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20TH-CENTURY CHANGES OF TEMPERATURE IN THE MOUNTAIN REGIONS OF CENTRAL EUROPE

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Abstract. Daily maximum and minimum temperatures from 29 low-lying and mountain stations of 7 countries in Central Europe were analyzed. The analysis of the annual variation of diurnal temperature range helps to distinguish unique climatic characteristics of high and low altitude stations. A comparison of the time series of extreme daily temperatures as well as mean temperature shows a good agreement between the low-lying stations and the mountain stations. Many of the pronounced warm and cold periods are present in all time series and are therefore representative for the whole region. A linear trend analysis of the station data for the period 1901–1990 (19 stations) and 1951–1990 (all 29 stations) shows spatial patterns of similar changes in maximum and minimum daily temperatures and diurnal temperature range. Mountain stations show only small changes of the diurnal temperature range over the 1901-1990 period, whereas the low-lying stations in the western part of the Alps show a significant decrease of diurnal temperature range, caused by strong increase of the minimum temperature. For the shorter period 1951–1990, the diurnal temperature range decreases at the western low-lying stations, mainly in spring, whereas it remains roughly constant at the mountain stations. The decrease of diurnal temperature range is stronger in the western part than in the eastern part of the Alps.

1. Introduction

Many climatologists (IPCC, 1990, 1992) agree on a large-scale warming of Earth's surface over the last hundred years. The observed warming is, however, not uniform on the globe, it has a pronounced seasonal dependence, and it shows also a diurnal asymmetry. In a series of publications, Karl et al. (1984, 1991, 1993) have presented evidence that in the last decades the daily minimum temperature has increased in relation to the daily maximum temperature. This asymmetric evolution of daily extreme temperatures caused a decrease in the diurnal temperature range (DTR), defined as the difference of daily maximum and daily minimum temperature. Equilibrium general circulation model experiments (Cao et al., 1992) for a climate under doubled CO_2 concentration also yield a general decrease of DTR, however, with a smaller amplitude compared to the increase of the mean temperature. Including the effects of sulphate aerosols in the atmosphere, Hansen et al. (1995) obtained with their model larger decreases of DTR under a general global increase of mean temperature. Their model results indicate that the decrease in DTR is a combined effect of large-scale warming, changes in cloud cover, and increase of aerosol optical depth. As the latter two factors vary substantially on Earth's surface, it is assumed that changes in DTR will be regionally different.

In order to detect any spatial variability of changes in DTR, it is necessary to use data from a rather dense network of stations. Karl et al. (1993) used for the period 1951–1990 data from stations covering large areas of the land surface (37% of the global land mass), but still leaving wide land areas uncovered. Further studies (Salinger et al., 1993; Rupa Kumar et al., 1994; Horton, 1995; Jones, 1995b; Plummer et al., 1995; Salinger, 1995) analyzed daily extreme temperatures from many more regions of the world, which are not included in Karl et al. (1993). Until recently, data from Europe as a whole have not been well investigated despite the fact that many well documented long records of instrumental data exist in Europe. Daily extreme temperatures from parts of Europe were analyzed for example in Beniston et al. (1994); Böhm and Auer (1994); Brázdil et al. (1994, 1995, 1996); Niedźwiedź and Ustrnul (1994); Weber et al. (1994); Balling (1995); Gajić–Čapka and Zaninović (1995, 1996); Jones (1995a); Kaas and Frich (1995), showing spatially inhomogeneous changes in DTR. However, many of the mentioned studies used only 30 to 40 years of data, which is not sufficient to detect long-term changes in the temperature records. Data from high elevation sites in Europe were only discussed for few stations or single countries (Bücher and Dessens, 1991; Weber et al., 1994; Böhm and Auer, 1994; Beniston et al., 1994; Brázdil et al., 1994, 1995; Dessens and Bücher, 1995; Gajić–Čapka and Zaninović, 1996). The present paper aims at a more comprehensive analysis of temperature data from high elevation sites in the Central European region.

Meteorological stations on mountain tops differ in several aspects from stations at lower altitude. Many of the low-lying stations are located close to or even within cities and can therefore be affected by changes in urbanization (Karl et al., 1988). In contrast, the mountain stations are presumably sufficiently far away from towns not to be influenced by urbanization effects. In this respect, they can be considered as truly rural stations. High elevation sites may be, at least part of the year, above the planetary boundary layer and can possibly probe the free troposphere. High elevation stations should be less affected by local effects, and rather measure features of the atmosphere on larger scales. The Alps and other mountain ranges in Europe are presumably among the few locations on Earth where some meteorological stations at high elevation sites have been in operation for several decades. The neighboring lower altitude regions of the Alps are also well covered by meteorological stations. This allows us to compare data from high and low elevation sites.

2. Data

Temperature data from stations in France, Germany, Switzerland, Austria, the Czech Republic, the Slovak Republic and Croatia were used in the present study. Monthly, or in some cases seasonal, averages of the daily maximum and minimum temperatures, of the daily mean temperature and of the diurnal temperature range (DTR) were available. Data were already checked and corrected for inhomogeneities within each country (Böhm, 1992a,b; Böhm and Auer, 1994; Weber et al., 1994; Brázdil et al., 1995; Gajić–Čapka and Zaninović, 1996). The annual and seasonal mean values were further checked for inhomogeneities by comparing pairs of stations from different countries. The daily mean temperature is calculated from several daily readings. The times of observation and the weighting scheme of the observations differ between the countries.

Figure 1 shows the locations of all 29 investigated stations. 15 stations are situated at lower altitude, and 14 stations (7, 9, 10, 12, 14, 16, 19, 22, 24, 25, 26, 27, 28, and 29) are located on mountains, ranging from 835 m (Milešovka) to 3106 m (Sonnblick) height above sea level. The main mountain range of the Alps is covered by several mountain stations (7, 9, 10, 12, 14, and 16). Two high elevation stations (19 and 22) are located in the Dinaric mountains.

Figure 2 shows the annual variation of DTR for all mountain stations from which monthly data were available (7, 9, 10, 12, 14, 16, 19, and 22) and for some of the lower altitude stations (3, 4, 8, 17, and 23), see also Figure 4 of Böhm and Auer (1994). The highest stations Säntis (7), Zugspitze (10), Sonnblick (12), and Dobratsch (16) with altitude higher than 2000 m MSL, have hardly any seasonal dependence of DTR. The lower the mountain stations are located, the more pronounced a seasonal cycle of DTR becomes and the larger its amplitude becomes (14, 22, 19, 9). The station in Bregenz (8) has the smallest amplitude of the seasonal cycle of DTR among all low-lying stations. This may be caused by the damping effect of the large water body of the lake Konstanz (Bodensee). The Croatian station Gospić (23) has the largest amplitude of seasonal cycle of DTR, which may be due to its location in a wide karst field, protected from the maritime influence by a mountain range. The pronounced seasonal dependence of DTR at the low-lying stations is probably due to direct influences of the seasonal change of incoming solar radiation and the seasonal change of latent heat flux. At high elevation sites the influence of such surface effects is smaller. In addition, at mountain stations the turbulent mixing is more effective and reduces diurnal effects and the occurrence of local inversions.

3. Long Term Changes

Although a few stations have data extending back to the 19th century (for instance Vienna since 1836), we concentrate here on the analysis of data from the 20th

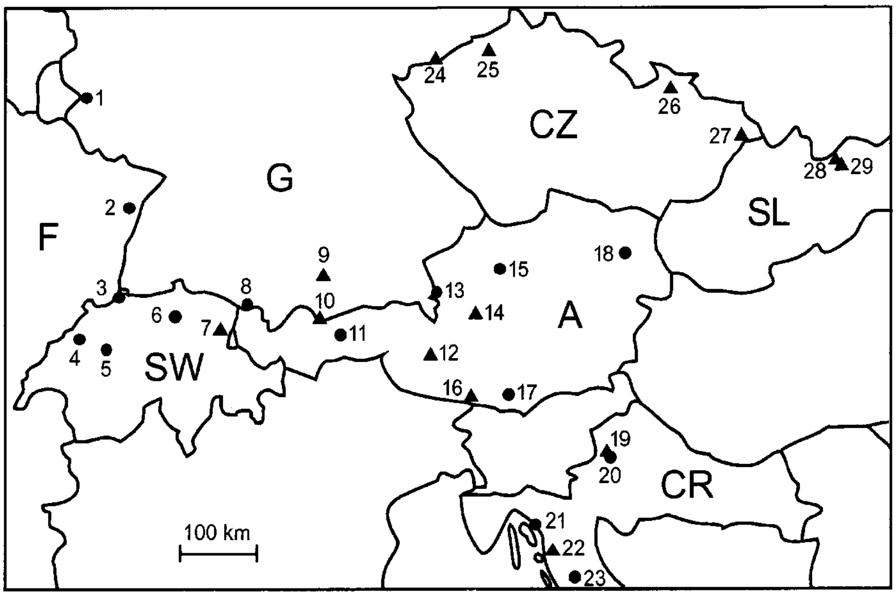

Figure 1. Locations of the meteorological stations used in the present study. Low-lying stations are marked with a circle, mountain stations with a triangle. The area in the box extends roughly from 44° to 51° N, and from 6° to 21° E. *France (F)*: 2 – Strasbourg (height above sea level H = 150 m); *Germany (G)*: 1 – Trier (H = 144 m); 9 – Hohenpeissenberg (H = 977 m); 10 – Zugspitze (H = 2960 m); 24 – Fichtelberg (H = 1214 m); *Switzerland (SW)*: 3 – Basel–Binningen (H = 316 m); 4 – Neuchâtel (H = 485 m); 5 – Bern–Liebefeld (H = 565 m); 6 – Zürich SMA (H = 556 m); 7 – Säntis (H = 2500 m); *Austria (A)*: 8 – Bregenz (H = 424 m); 11 – Innsbruck Universität (H = 577 m); 12 – Sonnblick (H = 3106 m); 13 – Salzburg Flughafen (H = 434 m); 14 – Feuerkogel (H = 1618 m); 15 – Kremsmünster (H = 383 m); 16 – Dobratsch (H = 2140 m); 17 – Klagenfurt Flughafen (H = 447 m); 18 – Wien Hohe Warte (H = 202 m); *Croatia (CR)*: 19 – Puntijarka (H = 988 m); 20 – Zagreb–Grič (H = 157 m); 21 – Crikvenica (H = 2 m); 22 – Zavižan (H = 1594 m); 23 – Gospić (H = 564 m); *Czech Republic*: 25 – Milešovka (H = 835 m); 26 – Praděd (H = 1492 m); 27 –Lysá hora Mt. (H = 1324 m); *Slovak Republic*: 28 – Lomnický štít (H = 2635 m); 29 – Skalnaté Pleso (H = 1778 m).

century, when many stations have data available and a mutual comparison of the stations is possible. Figure 3 shows the mean annual maximum and minimum temperatures of the 15 low altitude stations. There are some general features which show up in the temperature series of all stations. A decade of warm years occurred around 1947, accompanied by very cold years in 1940 and 1956. The warm period of the forties and fifties represents a large-scale temperature anomaly on Earth since it can also bee seen in the mean temperature of the Northern Hemisphere (IPCC, 1992) and, to a lesser extent, in the Southern Hemisphere. Around 1960, a period of about five warm years can be seen. After the cold years just before 1980, a very strong increase of temperature took place. These events affected both maximum and minimum temperature. Maximum temperature alone was very high in 1920–1921 at many, especially western stations.

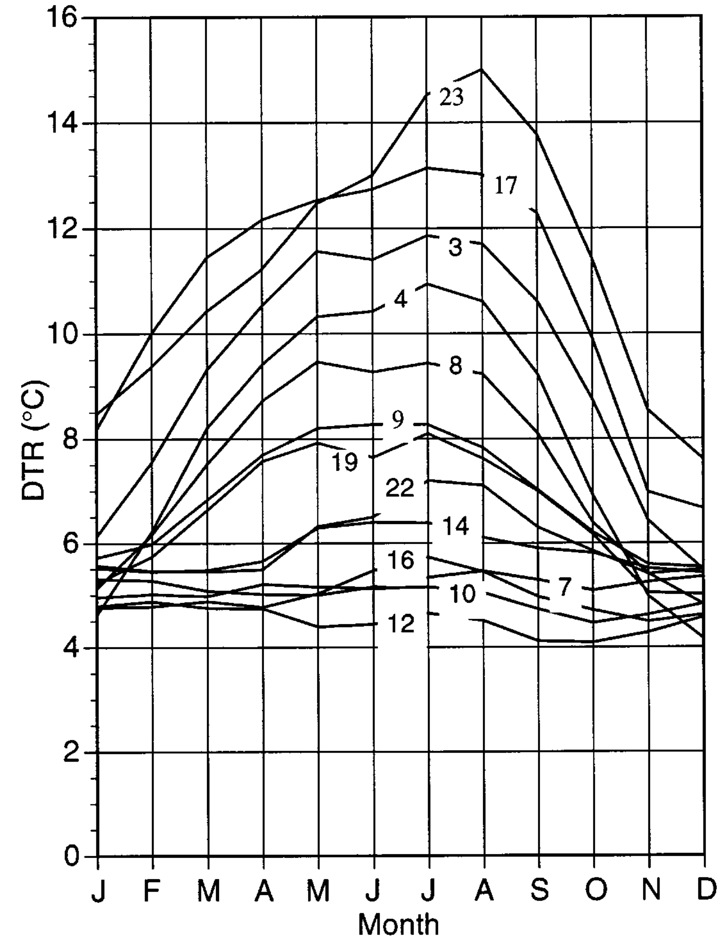

Figure 2. Annual variation of the diurnal temperature range for several stations, averaged over all years with data available. The mountain stations shown are Sonnblick (12, height above sea level H = 3106 m), Zugspitze (10, H = 2960 m), Säntis (7, H = 2500 m), Dobratsch (16, H = 2140 m), Feuerkogel (14, H = 1618 m), Zavižan (22, H = 1594 m), Puntijarka (19, H = 988 m), and Hohenpeissenberg (9, H = 977 m). The low altitude stations shown are Bregenz (8, H = 424 m), Neuchâtel (4, H = 485 m), Basel–Binningen (3, H = 316 m), Klagenfurt Flughafen (17, H = 447 m), and Gospić (23, H = 564 m).

In Figure 4, the annual mean maximum and minimum temperatures of the 14 mountain stations are shown. The high elevation stations with long records as Säntis (7, H = 2500 m), Hohenpeissenberg (9, H = 977 m), Zugspitze (10, H = 2960 m), Sonnblick (12, H = 3106 m), Feuerkogel (14, H = 1618 m), and Dobratsch (16, H = 2140 m) show the same warm and cold periods as the low altitude stations. The years 1920–1921 have both high maximum and minimum temperatures on the mountain tops. All mountain stations show the same strong increase of maximum and minimum temperature after 1980 as the low-lying stations.

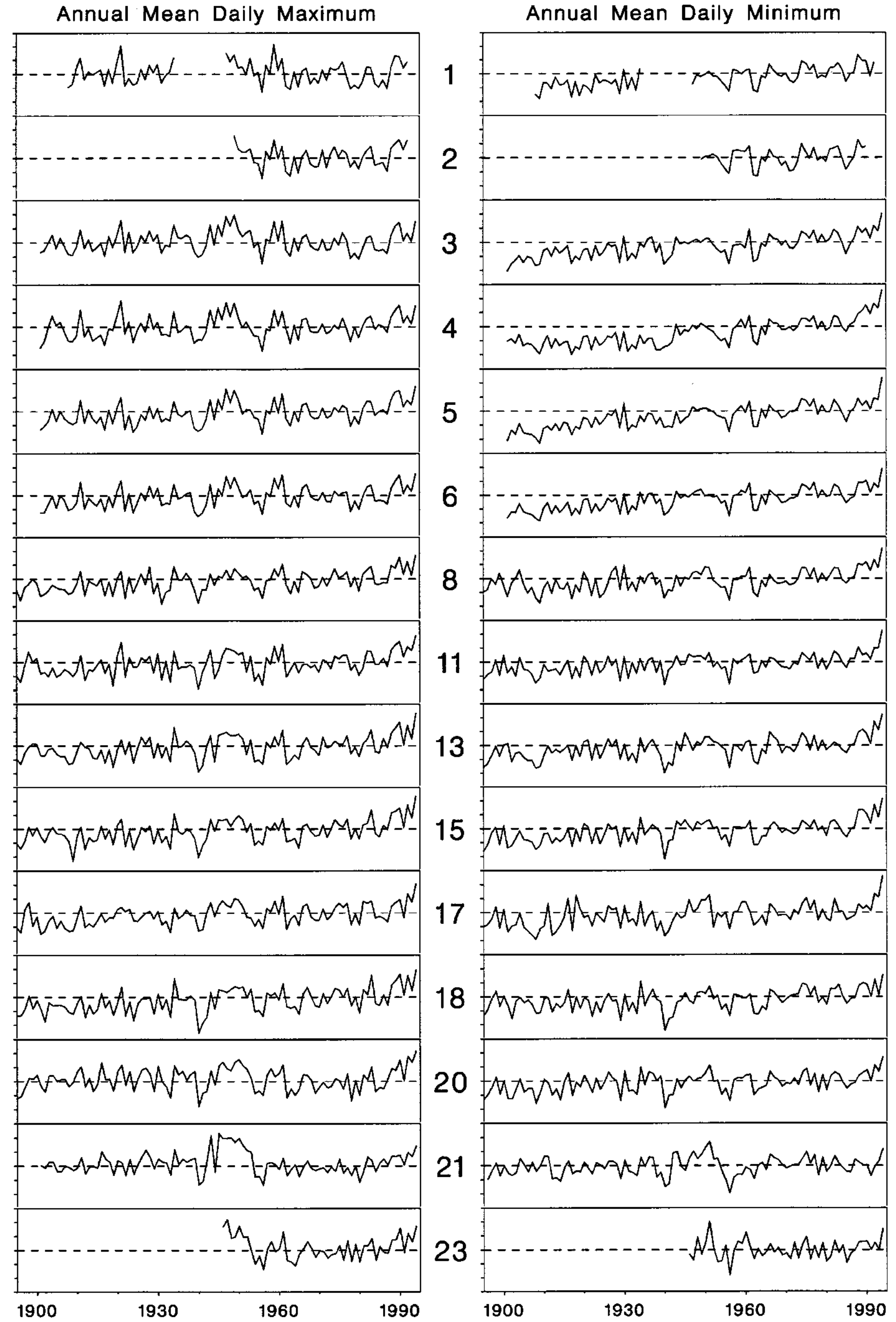

Figure 3. Annual mean maximum daily temperature (left column) and annual mean minimum daily temperature (right column) for the 15 low altitude stations. The data are expressed as anomalies from the reference period 1951–1990. Each tick mark corresponds to 1 °C.

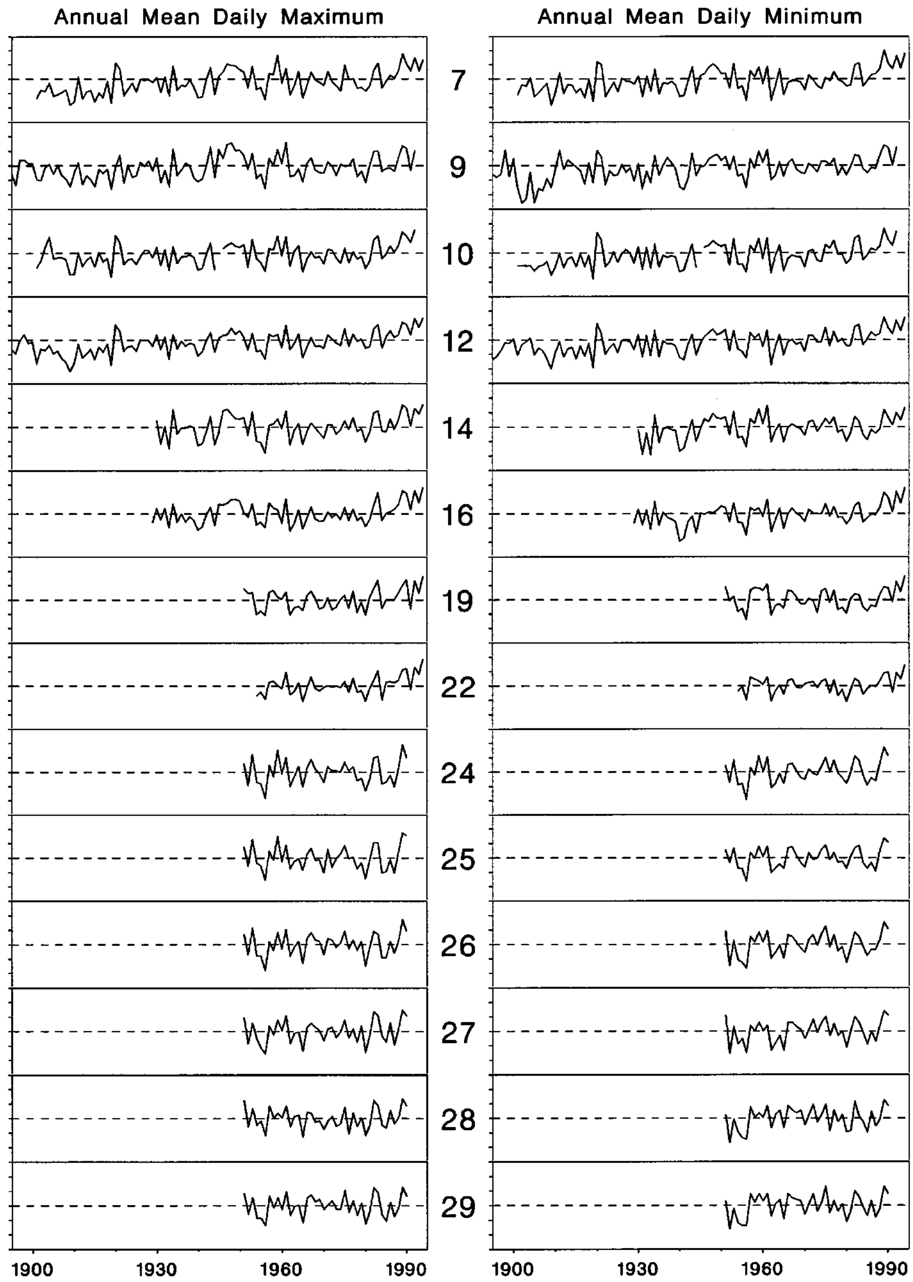

Figure 4. Same as Figure 3, but for the 14 mountain stations.

Figure 5 shows superpositions of graphs of all low-lying stations for the annual mean of daily maximum and minimum temperature, of the mean temperature and of DTR. These graphs demonstrate the agreement of the time series even clearer.

Both the extreme temperatures and the independently measured and calculated mean temperature are in close agreement for all stations. As the stations are located in different countries, whose instrumentation and changes in observation practices differ, the main features of the temperature records can confidently be taken as representative features of the lower troposphere over the observation region. A few stations show pronounced differences in their time series from the general behavior. For example, the maximum daily temperatures at Zagreb–Grič (20) and Crikvenica (21) have positive peaks in 1916. In 1909 the station in Kremsmünster (15) has a very low maximum daily temperature. It is not clear whether these anomalies and similar anomalies in minimum temperature at single stations are caused by local climatic effects, undetected measurement errors or inhomogeneities. After 1950 the maximum and minimum temperature records of the stations agree better than before 1950. The mean annual temperature shows an even more homogeneous temporal evolution at the different stations during the whole century.

The corresponding superimposed graphs of the mountain stations are shown in Figure 6. Large discrepancies between the time series of maximum and minimum daily temperatures occurred before 1950. For example, in 1902–1903 and 1905 the minimum at Hohenpeissenberg (9) was much lower than that at the other mountain stations. This may be due to the fact that Hohenpeissenberg is less than 1000 m high, whereas the other three stations operating at that time (Säntis, Zugspitze, and Sonnblick) are all higher than 2500 m. The mean temperatures of the mountain stations are in closer agreement than the extreme temperatures during the whole century.

For mountain stations (Figure 6) and low-lying stations (Figure 5) the DTR time series are less uniform among the different stations, especially before 1920. The German Hohenpeissenberg (9) and Zugspitze (10) have high values of DTR in 1900–1910. It is not clear whether these values are observational errors. As DTR is a function of both daily maximum and minimum temperature, it is more prone to measurement errors than the maximum or minimum temperatures alone. This may partly cause the large differences between the DTR time series. However, DTR is also expected to show spatial variability on a smaller scale than mean temperature or mean extreme temperatures due to regionally different climate.

As a further measure for the agreement of the temperature records at different stations, the linear correlation coefficient r is calculated (Table I) for a group of mountain stations (7, 10, 12, and 16) and a group of low-lying stations (6, 11, 17, and 18). The mountain stations have high correlation among each other for both maximum and minimum temperature. The low-lying stations have slightly lower correlations of the minimum temperature than of the maximum temperature. The correlations between the two groups are lower than within each group. The correlations among the mountain stations are larger than the correlations among the low-lying stations, although the spatial separation of the stations within both groups is about the same. This observation suggests that the mountain stations better represent larger-scale features of the atmosphere.

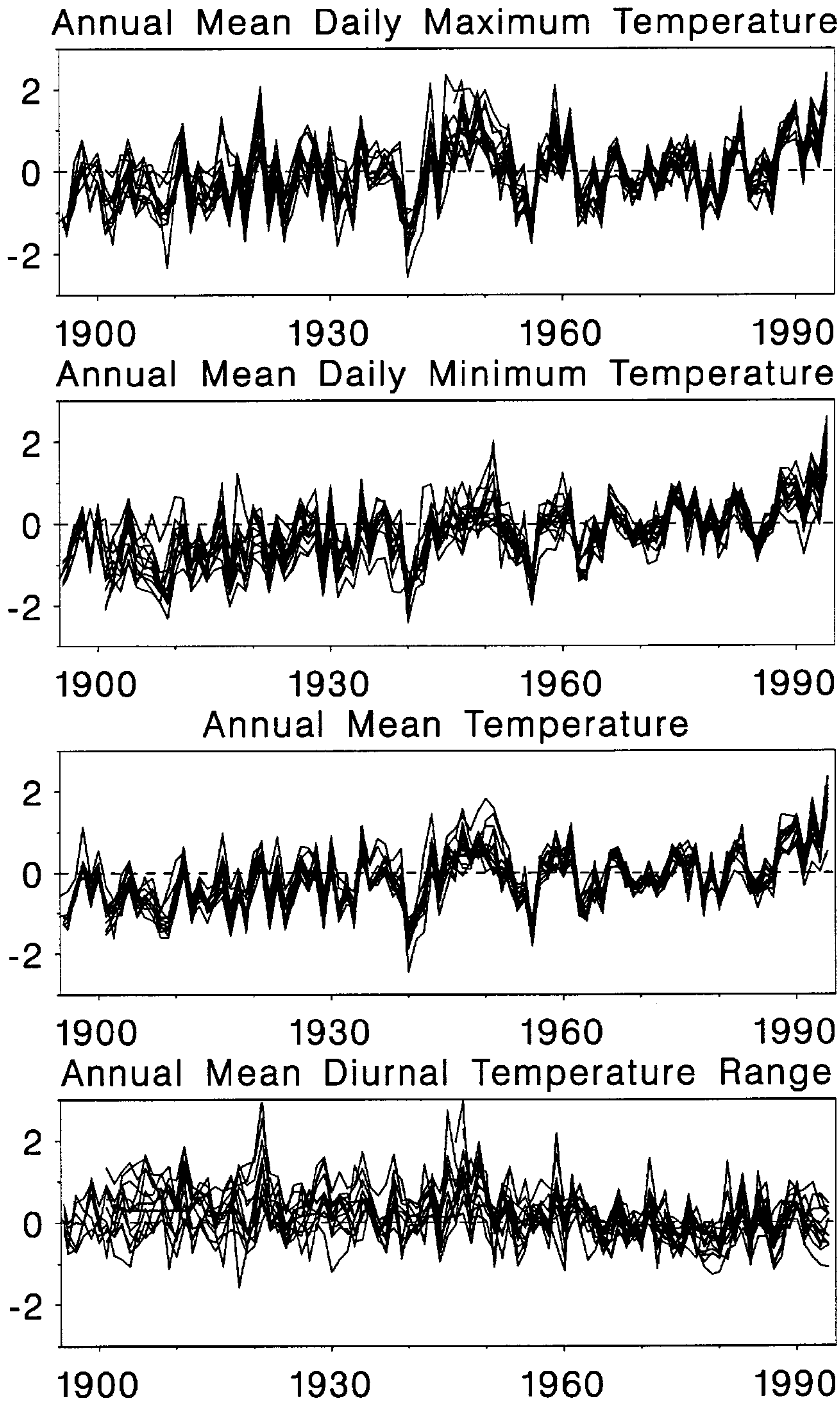

Figure 5. Composite picture of anomalies (in °C) of the annual mean maximum and minimum temperatures, the annual mean temperature, and the diurnal temperature range for 15 low-lying stations (reference period 1951–1990).

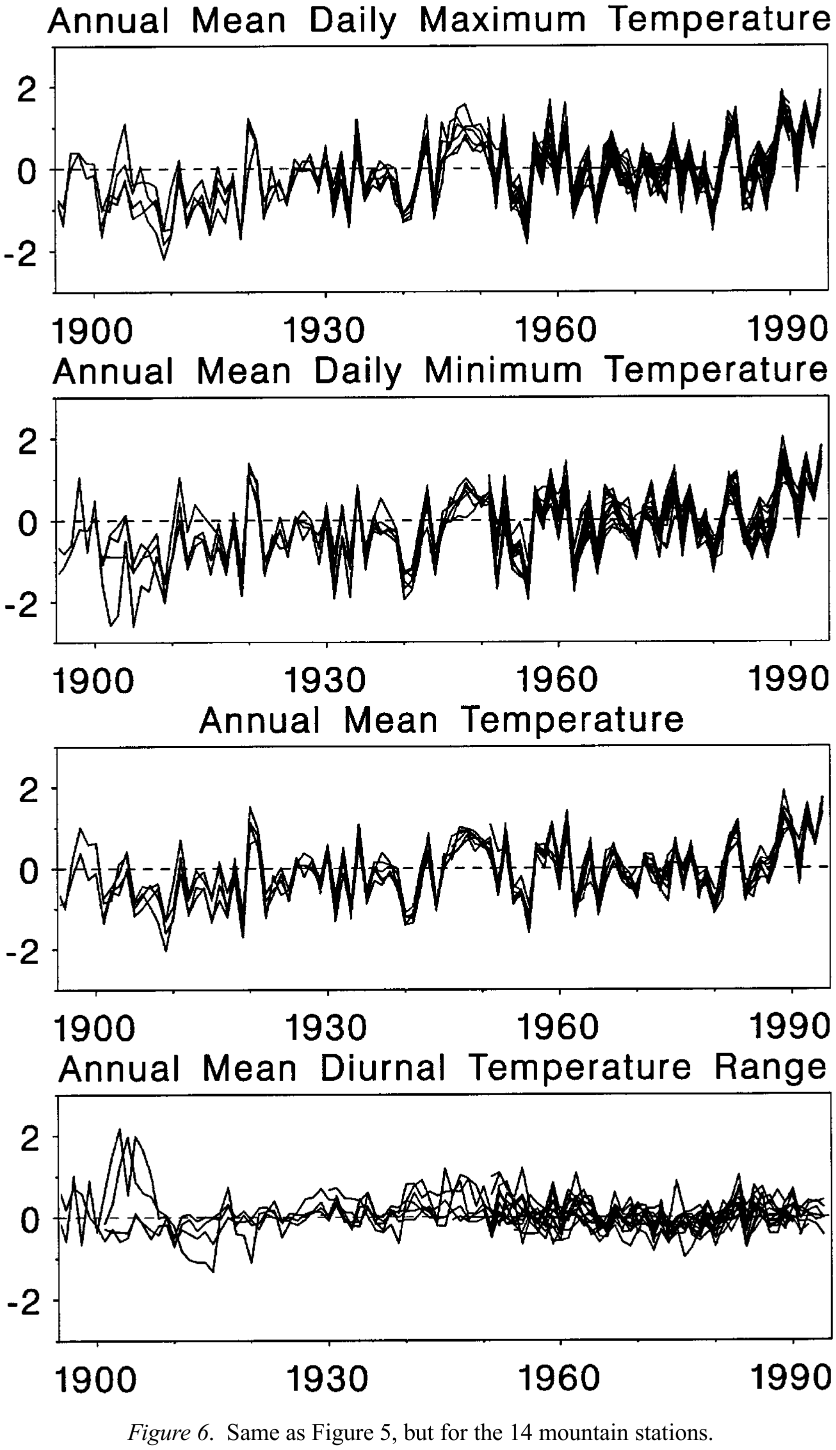

Figure 6. Same as Figure 5, but for the 14 mountain stations.

Table I

Correlation coefficients ($r \times 100$) between some mountain stations (7, 10, 12, and 16) and some low-lying stations (6, 11, 17, and 18), calculated for the annual mean daily extreme temperatures over the period 1901–1990. For the sake of convenience mountain stations and low-lying stations are separated by empty lines

Station	7	10	12	16	6	11	17
Maximum							
10	90						
12	92	88					
16	91	90	93				
6	79	72	71	77			
11	85	81	82	84	83		
17	77	68	76	77	83	80	
18	74	70	73	82	83	81	82
Minimum							
10	95						
12	94	93					
16	88	90	92				
6	73	74	77	79			
11	58	61	64	73	88		
17	58	61	64	73	74	76	
18	61	63	69	80	81	80	72

As a quantitative measure of the temporal evolution, linear trends of the temperature series can be considered, indicating a possible mean increase or decrease of temperature. In Table II the linear trends of all stations with long data records are summarized for the annual mean extreme temperatures, the DTR and the mean temperature. All stations have a positive trend in the minimum daily temperature over the period 1901–1990, which is significant for all stations with the exception of Feuerkogel (14) and Crikvenica (21). The maximum daily temperature did not significantly increase at the Swiss low-lying stations Basel (3), Neuchâtel (4), at Trier (1) in Germany, and at Zagreb–Grič (20) and Crikvenica (21) in Croatia, leading to a decrease of DTR at these stations. Though the stations at Bern (5) and Zürich (6) show a significant increase in the maximum temperature, the DTR is still decreasing. The other low altitude stations, located in Austria, show an equal increase of both maximum and minimum temperature, leaving DTR unchanged (see also Böhm and Auer, 1994). For the daily mean temperature the picture is more uniform. All stations show an increase of mean temperature, statistically significant with the exception of the Croatian stations. There is more or less a west-east

Table II

Linear trends (in °C/100 years) of annual mean temperature characteristics over the period 1901–1990. Trends which are, according to a standard Student-t test, significant at a two-tailed level of 5% are printed in bold face. MAX and MIN denote the annual means of daily maximum and minimum temperatures, respectively. DTR stands for the mean diurnal temperature range and MEAN denotes the annual mean temperature as obtained from several daily readings

Station	MAX	MIN	DTR	MEAN
Low-lying stations				
1	–0.1	**1.7**	**–1.9**	**0.9**
3	0.1	**1.8**	**–1.7**	**1.5**
4	0.6	**2.2**	**–1.6**	**0.8**
5	**1.0**	**2.1**	**–1.1**	**1.4**
6	**0.8**	**1.8**	**–1.1**	**1.1**
8	**1.1**	**1.1**	0.0	**1.1**
11	**1.0**	**1.0**	–0.1	**1.0**
13	**1.0**	**1.0**	0.0	**1.1**
15	**1.1**	**1.3**	–0.1	**1.2**
17	**1.0**	**1.1**	–0.1	**1.1**
18	**1.3**	**1.1**	0.2	**1.1**
20	–0.2	**0.8**	**–1.0**	0.3
21	–0.1	0.4	–0.4	0.4
Mountain stations				
7	**1.4**	**1.1**	**0.3**	**1.1**
9	**1.0**	**1.4**	–0.4	**0.8**
10	**0.7**	**1.2**	**–0.4**	0.5
12	**1.4**	**1.2**	0.2	**1.2**
14	0.8	1.0	–0.2	0.3
16	0.7	**1.2**	**–0.5**	0.9

gradient in the strength of the increase, as the western stations have larger positive trends than the eastern stations.

At the mountain stations the trends of maximum and minimum daily temperature are of similar size over the whole area of investigation. This causes smaller trends in DTR, partly not significant, than at the low-lying stations (see also Weber et al., 1994). The mean temperature has increased at all mountain stations, but significantly only at Hohenpeissenberg (9), Säntis (7), and Sonnblick (12).

Table III gives the seasonal trends of maximum and minimum daily temperatures and DTR for winter (DJF), spring (MAM), summer (JJA), and autumn (SON). Most low–lying stations show a significant increase of the maximum daily temperature in autumn. During the other seasons the increase is mostly insignificant. A few stations (8, 11, 15, 18, and 20) have significant positive trends in winter, spring or summer. The minimum daily temperature has significantly increased in all seasons at all western stations (3, 4, 5, and 6) and in summer, autumn, and partly in spring at the other low-lying sites. The trends of DTR are thus significantly negative for all western stations in all seasons, most pronounced in spring and summer. As maximum and minimum daily temperatures of the Austrian stations (8, 11, 13, 15, 17, and 18) increased by about the same amount, their DTR shows no significant trend with the exception of Innsbruck (11), where DTR increased in winter and autumn and decreased in summer. At Croatian Zagreb (20), the decrease of maximum and the increase of minimum daily temperature in summer causes a strong, significant decrease of DTR in summer, as well as in winter and spring.

Most mountain stations show a significant increase of maximum daily temperature in autumn, and a significant increase of minimum daily temperaturein summer and autumn. As the trends of maximum and minimum temperatures are of equal size in all seasons, the changes in DTR are considerably smaller than at the western low-lying stations. In winter, spring and summer most linear trends are negative, and in autumn positive at the mountain stations.

4. Changes Since 1951

Much of the analysis of DTR on a global scale concentrated on the period from the fifties to the nineties (Karl et al., 1991, 1993; Horton, 1995). For the period 1951–1990, most of the European stations considered in this study have continuous data records, only Zugspitze (10) and Trier (1) have a few years with missing data. Hence, a comparison of all the European stations shown in Figure 1 becomes possible for the period 1951–1990. The linear trends of the temperature characteristics at all stations were therefore computed for this forty-year period. However, considering the large year-to-year fluctuations and the decadal variability of the temperature series (Figures 3–6), a forty-year period is rather short to detect long-term changes.

Table IV shows the linear trends of annual and seasonal maximum and minimum daily temperature and DTR over the period 1951–1990. At the western low-lying stations (1, 2, 3, 4, 5, 6, and 8) the minimum daily temperature increased in all seasons and consequently in the annual average, whereas the maximum daily temperature prevailingly increased, but at a slower rate. The exception is spring when all quoted stations show a decrease of maximum daily temperature. This leads to a decrease of DTR, which is most pronounced and significant in spring. The low-lying stations in Austria (11, 13, 15, 17, and 18) show similar positive trends in both maximum and minimum temperature, which causes no significant trends in DTR. The linear trends at the mountain stations identify three regions with different behavior. In the central part of the Alps (7, 9, 10, and 12), maximum and minimum daily temperatures increased mainly in winter. As the annual trends

Table III

Linear trends (in °C/100 years) of seasonal mean maximum and minimum daily temperature and DTR over the period 1901–1990. Trends which are, according to a standard Student-*t* test, significant at a two-tailed level of 5% are printed in bold face

Station	Maximum				Minimum				DTR			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Low-lying stations												
1	–0.3	–0.9	0.2	0.5	0.8	**1.6**	**2.4**	**2.2**	**–1.1**	**–2.5**	**–2.2**	**–1.7**
3	0.1	–0.4	–0.5	**1.1**	**1.5**	**1.6**	**1.9**	**2.0**	**–1.4**	**–2.0**	**–2.4**	**–0.8**
4	0.8	0.2	0.1	**1.2**	**2.1**	**1.8**	**2.4**	**2.6**	**–1.3**	**–1.6**	**–2.4**	**–1.4**
5	1.0	0.3	0.8	**1.7**	**2.4**	**1.8**	**1.9**	**2.2**	**–1.4**	**–1.5**	**–1.1**	–0.5
6	0.8	0.3	0.5	**1.5**	**2.0**	**1.5**	**1.5**	**2.2**	**–1.2**	**–1.2**	**–1.0**	**–0.7**
8	1.1	0.6	**1.0**	**1.7**	1.2	0.7	**0.8**	**1.7**	–0.1	–0.1	0.1	0.0
11	**2.5**	0.0	–0.7	**2.0**	1.3	0.6	**0.9**	**1.1**	**1.2**	–0.6	**–1.7**	**0.9**
13	0.9	0.7	0.7	**1.7**	0.5	**0.9**	**1.0**	**1.6**	0.3	–0.2	–0.3	0.1
15	0.7	0.9	**1.2**	**1.6**	1.0	**1.1**	**1.3**	**1.6**	–0.3	–0.2	–0.1	0.0
17	1.1	0.7	0.7	**1.7**	1.1	**0.8**	**1.0**	**1.6**	–0.1	–0.1	–0.3	0.1
18	0.6	**1.3**	**1.4**	**1.7**	0.8	**1.0**	**1.1**	**1.4**	–0.1	0.3	0.3	0.2
20	0.3	–0.2	**–1.1**	0.4	1.1	0.7	**0.8**	0.8	**–0.8**	**–0.9**	**–1.9**	–0.4
21	0.3	–0.2	–0.9	0.5	0.4	–0.1	**0.9**	0.4	0.1	–0.1	–1.8	0.1
Mountain stations												
7	**1.3**	0.9	**1.0**	**2.2**	0.9	0.5	**1.0**	**1.9**	**0.5**	**0.4**	–0.1	**0.3**
9	0.9	0.4	0.3	**2.2**	1.3	**1.1**	**1.2**	**2.0**	–0.4	**–0.6**	**–0.9**	0.2
10	0.4	0.0	0.7	**1.8**	0.9	0.7	**1.2**	**1.8**	**–0.5**	**–0.7**	**–0.5**	0.0
12	0.9	0.9	**1.5**	**2.4**	1.1	0.9	**1.0**	**1.9**	–0.2	0.0	**0.5**	**0.5**
14	**3.4**	–0.7	–1.1	**2.0**	**3.2**	0.3	–0.2	1.1	0.2	**–1.0**	**–0.9**	**0.9**
16	2.1	–0.1	–0.6	1.4	2.1	0.7	0.3	**1.6**	–0.1	**–0.7**	**–1.0**	–0.2

of the extreme daily temperatures are roughly equal, only small, insignificant trends of annual mean DTR result. In spring and summer, the differences between the trends in maximum and minimum daily temperatures are largest and DTR decreases in these seasons. The stations in the eastern part of the Alps (14, 16, 19, and 22) show mainly positive trends of maximum temperature, but no trend of minimum temperature, and hence an increase of DTR. The stations in mountain ranges northeast of the Alps (24–29) show mainly a strong significant increase of minimum daily temperature in spring. The DTR at these sites decreases, although mostly not significantly.

5. Summary and Conclusions

Temperature records from 29 Central European stations at both low altitude and at high elevation were analyzed. Marked warm periods around 1950 and around 1960 are present in maximum, minimum and mean daily temperatures at all stations. This gives confidence that these features are representative for the whole region, or even a larger area of the globe. After 1980, a strong increase is evident in all temperature records, in maximum, minimum and mean temperatures. Most of the differences between the temperature series at the different stations occur before 1950. After 1950, either measurement errors have become much smaller, or the spatial variability of the surface temperature has decreased.

A linear trend analysis of maximum and minimum daily temperatures and DTR was performed for two periods: 1901–1990 (with 19 stations) and 1951–1990 (with all 29 stations). Several differences between low-lying stations and high elevation sites can be observed. Mountain stations show no, or only small changes of DTR over the 1901–1990 period, whereas low-lying stations in the western part of the Alps show a strong decrease of DTR. At the western low-lying stations minimum daily temperature increases in all seasons, whereas maximum daily temperature increases mainly in autumn, leading to the observed changes in DTR. At mountain stations positive trends of minimum daily temperature occur mostly in summer and autumn and are of smaller amplitude than at low altitude sites.

Over the shorter period 1951–1990 the mountain stations show significant changes in maximum and minimum daily temperatures only in winter and spring. Whereas the western low-lying stations have a strong decrease of DTR in spring, a much smaller, mostly not significant, decrease of DTR shows up at the high elevation sites. There is some west-east gradient in the trends of DTR as the minimum temperature shows a stronger increase in the western part of the area.

The existence of regionally and vertically different trends of DTR is not astonishing. The natural as well as possible anthropogenic forcing factors may both show such variations too. Cloudiness for example is very different in the lowlands than in the mountains and can have even different trends under the same large-scale conditions. A detailed study for the investigation area is planned as soon as

Table IV

Linear trends (in °C/100 years) of annual (Year) and seasonal mean maximum and minimumdaily temperatures and DTR over the period 1951–1990.Trends which are, according to a standard Student-t test, significant at a two-tailed level of 5% are printed in bold face

Station	Maximum					Minimum					DTR				
	Year	DJF	MAM	JJA	SON	Year	DJF	MAM	JJA	SON	Year	DJF	MAM	JJA	SON
Low-lying stations															
1	–0.7	1.8	–3.0	0.4	–1.5	**2.5**	3.3	**2.7**	**2.6**	1.7	**–3.2**	–1.5	**–5.7**	–2.2	**–3.2**
2	0.6	2.5	–1.5	1.3	0.8	1.5	2.8	1.5	0.6	1.2	–0.8	–0.3	**–3.1**	0.6	–0.4
3	–0.6	1.9	–3.2	–0.5	–0.1	**2.8**	4.4	**2.6**	**2.1**	2.4	**–3.4**	**–2.5**	**–5.8**	–2.6	**–2.5**
4	1.8	**3.9**	–1.6	2.4	**2.6**	**3.3**	**5.2**	**2.4**	**2.8**	**3.2**	**–1.5**	–1.3	**–3.9**	–0.4	–0.5
5	**1.8**	3.5	–2.3	3.0	**3.5**	**2.0**	3.1	1.9	**1.9**	1.4	–0.2	0.4	**–4.2**	1.1	2.0
6	0.6	3.4	–2.3	0.2	1.5	**2.2**	**4.2**	1.5	1.1	**2.4**	**–1.6**	–0.9	**–3.8**	–0.9	–0.8
8	**1.8**	3.9	–0.3	1.7	2.2	**2.6**	3.8	2.2	**2.1**	**2.5**	–0.8	0.1	**–2.5**	–0.5	–0.2
11	**2.1**	3.1	2.2	1.4	2.2	**1.7**	2.9	2.1	0.3	1.9	0.4	0.3	0.1	1.1	0.3
13	**2.5**	4.1	2.8	1.5	2.2	1.5	3.0	2.1	0.3	0.8	1.1	1.0	0.7	1.3	1.4
15	**2.4**	3.9	**3.4**	1.9	0.8	**2.1**	3.8	**2.6**	1.2	1.1	0.3	0.1	0.8	0.6	–0.3
17	1.3	2.8	1.7	0.1	0.5	0.7	2.6	0.7	0.1	–0.9	0.6	0.1	1.0	–0.1	1.4
18	1.8	4.0	3.1	0.9	–0.3	**2.2**	3.5	**3.3**	0.8	1.5	–0.4	0.5	–0.2	0.1	–1.8
20	0.3	2.4	1.8	–1.7	–1.2	1.1	2.8	2.1	0.0	–0.9	–0.8	–0.4	–0.4	–1.8	–0.3
21	0.2	1.6	–0.4	–0.1	0.0	0.8	0.6	1.9	1.0	–0.3	–0.6	1.0	**–2.4**	–1.1	0.3
23	1.1	2.6	1.7	–0.5	0.4	0.0	0.8	1.6	–0.3	–2.2	1.0	1.8	0.1	–0.1	2.6
Mountain stations															
7	1.3	**6.0**	–0.9	–1.2	2.0	**2.1**	**5.2**	0.4	1.1	2.3	–0.8	0.8	–1.2	**–2.3**	–0.3
9	1.0	3.4	–0.1	0.3	0.9	1.3	3.6	0.3	0.5	1.4	–0.4	–0.2	–0.5	–0.2	–0.6
10	1.3	**4.4**	0.3	–0.4	1.6	2.0	**4.3**	1.8	0.9	1.4	–0.6	0.1	**–1.5**	**–1.3**	0.2
12	**2.2**	**3.9**	1.5	2.1	1.7	**2.3**	**4.4**	2.2	1.2	1.8	–0.1	–0.5	–0.7	0.8	–0.1
14	**2.0**	**5.1**	1.4	0.4	1.9	0.0	3.1	0.0	–1.6	–0.9	**2.0**	**2.0**	**1.4**	**2.0**	**2.7**
16	**1.6**	**4.8**	0.7	0.2	2.8	1.5	3.3	0.8	0.4	1.8	0.5	**1.4**	–0.2	–0.3	1.0
19	1.2	2.4	2.5	1.2	–0.2	–0.1	2.5	1.3	–1.7	–1.5	**1.3**	–0.1	1.2	**2.9**	1.3
22	**1.9**	3.8	1.8	0.8	1.5	0.7	2.4	0.9	–0.5	–0.1	**1.2**	**1.4**	0.9	**1.3**	**1.6**
24	0.7	3.4	0.6	–1.1	0.0	1.7	3.3	2.3	–0.4	0.8	**–0.9**	0.0	**–1.7**	–0.7	–0.7
25	0.4	2.9	1.3	–1.3	–1.0	1.1	3.3	2.2	–0.5	–0.1	–0.7	–0.4	–0.9	–0.9	–0.9
26	1.0	2.8	2.4	–0.6	–0.1	1.7	3.5	**3.7**	–0.3	–0.1	–0.7	–0.6	–1.3	–0.3	–0.1
27	1.3	3.1	3.5	–0.8	–0.6	1.8	3.7	**3.7**	–0.6	0.1	–0.5	–0.7	–0.1	–0.2	–0.6
28	0.3	2.6	2.3	–2.5	0.2	1.5	3.7	**3.8**	–0.8	–0.2	–1.2	–1.1	**–1.5**	**–1.7**	0.4
29	0.5	2.8	2.1	–1.8	–0.5	1.5	4.0	**3.5**	–1.0	–0.3	**–1.0**	–1.2	**–1.5**	–0.8	–0.2

homogenized long-term time series of cloudiness, snow conditions and other forcing agents of DTR will be available for the Central European mountains. To study possible greenhouse effects on DTR model results of higher spatial resolution than present climate models have are necessary.

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