	5 May 1992–31 December 2022 (99.9%)
Campodarsego	11.9137	45.4948	15 m	1 January 1993–31 December 2022 (100.0%)
Legnaro	11.9524	45.3467	10 m	17 July 1991–31 December 2022 (99.3%)
Este	11.6606	45.2244	12 m	1 February 1980–31 December 1999 (78.4%)
Lozzo Atestino	11.6307	45.2893	15 m	1 January 1985–31 December 1996 (79.3%)
Stra	12.0084	45.4107	9 m	28 January 1985–31 December 2004 (88.1%)
Mirano	12.0797	45.4930	10 m	1 January 1988–30 November 2004 (100.0%)
Montegaldella	11.6710	45.4383	22 m	1 April 1993–31 December 2004 (98.6%)
Treviso Istrana	12.1013	45.6887	41 m	1 January 1980–31 December 2022 (98.6%)
Treviso S. Angelo	12.1978	45.6508	17 m	1 January 1980–31 December 2022 (97.0%)
Venice Tessera	12.3519	45.5053	2 m	1 January 1980–31 December 2022 (99.8%)
Vicenza airport	11.5167	45.5667	39 m	1 January 1980–29 February 2008 (98.1%)
Verona Villafranca	10.8881	45.3964	72 m	1 January 1980–31 December 2022 (98.8%)

All the homogeneity tests, both absolute and relative, were implemented with R (https://www.r-project.org/ (accessed on 30 October 2023)). They were applied to monthly anomalies series calculated with respect to the 30-year period 1993–2022.

3. Results

3.1. Absolute Tests

The results of the absolute tests are reported in Table 4. STARS and cpt.mean tests are quite sensitive to the choice of some input parameters which provide sensibility thresholds for the number of CPs. For STARS, a cutoff length has to be selected, that is, the minimum length of a subdivision of the series needed to confirm that a CP is present at a given time. Since a potential CP is in March 2019, a value less than ~3.5 years had to be chosen, i.e., before the series ends, otherwise the algorithm would not be able to detect it. Several trials were made in the range 12–42 months (i.e., 1–3.5 years), and the most frequent CPs the algorithm provided were selected. Similarly, in the cpt.mean test, a penalty value controls the maximum number of potential CPs. An “elbow plot” was used to find the most reliable penalty value; the number of changes decreases as the penalty value increases, until it becomes constant. A value on the last part of this curve was selected to reduce CPs induced by noise. Several CPs were caused by the noise in the series and not confirmed by metadata, so they were disregarded.

Table 4. Results of absolute tests applied to monthly minimum and maximum temperatures in Padua over the period 1980–2022.

Test	Change-Points	
	Minimum Temperature	**Maximum Temperature**
SNH [1]	February 2000	March 2000
Pettitt [1]	February 2000	March 2000
Buishand U [1]	February 2000	March 2000
Buishand Range [1]	February 2000	March 2000
Von Neumann ratio [1]	yes	yes
F-test [1]	February 2000	March 2000
cpt.mean [2]	March 2000	April 1982 March 2000 April 2003 August 2003 February 2011
STARS [3]	September 1987 July 2013 March 2020	July 1985 April 2000 January 2004 September 2006

[1] p-value < 0.01. [2] The package does not calculate traditional p-values directly related to the changes. [3] p-value $\leq$ 0.01 and cutoff length in the range 12–42 (i.e., 1–3.5 years).

The only CP found by all the absolute tests is at the beginning of 2000 (February–March) for both minimum and maximum temperatures. This result can be referred to as the time at which the change and relocation of instruments took place, i.e., between April and May 2000.

3.2. Relative Tests

A few stations apart from Padua recorded observations continuously over the whole 1980–2022 period (see Table 3). These series may present CPs not related to climate, but due to substitution of sensors, maintenance, presence of vegetation, etc. For example, some relative tests were applied to the monthly differences between Padua and Legnaro, which is one of the stations most similar to Padua (see Table 5) for which the maintenance history is known. The anomaly of the minimum temperature shows a CP in the first months of 2002. This is very likely explained by the change of the radiation shield, which occurred in May 2002. The previous shield was made of metal and was replaced with a plastic one. As expected, the tests are sensitive to CP not related to any climatic signal.

Table 5. Pearson correlation coefficient (c_Pearson) and RMSE obtained comparing Padua daily observations to those of other stations and reanalysis data over 1993–2022. In parenthesis, the values obtained after having removed the seasonal components (using R package "stlplus").

Datasets over 1993–2022	Minimum Temperature		Maximum Temperature	
	c_Pearson	**RMSE (°C)**	**c_Pearson**	**RMSE (°C)**
ERA5	0.980 (0.866)	2.25	0.986 (0.904)	1.48
MERIDA	0.987 (0.912)	1.17	0.990 (0.926)	1.28
Campodarsego	0.982 (0.911)	2.47	0.995 (0.965)	1.01
Legnaro	0.986 (0.923)	1.83	0.994 (0.962)	0.93
Codevigo	0.983 (0.904)	1.76	0.991 (0.936)	1.22
Mira	0.983 (0.915)	2.25	0.992 (0.953)	1.08
Tribano [1]	0.985 (0.912)	1.88	0.992 (0.946)	1.23
Treviso Istrana	0.983 (0.898)	1.86	0.991 (0.936)	1.37
Treviso S. Angelo	0.987 (0.919)	1.56	0.991 (0.941)	1.26
Venice Tessera	0.990 (0.929)	1.22	0.986 (0.908)	1.62
Verona Villafranca	0.982 (0.884)	2.06	0.987 (0.908)	1.50

[1] 1996–2022.

For this reason, the reanalysis datasets were considered as references for relative tests. Their robustness was checked by comparing the Pearson correlation coefficients and the root mean square errors (RMSE) obtained coupling the reference series and Padua observations. In Table 5, these indicators are reported for ERA5, MERIDA, and some stations listed in Table 3 for which data are available over 1993–2022. Some observations go even further back in time, but the timeframe common to all datasets was selected.

All the correlations coefficients are very high, even excluding the seasonal components of the series. MERIDA reanalysis shows a clear improvement with respect to ERA5. RMSE for minimum temperature from MERIDA is even the best among all cases. On the other hand, RMSE of maximum temperature from MERIDA shows no improvement with respect to the stations, but it is still comparable. Overall, these indicators support the idea of using MERIDA series as reference for the relative tests. However, MERIDA covers only the 1993–2022 period, and the maintenance history of the Air Force stations (which also have some gaps) is not known. Consequently, there was no choice but to use ERA5 to explore the whole 1980–2022 period to evaluate the presence of CPs around 1993, the first time the instrument changed. In Tables 6 and 7, the results of the relative tests using ERA5 and MERIDA as reference, respectively, are reported.

Table 6. Relative tests results for monthly temperature series in Padua using ERA5 as the reference over 1980–2022.

Test	Padua-ERA5 Change-Points	
	Minimum Temperature	**Maximum Temperature**
F-test	June 2018 [1]	April 2000 [2]
cpt.mean	February 1991 [2] June 2004 [2] March 2019 [2]	August 1980 [2] April 1983 [2] February 1993 [2] April 2000 [2]
STARS	May 1983 [3] March 1991 [3] July 1996 [3] October 2000 [3] April 2019 [3]	May 1983 [3] December 1990 [3] February 1994 [3] May 2000 [3] September 2003 [3]

[1] p-value < 0.01. [2] The package does not calculate traditional p-values directly related to the changes. [3] p-value $\leq$ 0.01 and cutoff length in the range 12–42 months (i.e., 1–3.5 years).

Table 7. Relative tests results for monthly temperature series in Padua using MERIDA as the reference over 1993–2022.

Test	Padua-MERIDA Change-Points	
	Minimum Temperature	**Maximum Temperature**
F-test	November 2018 [1]	April 2000 [2]
cpt.mean	November 2018 [2]	May 1996 [2] April 2000 [2] August 2003 [2]
STARS	August 1996 [3] May 2016 [3] April 2019 [3]	June 1996 [3] October 1998 [3] May 2000 [3] September 2003 [3] January 2004 [3] May 2015 [3]

[1] p-value < 0.01. [2] The package does not calculate traditional p-values directly related to the changes. [3] p-value $\leq$ 0.01 and cutoff length in the range 12–42 months (i.e., 1–3.5 years).

Once again, cpt.mean and STARS identified many CPs but most of them can be disregarded and are not linked to climatic signals or changes in the station. Additionally, the Climatol package, which uses all the available observations, even the very sparse ones (reported in Table 3), was applied. Climatol identified two CPs for minimum temperature, i.e., in May 1991 and April 2019, and three CPs for maximum temperatures, i.e., in May 1983, May 1994, and May 2000.

In conclusion, the relative tests applied to Padua series agree in identifying two CPs for minimum temperature, i.e., in 1991 and 2019, and three CPs for maximum temperature, i.e., in 1983, at the end of 1993/beginning of 1994, and in 2000. The timing of some CPs has more variability with respect to the others as the meteorological variability overlaps with the signal affecting the outcome of the tests. Nonetheless, the exact months of these CPs could be identified according to the information available on the station. The main difference with the absolute tests is that the latter also indicate a CP for minimum temperature in February or March 2000. A trend in the series could sometimes lead to the identification of a fictitious CP usually in the middle of the series. The Mann–Kendall test detects a significant trend (p-value < 0.01) both for monthly minimum and maximum temperatures over the 1980–2022 period. Since no relative test has detected the 2000 timing, this CP for minimum temperature was excluded. The final CPs are reported in Table 8.

Table 8. Summary of the change-points documented and identified by the absolute and relative tests for the Padua minimum and maximum series over the period 1980–2022.

	Change-Points	
	Timing	**Cause**
Minimum temperature	24 October 1990 11 March 2019	Instrument change Location change
Maximum temperature	1 January 1984 1 October 1993 1 May 2000	Instrument change Instrument change Instrument and location change

3.3. Homogeneization

Once the CPs have been identified, the sub-periods have to be corrected to homogenize the series. As the overlapping windows (Table 1) are very short or absent, the Climatol package was used again. OB_ARPAV was chosen as a reference with respect to the other series which have to be corrected because it is the longest available homogeneous series. The current station CUS_ARPAV was not considered because the location is supposed to be temporary and the station could be relocated again in the future. For minimum temperature, three homogeneous subperiods are available: i.e., January 1980–October 1990 (1), November 1990–February 2019 (2), and March 2019–December 2022 (3); (1) and (3) should be corrected to make them homogeneous with respect to (2). For the maximum temperature, four homogeneous subperiods are available: i.e., January 1980–December 1983 (1), January 1984–September 1993 (2), October 1993–April 2000 (3), May 2000–December 2022 (4); (1), (2), and (3) should be corrected to make them homogeneous with respect to (4). Climatol allows for the reconstruction, back and forward in time, of the sub-series identified by the CPs to cover the whole period 1980–2022. In this way, the series overlap enough to calculate transfer functions. These functions are evaluated as already done for previous Padua observations [25]; month by month, each series was compared with the others, excluding measurements exceeding the 10th and 90th percentiles of the daily differences between the two series, and the least square interpolation polynomials calculated. Results are reported in Tables S1 and S2 for minimum temperature and in Tables S3–S5 for maximum temperature.

More measurements are expected to be included to extend the series and keep it up to date. Therefore, the use of the transfer functions is the more practical and immediate way to include future observations from *CUS_ARPAV*. Minimum temperature values must be converted in the future using the transfer functions of Table S2 while future maximum temperatures do not need correction.

In Figure 2a, the daily corrections to the minimum temperature are shown, with most of them ranging from −1.0 °C to +0.1 °C in January 1980–October 1990 and +0.1 °C to +1.5 °C in March 2019–December 2022. Figure 2b compares the yearly values of both the corrected and the original series.

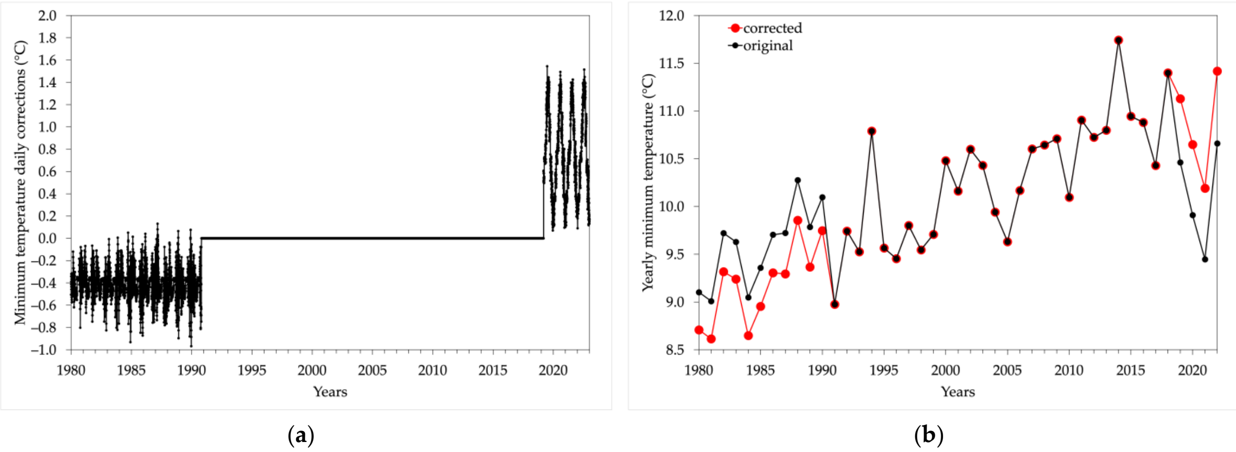


Figure 2. (**a**) Daily corrections applied to minimum temperature. (**b**) Yearly mean of the original series (black) and the corrected one (red).

Figure 3 shows the same analysis but for the daily corrections of the maximum temperature, with most of the corrections of the January 1980–December 1983 period ranging from +0.2 °C to +0.9 °C, of the January 1984–September 1993 period ranging from −0.8 °C to +0.0 °C, and of the October 1993–April 2000 period ranging from −0.3 °C to +1.9 °C.

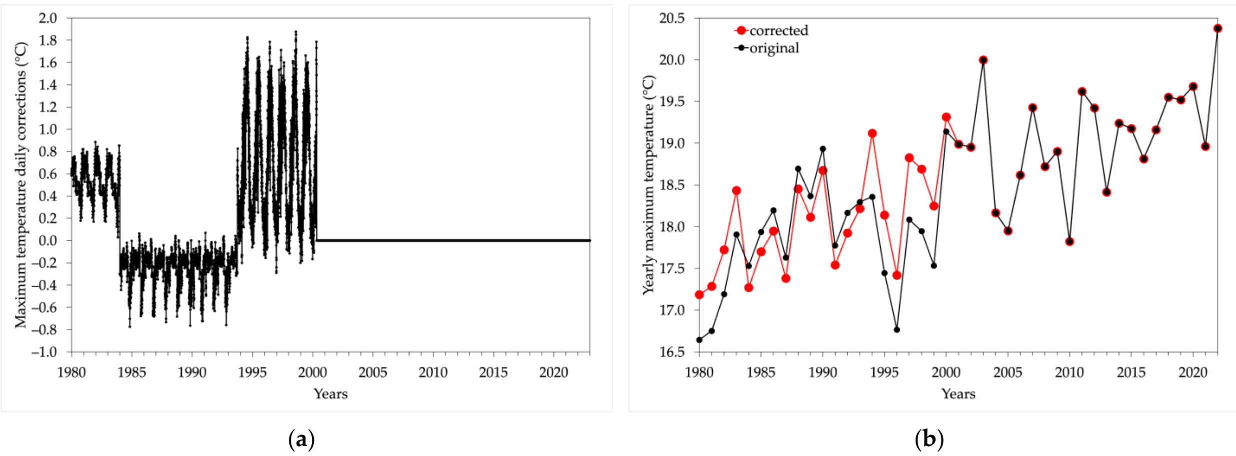


Figure 3. (**a**) Daily corrections applied to maximum temperature. (**b**) Yearly mean of the original series (black) and the correction (red).

4. Discussion

Change-points in the monthly series of minimum and maximum temperatures in Padua have been investigated with absolute and relative tests. Results showed two CPs for the minimum temperatures in 1991 and 2019, and three CPs for maximum temperatures in 1983, 1993, and 2000. By applying the R package Climatol to the sub-series identified by the CPs, they have been extended back and forward to have an overlapping window of more than forty years between 1980 and 2022. The transfer functions have been calculated in the overlapping window, and the 1980–2022 series have been homogenized with respect to the central period, 2000–2019, when *OB_ARPAV* was active.

Lastly, the yearly differences between Padua and ERA5 temperature series over 1980–2022 and between Padua and MERIDA ones over 1993–2022 for both the original and corrected series were calculated. Results are reported in Figure 4a,b for minimum and maximum temperatures, respectively. As already shown in Section 3.2, ERA5 has a larger bias than MERIDA for minimum temperature. The corrected Padua series exhibits a more coherent behavior in the first and last years compared to the original one. The range of the differences between the original Padua minimum temperature series and ERA5 is 3.3 °C, which decreases to 1.0 °C after correction. Considering MERIDA, the range decreases from 1.1 °C to 0.7 °C (Figure 4a). Regarding maximum temperatures, there is a strong improvement after correction in the 1980–1993 period using ERA5 as the reference dataset, and in the 1993–2000 period using both ERA5 and MERIDA. The range of the differences between the original Padua series and ERA5 is 1.8 °C, while after correction, it is 1.2 °C; considering MERIDA, the range decreases from 1.7 °C to 1.1 °C (Figure 4b). Overall, the corrections applied to the Padua series for both minimum and maximum temperatures provide more consistent differences with respect to the reanalysis products, exhibiting more stable evolutions.

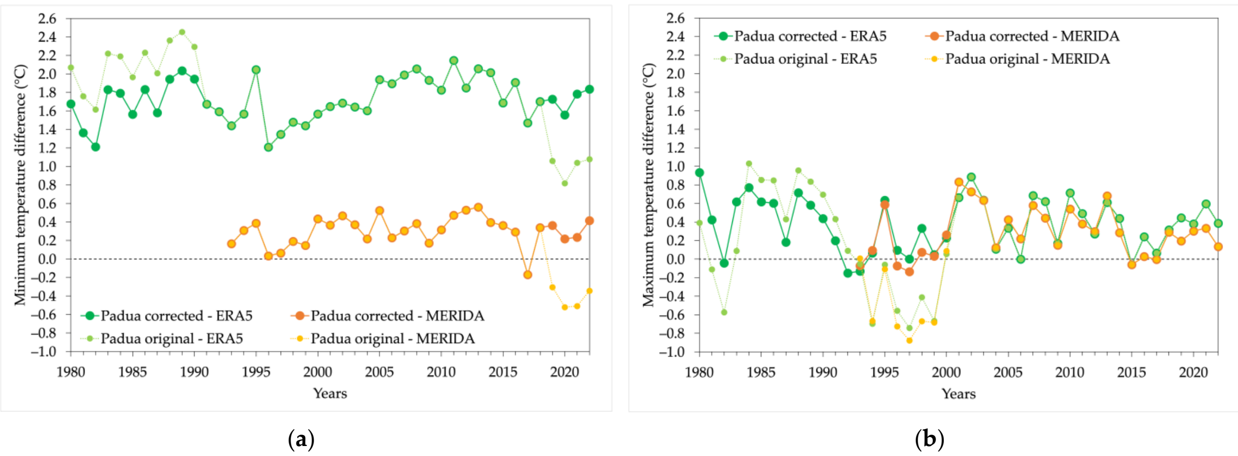


Figure 4. (**a**) Difference of yearly minimum temperatures between the Padua, original and corrected, and ERA5 series over 1980–2022 (green) and between MERIDA over 1993–2022 (orange). (**b**) The same but for maximum temperature. The continuous lines highlight the zero value.

The effect of these corrections on the overall trend was also explored. Considering the monthly anomalies series over the 1993–2022 period, the slopes of the linear regression are reported in Table 9, while the slopes calculated over the whole 1980–2022 period are shown in Table 10. The slopes of the Padua corrected series are closer to the reanalysis datasets in all cases except for maximum temperatures over the 1980–2022 period, for which the original slope was already consistent with ERA5. This confirms the goodness of the corrections to the Padua series.

Table 9. Slopes of linear regressions for the Padua original and corrected series and MERIDA over the period 1993–2022.

1993–2022	Slopes (°C/Decade)	
	Minimum Temperature	**Maximum Temperature**
Padua original	+0.31 ± 0.08	+0.61 ± 0.09
Padua corrected	+0.48 ± 0.08	+0.40 ± 0.09
MERIDA	+0.46 ± 0.07	+0.39 ± 0.09

Table 10. Same as Table 9 but for ERA5 and the period 1980–2022.

1980–2022	Slopes (°C/Decade)	
	Minimum Temperature	**Maximum Temperature**
Padua original	+0.35 ± 0.05	+0.52 ± 0.06
Padua corrected	+0.54 ± 0.05	+0.48 ± 0.05
ERA5	+0.49 ± 0.05	+0.50 ± 0.06

5. Conclusions

In this paper, a methodology with which to reconstruct a homogeneous series of temperature observations has been presented. The daily minimum and maximum temperatures recorded in the city center of Padua, Italy, from 1980 to 2022 have been used as test datasets. Four main different sub-periods are present in this time frame, determined by a change of instruments or location or both. Fortunately, the dates of these changes are known, as well as the spatial coordinates of each new location. The application of the most-used and best-performing absolute and relative homogeneity tests allow us to identify the timing of the artificial CPs caused by these changes, i.e., those not related to climatic signals. Two CPs were found for minimum temperature in 1991 and 2019, and three CPs for maximum temperature in 1983, 1993 and 2000, all supported by metadata.

Once the homogeneous sub-periods have been identified, the complete, homogeneous series have been obtained using monthly transfer functions. Since the overlaps between the sub-series are very short or absent, the Climatol algorithm provided by R [23] has been used to extrapolate the values of all the series over the entire 1980–2022 period. In this way, it was possible to calculate the transfer functions which allow the blending of future measurements.

A comparison of the differences between the original and corrected Padua series with the ERA5 and MERIDA reanalysis datasets confirms that the reconstructions are reliable and more coherent with the modern warming trend.

The methodology described in this work can be used to address the issue of the homogenization of any series of meteorological observations. It provides a practical method that allow to extend the series, blending the most recent observations with existing ones.

The method described in this work was successfully applied to the long meteorological observations of Padua. Daily minimum and maximum temperatures have been available since 1774 and daily mean values since 1725. Previous works reconstructed and homogenized the observations from mid-18th to mid-19th century [1,2]. A future work will address the problem of homogenizing observations before 1980 to the modern era; in this way, it will be possible to extend correctly the nearly 300-year series, thus exploring the entire transition from the pre-industrial to the modern era.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/cli11120244/s1, Table S1: Transfer functions from *OB_UNIPD* of the period 1 Jan 1980–23 Oct 1990 to *OB_ARPAV* for minimum temperature; Table S2: Transfer functions from *CUS_ARPAV* to *OB_ARPAV* for minimum temperature; Table S3: Transfer functions from *OB_UNIPD* of the period 1 Jan 1980–31 Dec 1983 to *OB_ARPAV* for maximum temperature; Table S4: Transfer functions from *OB_UNIPD* of the period 1 Jan 1984–30 Sep 1993 to *OB_ARPAV* for maximum temperature; Table S5: Transfer functions from *OB_micros_UNIPD* to *OB_ARPAV* for maximum temperature.

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