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Circulation and Climate Variability in the Czech Republic between 1961 and 2020: A Comparison of Changes for Two "Normal" Periods

Rudolf Brázdil [1,2,*], Pavel Zahradníček [2,3], Petr Dobrovolný [1,2], Jan Řehoř [1,2], Miroslav Trnka [2,4], Ondřej Lhotka [2,5] and Petr Štěpánek [2,3]

1 Department of Geography, Faculty of Science, Masaryk University, 611 37 Brno, Czech Republic; dobro@sci.muni.cz (P.D.); 433737@mail.muni.cz (J.Ř.)
2 Global Change Research Institute, Czech Academy of Sciences, 603 00 Brno, Czech Republic; zahradnicek.p@czechglobe.cz (P.Z.); trnka.m@czechglobe.cz (M.T.); ondrej.lhotka@ufa.cas.cz (O.L.); stepanek.p@czechglobe.cz (P.Š.)
3 Czech Hydrometeorological Institute, 616 67 Brno, Czech Republic
4 Department of Agrosystems and Bioclimatology, Mendel University in Brno, 613 00 Brno, Czech Republic
5 Institute of Atmospheric Physics, Czech Academy of Sciences, 141 00 Praha, Czech Republic
* Correspondence: brazdil@sci.muni.cz

Abstract: Thirty-year periods are treated in climatology as spans with relatively representative and stable climatic patterns, which can be used for calculating climate normals. Annual and seasonal series of circulation types were used to compare two 30-year sub-periods, 1961–1990 and 1991–2020, the second one being strongly influenced by recent global warming. This analysis was conducted according to the objective classification of circulation types and the climatic characteristics of sunshine duration, temperature, humidity, precipitation, and wind speed as calculated for the territory of the Czech Republic during the 1961–2020 period. For both sub-periods, their statistical characteristics were calculated, and the statistical significance of differences between them was evaluated. There was a statistically significant increase in the annual frequencies of anticyclonic circulation types and a significant decrease in cyclonic circulation types during 1991–2020 compared with 1961–1990. Generally, in both 30-year periods, significant differences in means, variability, characteristics of distribution, density functions, and linear trends appear for all climatic variables analysed except precipitation. This indicates that the recent 30-year "normal" period of 1991–2020, known to be influenced more by recent climate change, is by its climatic characteristics unrepresentative of the stable climatic patterns of previous 30-year periods.

Keywords: climate normal; circulation type; sunshine; temperature; humidity; precipitation; wind speed; statistical analysis; Czech Republic

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1. Introduction

Thirty-year periods are used and recommended in climatology as basic periods for the calculation of climate (climatological) normals when it is supposed that a 30-year interval is long enough to express relatively representative and stable climatic patterns. Climate normals "form a benchmark or reference against which conditions (especially current or recent conditions) can be assessed" and "are widely used for predictive purposes, as an indicator of the conditions likely to be experienced in a given location" [1,2]. Besides the use of non-overlapping 30-year intervals, for which climate standard normals were calculated worldwide (see, e.g., [3] for 1931–1960 or [4] for 1961–1990) it was also recommended to use climate normals calculated from 30-year periods ending by 0 in the last year of the corresponding time interval, e.g., such as 1921–1950, 1951–1980, or 1981–2010 [1,2]. The 1961–1990 period was especially recommended to be used "as a standard reference period for long-term climate change assessments" [2]. Following the year 2020, it is now possible to use another, more recent normal period, namely 1991–2020.

Given the recent climate warming starting in the late 1970s, which particularly intensified from the 1980s [5–7], there is a question of how the recent normal period of 1991–2020 expresses its climatic patterns compared to that of 1961–1990. We are trying to document this by carrying out a comparison of both 30-year climate normals for the homogenised annual and seasonal series of several climatic variables calculated for the territory of the Czech Republic during the 1961–2020 period. As Twardosz et al. [8] showed in their analysis of 210 stations in Europe, the air temperature has continued to grow linearly since 1985, i.e., 1961–1990 seems to be less influenced by recent global warming than 1991–2020. Despite the fact that the previous studies in the Czech Republic dealt with incomplete 60-year periods (for example, Brázdil et al. [9] with wind speed, Brázdil et al. [10] with precipitation or Zahradníček et al. [11] with temperatures), the last study by Zahradníček et al. [12], which dealt with temperature extremes during the entire 60-year period 1961–2020, clearly demonstrates significant differences between both 30-year normal sub-periods.

The current study set out to answer an important research question, i.e., whether it is appropriate to use the 1991–2020 climate normal instead of the 1961–1990 one. The testing of both standard normal periods 1961–1990 and 1991–2020 was conducted in the context of the whole 60-year period by applying different statistical methods to analyse the selected characteristics of circulation types, sunshine, temperature, humidity, precipitation, and wind for the entire Czech Republic. Section 2 briefly describes the study area, meteorological data and circulation types, the homogenisation procedure of meteorological data, and the methods of statistical analysis. Section 3 compares statistical characteristics of circulation types and the characteristics of five climate variables in two 30-year periods. The obtained results are discussed in a broader context in Section 4 and shortly summarised in the last section.

2. Materials and Methods

2.1. Study Area

The Czech Republic (afterward 'CR'), with a total area of 78,866 km^2, is located in central Europe (Figure 1). This position is influenced by the effects of the Atlantic Ocean, the Mediterranean Sea, and the Eurasian continent, which determines the temperature and humidity of air masses moving into central Europe. These airflow effects are modified at regional/local scales by orographic patterns (altitude, leeward, and windward effects) because altitudes over the CR territory range from 115 to 1603 m (mean altitude 390 m a.s.l.). According to the Köppen classification, the major part of the CR territory corresponds to the climate category of temperate broadleaf deciduous forest (Cfb), while the remaining areas are attributed to a boreal climate (particularly Dfb—boreal climate with warm summer, and, to a lesser extent, Dfc—boreal climate with cold summer; for more detail see [13]).

2.2. Meteorological Data

A series of annual and seasonal values of selected climatic variables measured at meteorological stations of the Czech Hydrometeorological Institute over the territory of the CR during the 1961–2020 period was used (Figure 1):

(i) Sunshine duration—79 stations;
(ii) Mean, maximum, and minimum temperatures—133 stations;
(iii) Relative humidity—133 stations;
(iv) Precipitation total—531 stations;
(v) Wind speed—119 stations.

Each of these series was homogenised (using the procedure described in Section 2.4.1), and missing observations were complemented by estimated values. Out of the entire network, we considered only stations that had at least 40 years of observations in the analysed 60-year period.

From the above-mentioned numbers of stations, mean annual and seasonal (DJF—winter, MAM—spring, JJA—summer, SON—autumn) series for the territory of the CR in the 1961–2020 period were calculated applying the method of arithmetic mean.

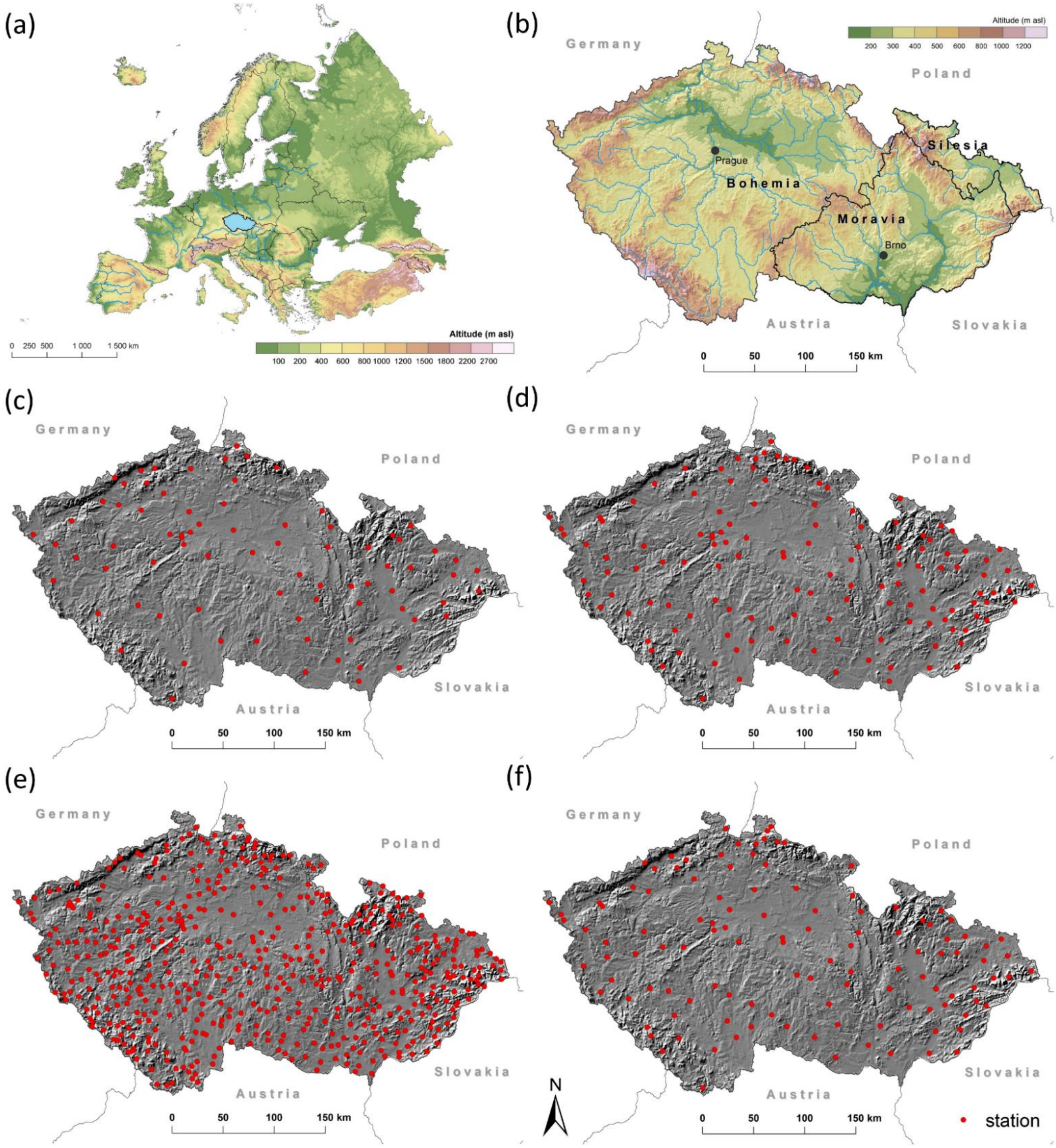

Figure 1. (**a**) The location of the Czech Republic in Europe, (**b**) the physical geographical map of the Czech Republic, and the network of meteorological stations of the Czech Hydrometeorological Institute used for the calculation of (**c**) sunshine duration, (**d**) temperatures and relative humidity, (**e**) precipitation totals, and (**f**) wind speed.

2.3. Circulation Types

For the characterisation of circulation types, an objective classification based on flow strength, flow direction, and vorticity [14,15] was used. Circulation types were calculated from sea level pressure according to the NCEP/NCAR reanalysis [16] at 16 points located around the geographic centre of the CR (coordinates 49.74°N and 15.33°E). An inverse distance-weighted mean of the nine closest NCEP/NCAR grids around a given point was used to calculate a corresponding sea level pressure field. In total, 27 circulation types were defined and divided; thus (for abbreviations of individual circulation types see Appendix A):

(i) Nine anticyclonic types (A, AN, ANE, AE, ASE, AS, ASW, AW, ANW);
(ii) Nine cyclonic types (C, CN, CNE, CE, CSE, CS, CSW, CW, CNW);
(iii) Eight directional types (N, NE, E, SE, S, SW, W, NW);
(iv) An unclassified type U.

Řehoř et al. [17,18] described this objective classification of circulation types in more detail and gave schemes of sea level pressure fields for individual circulation types.

2.4. Methods

2.4.1. Homogenisation

The homogenisation procedure of analysed climatic variables uses ProClimDB and AnClim software [19], based on broad practical experience with homogenisation (e.g., [20–22]). Because detailed descriptions of the whole procedure are already covered in several papers with applications to temperature [11,12], precipitation [10], and wind speed [9,23], only some basic steps of the homogenisation procedure are addressed below:

(i) Quality control of daily data (comparison with neighbouring stations);
(ii) Break-point detection (on the level of monthly data, applying both the Standard Normal Homogeneity Test [24] and the bivariate test [25] afterward);
(iii) Adjustment of the daily data (with respect to existing metadata and the evaluation of the importance of break-points detected, applying our own method of Distribution Adjustment by Percentile, developed from the "variable correction method" by [26]);
(iv) Filling gaps (by interpolation methods from neighbouring stations with respect to differences in their distance and altitude and correlation coefficients) [21].

2.4.2. Statistical Analysis

In order to compare annual and seasonal series of circulation types and climatic variables in the CR during the two 30-year normal periods of 1961–1990 and 1991–2020, their fluctuations were complemented by linear trend estimates. We applied the non-parametric Theil-Sen method, which is more robust to possible outlier values [27,28]. Moreover, this is also a more relevant method with respect to the length of the series compared. The overall tendency was expressed as a mean increase or decrease per 10 years for the entire 60-year period, as well as two 30-year sub-periods. The significance of linear trends was evaluated using the non-parametric Mann–Kendall test at the 0.05 significance level [29,30]. In cases of significant serial correlations in the analysed series, a modified Mann–Kendall test for autocorrelated data was applied (see Appendix B). In order to characterise the distribution of circulation types and climatic variables, their box plots (median, lower and upper quartile, maximum and minimum) for the above three basic periods were calculated. The related figures of individual variables were further complemented by density curves for two 30-year sub-periods. The density estimates were compared both graphically and formally with the bootstrapping method as implemented in the sm R-package [31]. This method allows the testing of equality between two density curves producing a reference band and corresponding p-value. The course of the density curves outside the reference band indicates a significant difference in the distribution of the two analysed sub-periods. Possible differences in means and variances between both 30-year datasets were evaluated by applying the t-test and the F-test, respectively. The variance of those variables measured on the ratio scale (all except air temperature) was characterised with the coefficient of the variation, and the possible difference between the coefficients of the variation in the two analysed sub-periods was formally tested with the asymptotic test as implemented in the cvequality R package [32].

Possible changes in the distribution of the two 30-year sub-periods were further characterised by the higher-order moments (skewness, kurtosis) and their differences tested. The test was also based on the bootstrapping previously mentioned. Observed differences in the skewness/kurtosis calculated from the sub-periods were compared to the distribution of such differences calculated from the 1000 subsets randomly generated from the original data.

In order to compare both 30-year periods from the point of view of their spatial patterns, maps were created showing differences between the 1991–2020 and 1961–1990 periods for the annual series of the analysed climate variables. Regression kriging was used to create such maps. This method entails applying climate variable dependence on the longitude, latitude, altitude, slope, aspect, and surface roughness in 500 × 500 m resolution.

3. Results

3.1. Circulation Patterns

When comparing circulation patterns over the CR in two 30-year normal periods (1961–1990 and 1991–2020) in the annual scale (Table 1), the group of anticyclonic circulation types from the objective classification dominates with a frequency of 149.4 and 167.4 days, respectively (i.e., 40.9 and 45.8%), followed by the directional circulation types with frequencies of 142.1 and 136.1 days, respectively (i.e., 38.9 and 37.3%). The cyclonic circulation types are much less frequent, with only 67.6 and 55.7 days, respectively (i.e., 18.5 and 15.2%). The rest of the days (1.7%) remained unclassified.

Table 1. Selected statistical characteristics of annual (Ann) and seasonal (DJF, MAM, JJA, and SON) frequencies of days with anticyclonic, cyclonic, and directional circulation types according to the objective classification for the territory of the Czech Republic during the 1961–1990 (A) and 1991–2020 (B) periods: means are in days, variation coefficients (CV) in %, and linear trends in days/10 years (in bold statistically significant at the 0.05 significance level). An asterisk * indicates statistically significant differences of a given characteristic between two 30-year periods.

Season	Period	Mean	CV	Skewness	Kurtosis	Slope
Anticyclonic circulation types						
Ann	A	149.4 *	15.5	−0.18	−0.57	**14.2**
	B	167.4 *	13.5	−0.09	−0.40	2.5
DJF	A	38.2 *	28.2	0.80	0.11	1.2
	B	44.2 *	24.1	−0.11	−0.17	−2.1
MAM	A	26.9 *	28.4	0.46	0.55	0.9
	B	33.7 *	25.6	0.76	0.02	0.9
JJA	A	40.6 *	22.9	−0.34	−0.36	**6.8**
	B	47.8 *	17.0	−0.10	−1.12	1.2
SON	A	43.8	27.2	−0.18	−0.77	5.0
	B	41.8	24.7	0.23	−0.03	0.9
Cyclonic circulation types						
Ann	A	67.6 *	28.1	0.66	0.42	**−14.4**
	B	55.7 *	20.5	0.28	0.94	0.0
DJF	A	12.9	46.9	0.12 *	−0.54 *	−1.4
	B	10.5	52.2	1.92 *	6.00 *	0.8
MAM	A	25.9 *	28.4	0.32	0.02	−3.3
	B	19.5 *	30.3	−0.10	−0.06	−1.2
JJA	A	16.1 *	47.7	0.51	−0.15	**−5.4**
	B	12.0 *	45.5	1.10	0.74	0.5
SON	A	12.6	52.4	0.46	−0.59	**−3.8**
	B	13.7	43.2	0.55	−0.46	0.0

Table 1. *Cont.*

Season	Period	Mean		CV	Skewness	Kurtosis	Slope
			Directional circulation types				
Ann	A	142.1		7.7	0.69	−0.14	0.0
	B	136.1		10.6	−0.14	0.12	−3.3
DJF	A	38.5		18.5	−0.36	0.37	−0.5
	B	35.2		23.0	0.27	0.01	0.6
MAM	A	37.8		14.9	−0.42	0.23	2.4
	B	37.3		14.4	−0.42	−0.16	−0.5
JJA	A	32.2	*	14.7	0.10	1.00	0.0
	B	28.8	*	19.9	−0.36	−0.38	−1.1
SON	A	33.6		22.0	0.22	−0.67	−0.5
	B	34.8		20.0	−0.27	0.46	−3.2

Concerning days with anticyclonic circulation types, their frequencies increased in the annual and seasonal series (except SON) in 1991–2020 compared with the preceding 30 years, and differences in related 30-year means between both periods were statistically significant at the 0.05 significance level (Table 1). While DJF frequencies exhibited a negative linear trend during 1991–2020, in all other cases, the corresponding trends were increasing (Figure 2a). This increase was statistically significant for JJA and annual series during 1961–1990. Moreover, the same series demonstrate a significant difference in the sloping trend of the two compared normal periods. Variability in the frequency of anticyclonic types expressed by the coefficient of variation decreased in the second 30-year period, but related differences were not statistically significant (Table 1). The 30-year density functions (Figure 2c) indicate significant differences in the frequency distribution between both compared periods for MAM and annual series. These differences are especially related to the shift of the whole distribution to higher values. Concerning skewness and kurtosis, no significant differences appeared in the values of related coefficients in any annual or seasonal series (Table 1).

Generally, opposite behaviour than in previous cases appears in annual and seasonal frequencies of days with cyclonic circulation types. Their frequencies in 1961–1990 were higher than those in 1991–2020 except SON (Table 1). Related differences in 30-year means were statistically significant for MAM, JJA, and annual series. While in 1961–1990, strong decreasing linear trends characterised all series (Figure 3a), statistically significant for JJA, SON, and annual frequencies, in the following 30-year period, all trends were non-significant or even close to zero (SON and annual series) (Table 1). Differences in the slopes of corresponding linear trends were statistically significant for JJA, SON, and annual series. As for the variability of cyclonic types expressed by the coefficient of variations, it was higher in the first 30 years in JJA, SON, and annual series, while in the case of DJF and MAM, it was the opposite. None of the series indicates a significant difference in the variability of the two periods. The 30-year box plots show smaller variability expressed by the interquartile range in 1991–2020 compared to the preceding 30 years, except SON (Figure 3b). Higher-order moments (skewness, kurtosis) demonstrate a significant change in the DJF distribution (Table 1). Furthermore, quite evident changes in the density functions can be seen for all series except SON (Figure 3c). These changes are significant, especially for the DJF, MAM, and annual series ($p < 0.05$) and also for JJA ($p < 0.10$).

Relatively stable patterns between both 30-year normal periods occur for frequencies of the group of directional circulation types. Their means were lower in the second analysed period compared to 1961–1990 for annual and seasonal series except for SON, but differences in means were statistically significant only for JJA frequencies (Table 1). All series of frequencies of directional types exhibit statistically non-significant linear trends, except the DJF negative trend during 1991–2020; in the preceding 30 years, JJA and annual frequencies experienced no trending (Figure 4a). No statistically significant differences were found in the slopes of these trends. Concerning the variability of directional types, it was, compared to 1961–1990, higher in 1991–2020 for the DJF, JJA, and annual series, and lower for transient seasons MAM and SON (Table 1). The 30-year coefficients of variation did not differ significantly. No statistically significant differences between both 30-year periods follow from other characteristics used, such as 30-year box plots (Figure 4b), density functions (except JJA) (Figure 4c), and the coefficients of skewness and kurtosis (Table 1).

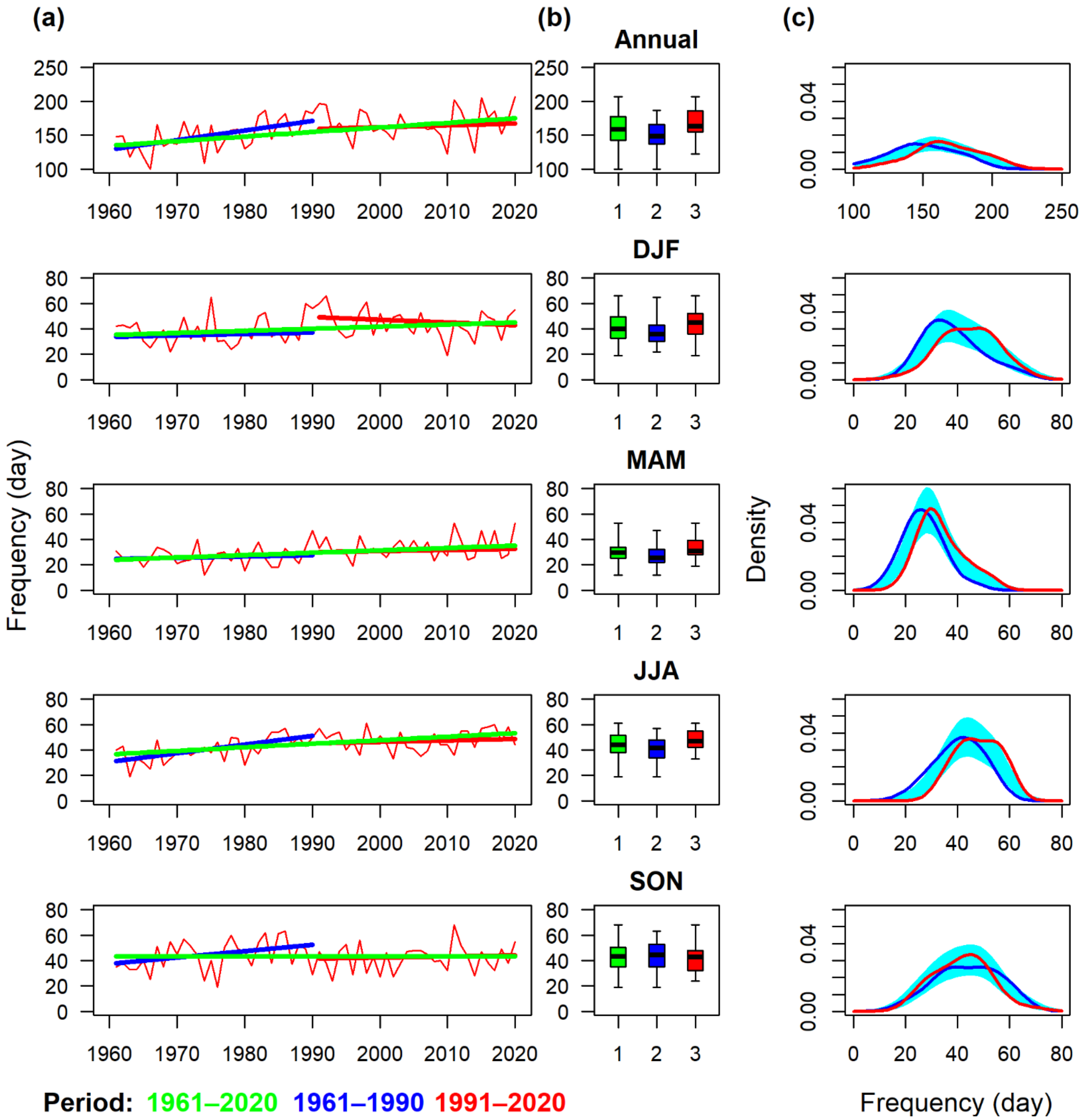

Figure 2. Annual and seasonal frequencies of days with anticyclonic circulation types according to the objective classification for the territory of the Czech Republic in the 1961–2020 period: (**a**) fluctuations with linear trends in the entire period, 1961–1990 and 1991–2020; (**b**) box plots (median, lower and upper quartile, minimum, and maximum) for 1961–2020 (1), 1961–1990 (2), and 1991–2020 (3); (**c**) the density distribution of the series in 1961–1990 and 1991–2020. The density curves outside the reference band (green–blue) indicate a significant difference in the two distributions (and vice versa).

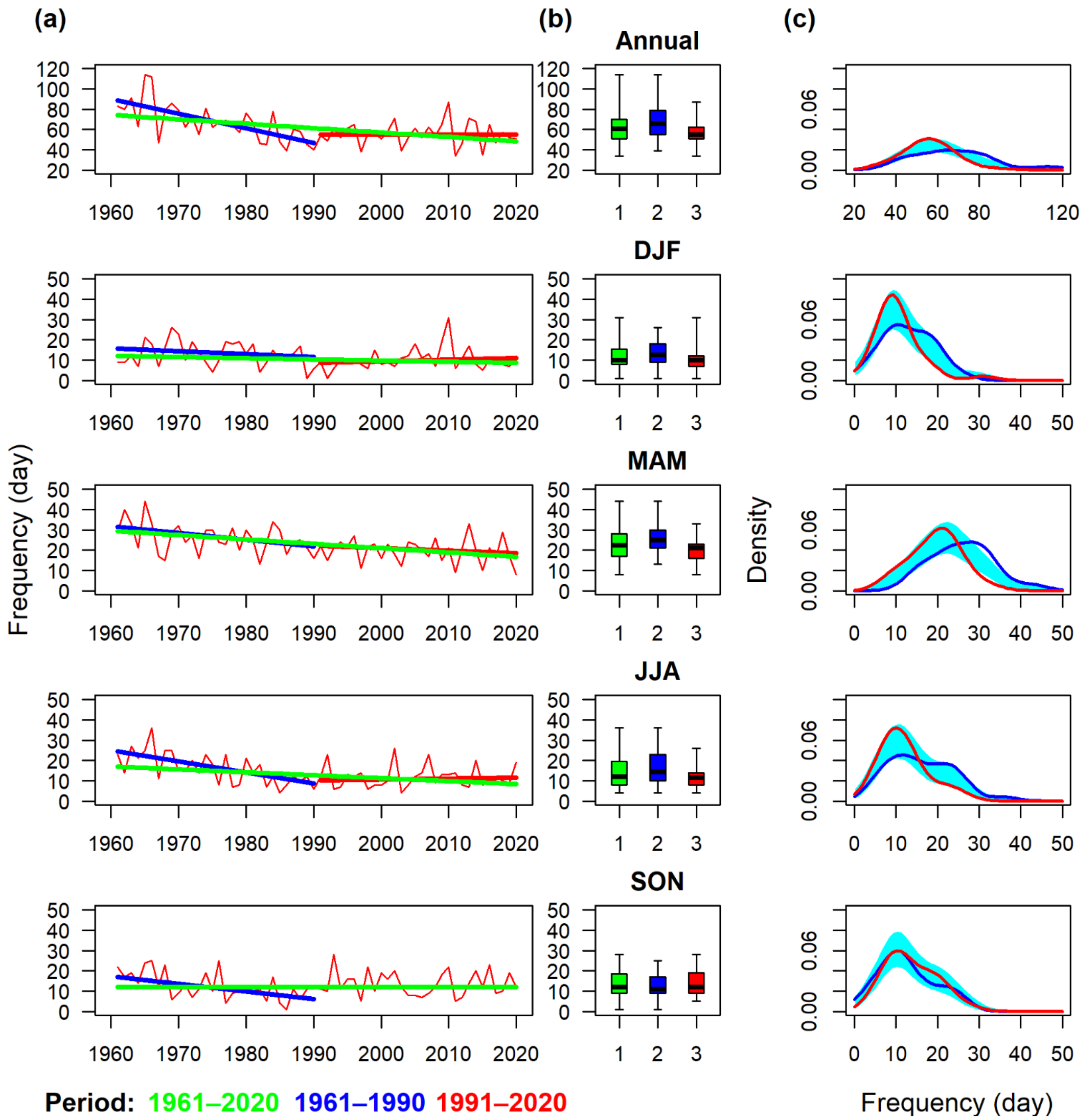

Figure 3. Annual and seasonal frequencies of days with cyclonic circulation types according to the objective classification for the territory of the Czech Republic in the 1961–2020 period: (**a**) fluctuations with linear trends in the entire period, 1961–1990 and 1991–2020; (**b**) box plots (median, lower and upper quartile, minimum, and maximum) for 1961–2020 (1), 1961–1990 (2), and 1991–2020 (3); (**c**) the density distribution of the series in 1961–1990 and 1991–2020. The density curves outside the reference band (green–blue) indicate a significant difference in the two distributions (and vice versa).

3.2. Sunshine

Means of sunshine duration for 1991–2020 increased compared to the preceding 30 years in annual and seasonal series except for SON, when they dropped (Table 2). Related differences in means were statistically significant for annual, MAM, and JJA values. The annual, JJA, and SON series exhibited negative linear trends during 1961–1990 (Figure 5a), while over the next 30 years, negative trends occurred in DJF and JJA; however, none of the trends were statistically significant. A comparison of slope trends showed no significant differences. As for the variability expressed by the coefficient of variation (Table 2), it decreased in the DJF and JJA series and increased through the year and two transient seasons. However, their differences between the two sub-periods do not differ significantly. In the box plots, the shift of related characteristics to higher values for annual, MAM, and JJA series and to lower values in the SON series is well expressed (Figure 5b). A comparison of the higher-order moments demonstrates no systematic shift to higher or lower skewness and kurtosis. The only significant change from positive to negative asymmetry appears in DJF (Table 2). Concerning density functions (Figure 5c), no statistically significant change was found in any seasonal or annual series.

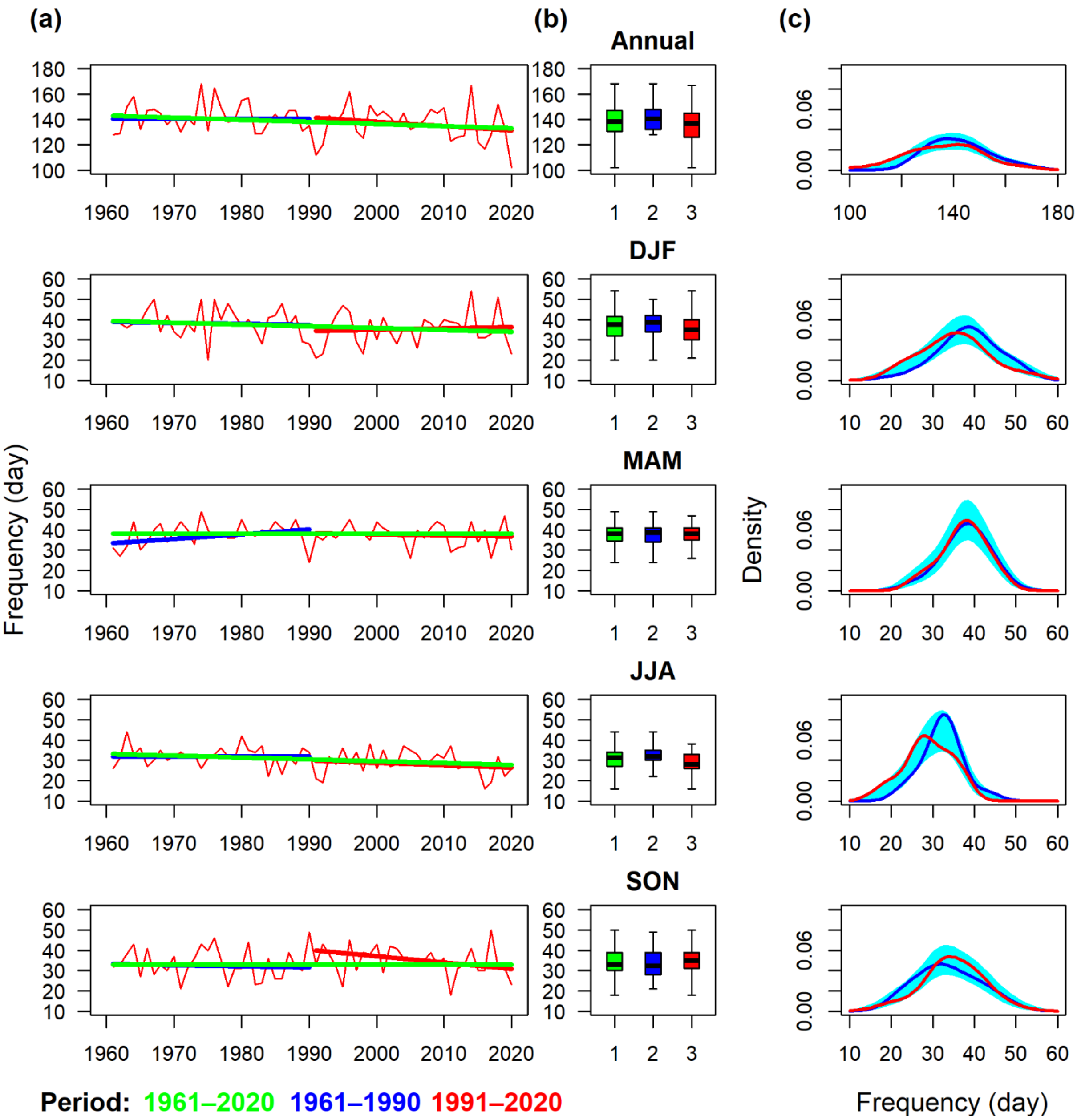

Figure 4. Annual and seasonal frequencies of days with directional circulation types according to the objective classification for the territory of the Czech Republic in the 1961–2020 period: (**a**) fluctuations with linear trends in the entire period, 1961–1990 and 1991–2020; (**b**) box plots (median, lower and upper quartile, minimum, and maximum) for 1961–2020 (1), 1961–1990 (2), and 1991–2020 (3); (**c**) the density distribution of the series in 1961–1990 and 1991–2020. The density curves outside the reference band (green–blue) indicate a significant difference in the two distributions (and vice versa).

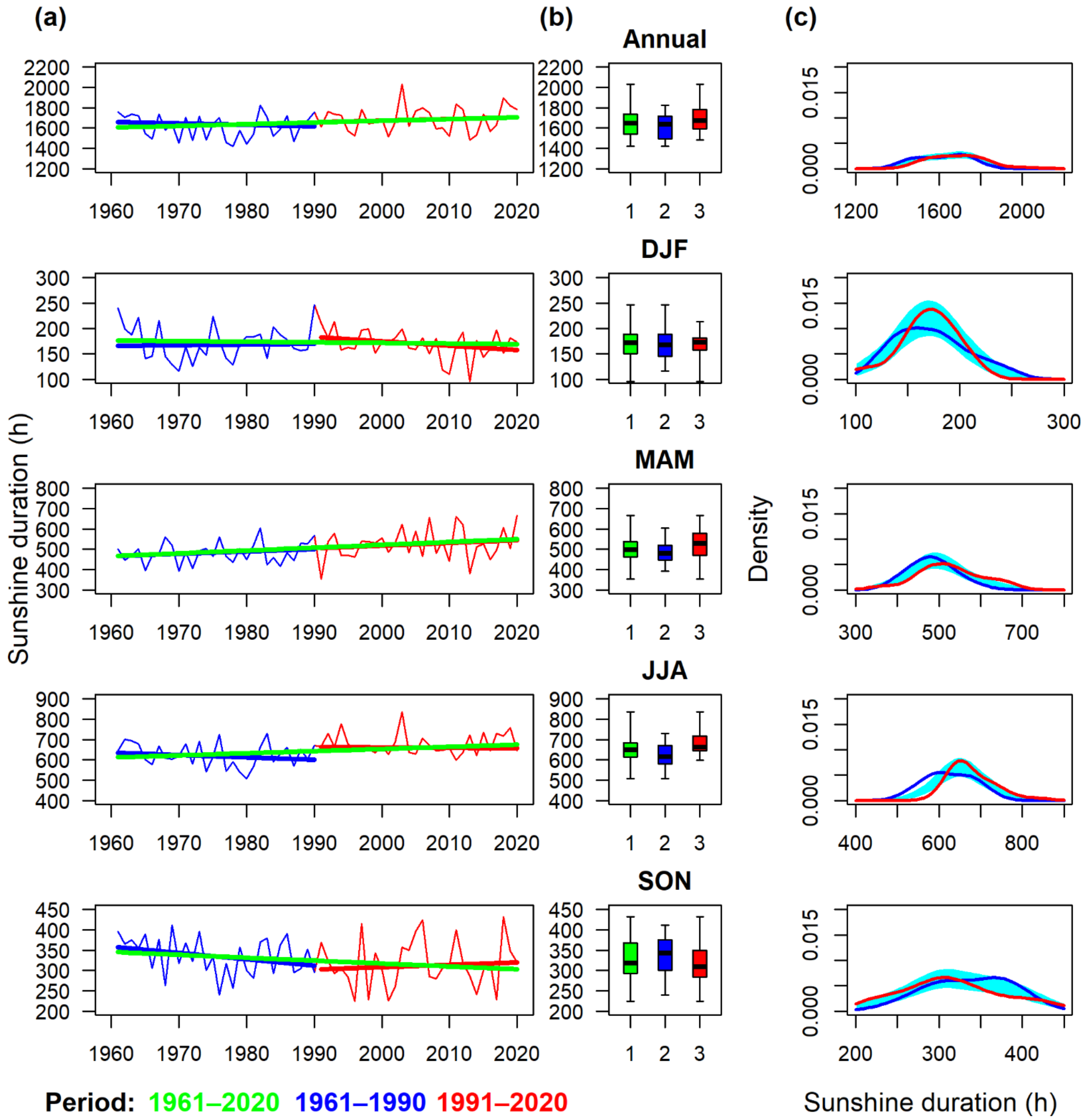

Figure 5. Mean annual and seasonal series of sunshine duration for the territory of the Czech Republic in the 1961–2020 period: (**a**) fluctuations with linear trends in the entire period, 1961–1990 and 1991–2020; (**b**) box plots (median, lower and upper quartile, minimum, and maximum) for 1961–2020 (1), 1961–1990 (2), and 1991–2020 (3); (**c**) the density distribution of the series in 1961–1990 and 1991–2020. The density curves outside the reference band (green–blue) indicate a significant difference in the two distributions (and vice versa).

3.3. Temperature

Mean annual, DJF, and MAM temperatures exhibited increasing trends during 1961–1990, while for JJA, there was no trend, and for SON, it was negative (Figure 6a). While none of these series experienced statistically significant linear trends, significant trends appeared in the annual, JJA, and SON series in the following 30 years (Table 3). Direct comparison of the two slope trends showed a significant difference only for SON temperatures. Mean annual and seasonal temperatures in the 1991–2020 period were higher between 1.5 °C (JJA) and 0.6 °C (SON) than during 1961–1960, and related differences in means between both 30-year intervals were statistically significant at the 0.05 significance level for all five series (Table 3). Similarly, values of 30-year box plots indicate a clear shift to higher values during 1991–2020 (Figure 6b), particularly for JJA and also for annual temperatures. No statistically significant differences were found in the variability of the above temperature series expressed by standard deviations in both periods (Table 3). Asymmetry of their distributions measured with skewness did not show any significant change. On the other hand, there is a statistically significant shift from negative to positive kurtosis in annual temperatures indicating distribution with heavier tails compared to normal. Under such a distribution, outlier probability occurrence is higher. As can also be seen from Figure 6c, density estimates differ significantly for annual, MAM, and JJA mean temperatures.

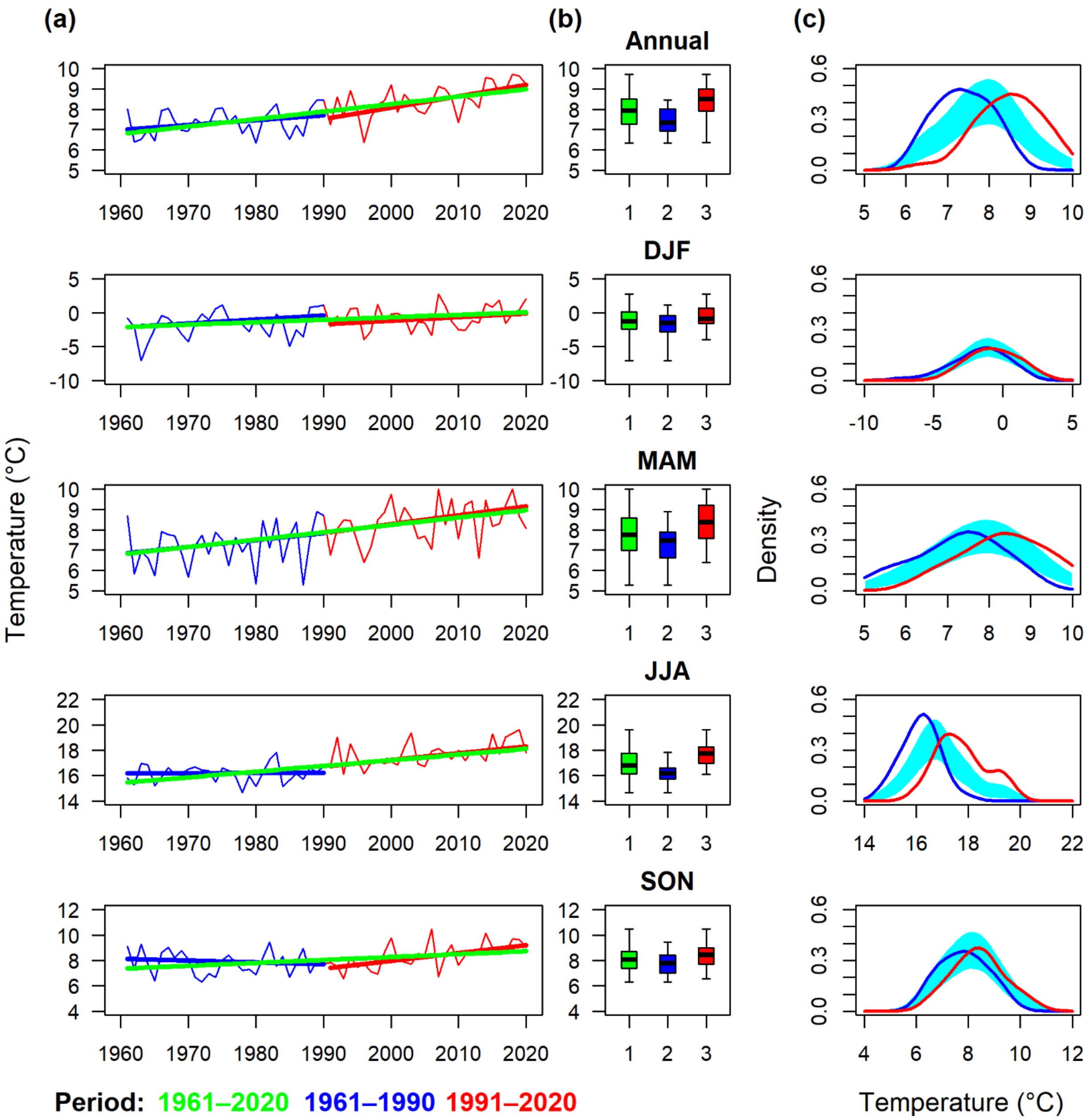

Figure 6. Mean annual and seasonal temperature series for the territory of the Czech Republic in the 1961–2020 period: (**a**) fluctuations with linear trends in the entire period, 1961–1990 and 1991–2020; (**b**) box plots (median, lower and upper quartile, minimum, and maximum) for 1961–2020 (1), 1961–1990 (2), and 1991–2020 (3); (**c**) the density distribution of the series in 1961–1990 and 1991–2020. The density curves outside the reference band (green–blue) indicate a significant difference in the two distributions (and vice versa).

Table 2. Selected statistical characteristics of mean annual (Ann) and seasonal (DJF, MAM, JJA, and SON) sunshine duration series in the Czech Republic during the 1961–1990 (A) and 1991–2020 (B) periods: means are in hours, coefficients of variation (CV) in %, linear trends in hours/10 years (none statistically significant at the 0.05 significance level). An asterisk * indicates statistically significant differences of a given characteristic between two 30-year periods.

Season	Period	Mean		CV	Skewness		Kurtosis	Slope
Ann	A	1613.9	*	7.3	−0.14		−1.33	−15.4
	B	1687.1	*	7.6	0.50		0.22	15.3
DJF	A	164.4		19.2	0.47	*	−0.34	1.5
	B	168.7		16.4	−0.84	*	0.94	−8.5
MAM	A	482.5	*	10.8	0.28		−0.20	11.6
	B	524.9	*	14.8	0.01		−0.10	13.6
JJA	A	624.8	*	9.3	−0.04		−0.81	−11.9
	B	677.8	*	7.8	1.18		1.40	–2.2
SON	A	335.7		13.9	−0.26		−0.98	−15.8
	B	315.9		18.8	0.29		−0.52	5.8

Table 3. Selected statistical characteristics of mean annual (Ann) and seasonal (DJF, MAM, JJA, and SON) temperature series in the Czech Republic in the 1961–1990 (A) and 1991–2020 (B) periods: means and standard deviations (SD) are in °C, linear trends in °C/10 years (in bold statistically significant at the 0.05 significance level). An asterisk * indicates statistically significant differences of a given characteristic between two 30-year periods.

Season	Period	Mean		SD	Skewness	Kurtosis		Slope	
Ann	A	7.4	*	0.6	0.01	−1.08	*	0.25	
	B	8.5	*	0.8	−0.48	0.23	*	**0.56**	
DJF	A	−1.7	*	2.0	−0.66	0.45		0.59	
	B	−0.7	*	1.7	0.05	−0.67		0.53	
MAM	A	7.3	*	1.0	−0.34	−0.68		0.34	
	B	8.4	*	1.0	−0.18	−0.71		0.44	
JJA	A	16.2	*	0.7	0.02	0.26		0.02	
	B	17.7	*	1.0	0.41	−0.66		**0.53**	
SON	A	7.8	*	0.9	0.09	−0.96		−0.14	*
	B	8.4	*	1.0	0.18	−0.30		**0.62**	*

Similar trends, as with mean temperatures, appear in the series of annual and seasonal mean maximum temperatures (Figure 7a). While in the 1961–1990 period, none of the annual and seasonal linear trends were statistically significant, in the following 30 years, every series except DJF experienced statistically significant trends (c. 0.6–0.7 °C/10 years) (Table 4). When comparing the two sub-periods, linear trends were significantly different only in SON. Annual and seasonal mean maximum temperatures increased during 1991–2020 compared with the preceding 30 years between 1.9 °C (JJA) and 0.4 °C (SON), and except SON, these differences were statistically significant. The reported period also exhibited a particular shift to higher values in JJA and annual box plots (Figure 7b). Variability of mean maximum temperatures expressed by the standard deviation did not differ in statistical significance between the 30-year periods, and the same result followed from the comparison of the higher-order moments (characterizing asymmetry and sharpness of the distribution) (Table 4). Density estimates, however, were significantly different for annual, MAM, and JJA mean maximum temperatures (Figure 7c).

Additionally, a series of annual and seasonal mean minimum temperatures (Figure 8a,b) express features described above for mean and mean maximum temperatures. Non-significant linear trends in all series during 1961–1990 were replaced by statistically significant increases in mean minimum temperatures for annual, JJA, and SON series (c. 0.5–0.6 °C/10 years) in the following 30 years (Table 5). Linear trend slopes were significantly different in JJA and SON mean minimum temperatures. The annual and seasonal mean minimum temperatures in 1991–2020, compared to 1961–1990, were higher with differences between 1.4 °C (JJA) and 0.7 °C (SON); these were statistically significant for annual, MAM, JJA, and SON series. No significant differences in variability expressed in standard deviations were detected between both the 30-year periods. Density estimates of mean minimum temperature series were significantly different for annual, MAM, and especially JJA series (Figure 8c), and there was no substantial difference in skewness and kurtosis between the periods analysed (Table 5).

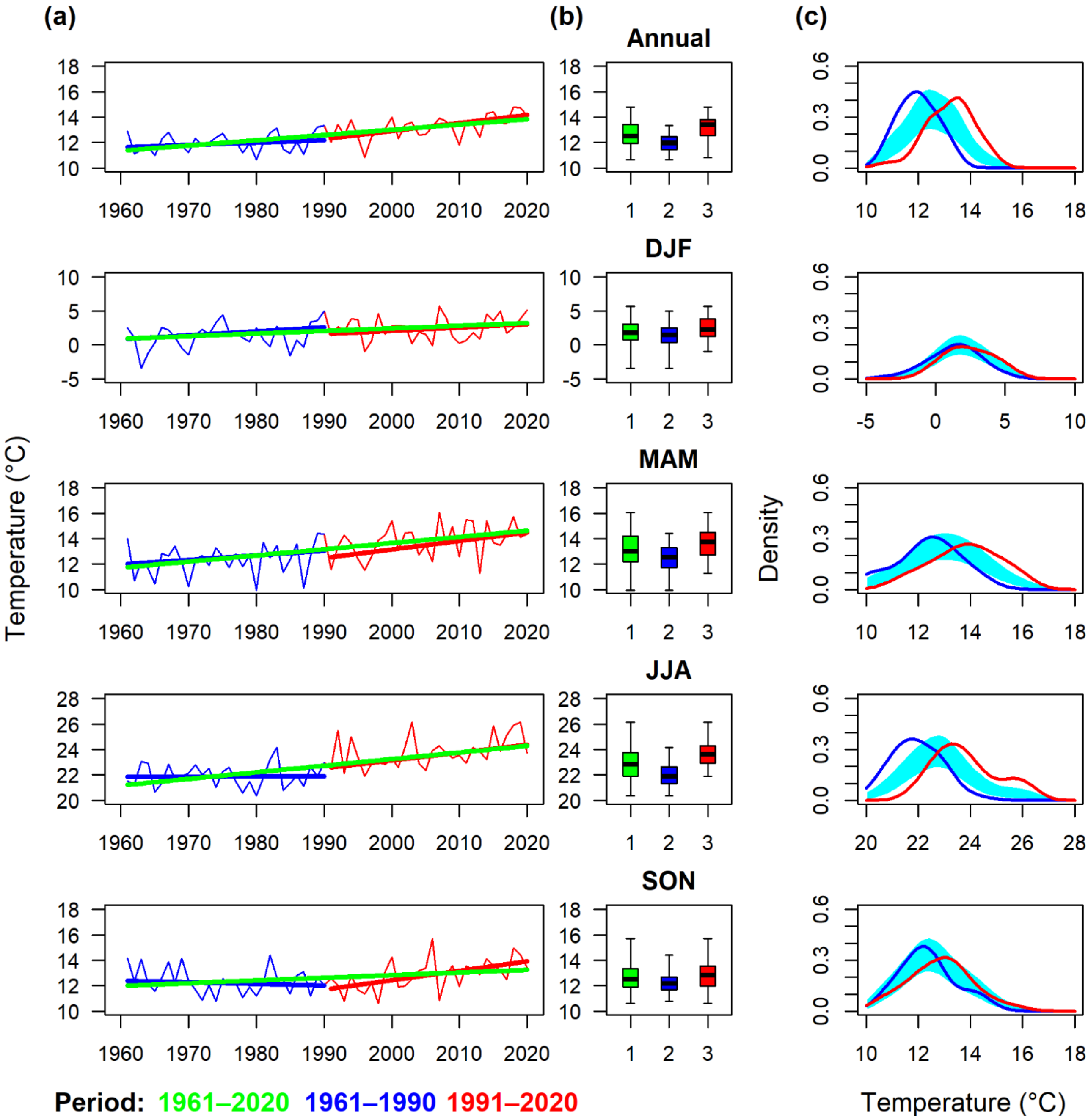

Figure 7. Annual and seasonal mean maximum temperature series for the territory of the Czech Republic in the 1961–2020 period: (**a**) fluctuations with linear trends in the entire period, 1961–1990 and 1991–2020; (**b**) box plots (median, lower and upper quartile, minimum, and maximum) for 1961–2020 (1), 1961–1990 (2), and 1991–2020 (3); (**c**) the density distribution of the series in 1961–1990 and 1991–2020. The density curves outside the reference band (green–blue) indicate a significant difference in the two distributions (and vice versa).

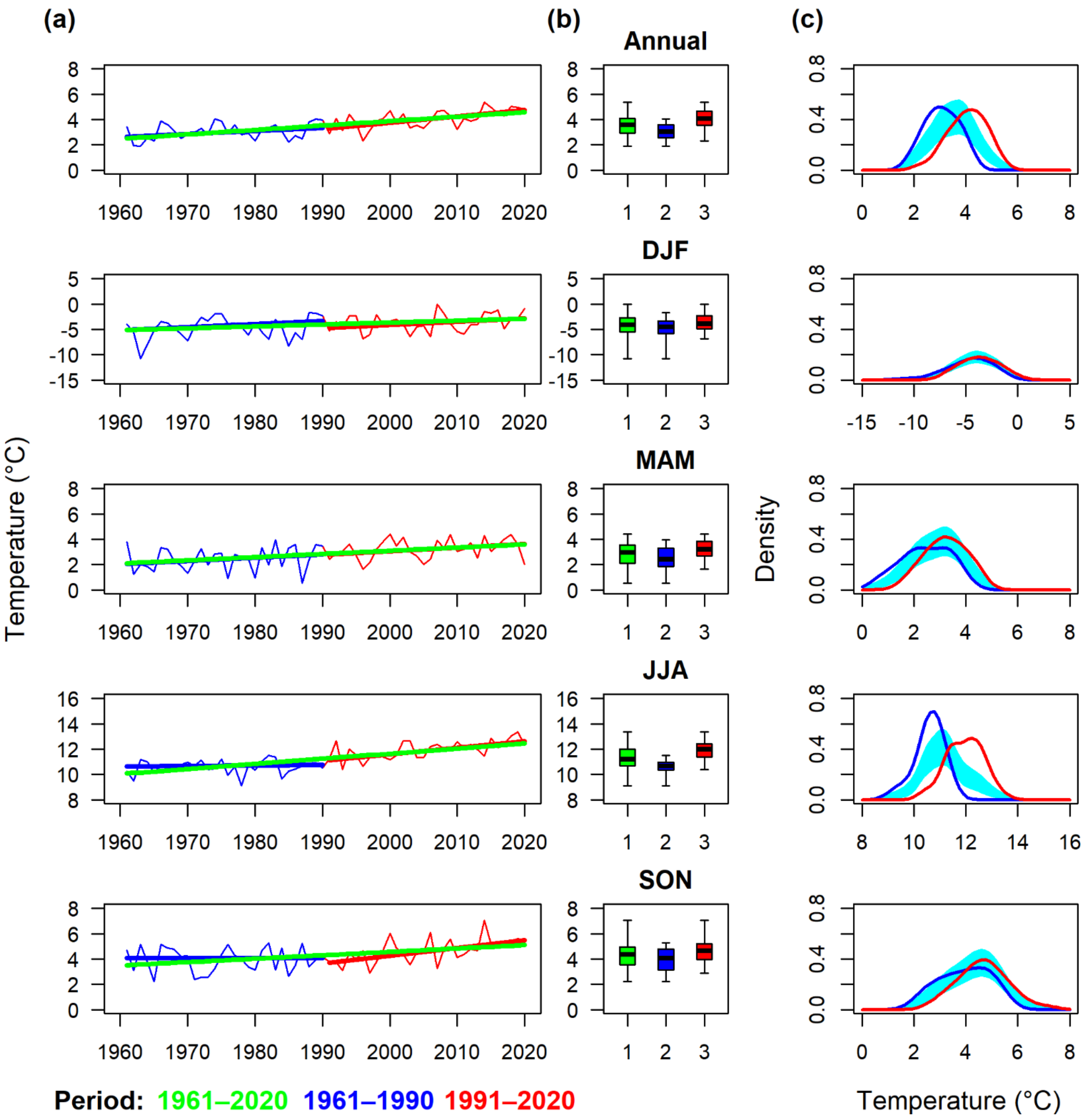

Figure 8. Annual and seasonal mean minimum temperature series for the territory of the Czech Republic in the 1961–2020 period: (**a**) fluctuations with linear trends in the entire period, 1961–1990 and 1991–2020; (**b**) box plots (median, lower and upper quartile, minimum, and maximum) for 1961–2020 (1), 1961–1990 (2), and 1991–2020 (3); (**c**) the density distribution of the series in 1961–1990 and 1991–2020. The density curves outside the reference band (green–blue) indicate a significant difference in the two distributions (and vice versa).

3.4. Humidity

All annual and seasonal series of mean relative humidity indicated in two 30-year periods decreasing tendencies (Figure 9a), which are expressed by linear trends (between –0.2%/10 years and –1.9%/10 years). They were statistically significant only for MAM in both periods and for annual values in 1961–1990 (Table 6). When comparing the slopes of the trend lines for the two sub-periods, no significant differences were found. Means of annual and seasonal relative humidity series decreased between 1961–1990 and 1991–2020 by 1–3% (but in SON, it increased by 1%); related differences were statistically significant in annual and seasonal series except for SON. On the other hand, the variability expressed by the standard deviation grew between two 30-year periods, but this increase was statistically significant only for annual and MAM series. Both the box plots (Figure 9b) and the density functions (Figure 9c) show a clear shift of the whole distribution of the relative humidity to lower values. This shift was statistically significant for annual and all seasonal series except SON. However, differences between both 30-year periods were not statistically significant for any of the coefficients of skewness or kurtosis (Table 6).

Table 4. Selected statistical characteristics of annual (Ann) and seasonal (DJF, MAM, JJA, and SON) mean maximum temperature series in the Czech Republic in the 1961–1990 (A) and 1991–2020 (B) periods: means and standard deviations (SD) are in °C, linear trends in °C/10 years (in bold statistically significant at the 0.05 significance level). An asterisk * indicates statistically significant differences of a given characteristic between two 30-year periods.

Season	Period	Mean		SD	Skewness	Kurtosis	Slope	
Ann	A	12.0	*	0.7	0.14	−0.80	0.20	
	B	13.2	*	0.9	−0.46	0.43	**0.63**	
DJF	A	1.3	*	1.9	−0.34	0.29	0.58	
	B	2.4	*	1.7	0.08	−0.78	0.50	
MAM	A	12.4	*	1.2	−0.37	−0.38	0.36	
	B	13.8	*	1.3	−0.20	−0.65	**0.67**	
JJA	A	21.9	*	0.9	0.32	−0.19	0.02	
	B	23.8	*	1.2	0.59	−0.54	**0.62**	
SON	A	12.4		1.0	0.54	−0.22	–0.14	*
	B	12.8		1.2	0.16	0.03	**0.74**	*

Table 5. Selected statistical characteristics of annual (Ann) and seasonal (DJF, MAM, JJA, and SON) mean minimum temperature series in the Czech Republic in the 1961–1990 (A) and 1991–2020 (B) periods: means and standard deviations (SD) are in °C, linear trends in °C/10 years (in bold statistically significant at the 0.05 significance level). An asterisk * indicates statistically significant differences of a given characteristic between two 30-year periods.

Season	Period	Mean		SD	Skewness	Kurtosis	Slope	
Ann	A	3.1	*	0.6	−0.10	−0.91	0.24	
	B	4.0	*	0.7	−0.37	−0.22	**0.51**	
DJF	A	−4.7		2.2	−0.73	0.49	0.59	
	B	−3.7		1.8	0.05	−0.71	0.64	
MAM	A	2.4	*	0.9	−0.28	−0.85	0.24	
	B	3.2	*	0.8	−0.15	−0.80	0.29	
JJA	A	10.6	*	0.6	−0.88	0.95	0.05	*
	B	12.0	*	0.7	−0.17	−0.27	**0.51**	*
SON	A	3.9	*	1.0	−0.24	−1.15	0.00	*
	B	4.6	*	0.9	0.28	0.30	**0.62**	*

3.5. Precipitation

Although fluctuations in annual and seasonal mean precipitation totals in two 30-year periods indicate slight increases (DJF, SON) or decreases (annual, MAM, JJA) in linear trends (Figure 10a), none of them are statistically significant (Table 7). Due to quite similar precipitation tendencies, there are no significant differences in the two sub-period trends in any season. Additionally, the values of 30-year box plots showed relatively similar patterns (Figure 10b). Differences in mean seasonal and annual precipitation totals between 1961–1990 and 1991–2020 were relatively small (maximally 17 mm in favour of the second period in annual series and 12 mm in SON), and they were not statistically significant at the 0.05 significance level (Table 7). Coefficients of variation indicate higher differences in precipitation variability in the last 30-years, particularly for MAM and SON, although these differences were not statistically significant. Similarly, we found no significant differences either in density functions (Figure 10c) or in the higher-order moments. This indicates that the precipitation totals dominate high variability without evident changes in their probability distribution. The only exception is a significant shift from highly positive to negative kurtosis in the case of the MAM series. This means that in the MAM precipitation totals measured during the later sub-period, a lower probability of the extremely high values can be found compared to the earlier sub-period.

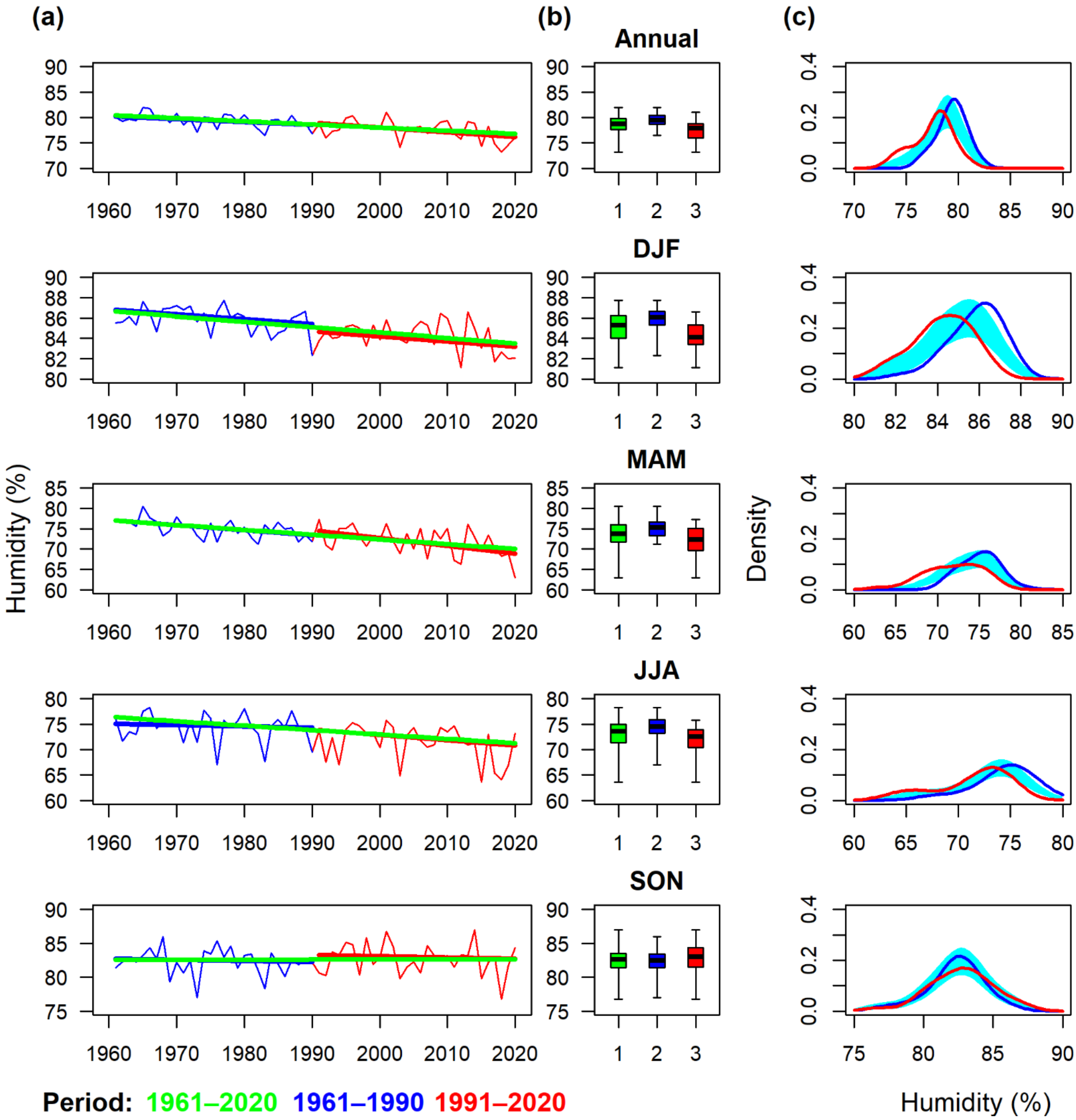

Figure 9. Annual and seasonal mean relative humidity series for the territory of the Czech Republic in the 1961–2020 period: (**a**) fluctuations with linear trends in the entire period, 1961–1990 and 1991–2020; (**b**) box plots (median, lower and upper quartile, minimum, and maximum) for 1961–2020 (1), 1961–1990 (2), and 1991–2020 (3); (**c**) the density distribution of the series in 1961–1990 and 1991–2020. The density curves outside the reference band (green–blue) indicate a significant difference in the two distributions (and vice versa).

Table 6. Selected statistical characteristics of annual (Ann) and seasonal (DJF, MAM, JJA, and SON) mean relative humidity series in the Czech Republic in the 1961–1990 (A) and 1991–2020 (B) periods: means and standard deviations (SD) are in %, linear trends in %/10 years (in bold statistically significant at the 0.05 significance level). The asterisk * indicates statistically significant differences of a given characteristic between two 30-year periods.

Season	Period	Mean		SD		Skewness	Kurtosis	Slope
Ann	A	79	*	1.3	*	−0.35	0.11	**−0.6**
	B	78	*	1.9	*	−0.55	−0.21	−1.0
DJF	A	86	*	1.3		–0.84	0.75	–0.5
	B	84	*	1.4		−0.43	−0.35	−0.5
MAM	A	75	*	2.2	*	0.06	−0.16	**−1.3**
	B	72	*	3.5	*	−0.52	−0.10	**−1.9**
JJA	A	74	*	2.8		−1.02	0.96	−0.2
	B	71	*	3.5		−0.96	−0.24	−1.0
SON	A	82		1.9		−0.79	1.43	−0.2
	B	83		2.2		−0.31	0.58	−0.2

Table 7. Selected statistical characteristics of annual (Ann) and seasonal (DJF, MAM, JJA, and SON) series of mean precipitation totals in the Czech Republic in the 1961–1990 (A) and 1991–2020 (B) periods: means are in mm, coefficients of variation (CV) in %, linear trends in mm/10 years (none statistically significant at the 0.05 significance level). An asterisk * indicates statistically significant differences of a given characteristic between two 30-year periods.

Season	Period	Mean	CV	Skewness	Kurtosis		Slope
Ann	A	681	12.8	0.44	–0.84		−2.4
	B	699	12.7	0.01	0.06		−1.7
DJF	A	128	25.6	−0.31	–0.16		6.8
	B	130	25.0	−0.33	–0.74		3.2
MAM	A	162	18.7	1.60	4.09	*	−8.1
	B	159	23.3	0.50	–0.55	*	−3.0
JJA	A	245	21.8	0.48	0.97		−3.0
	B	252	21.6	0.12	–0.42		−5.5
SON	A	146	23.5	0.56	0.95		1.4
	B	158	26.5	0.94	1.37		1.8

3.6. Wind Speed

Figure 11a demonstrates a clear reversal in annual and seasonal mean wind speeds when the relatively stable patterns of 1961–1990 were replaced from the 1990s by a drop in mean wind speeds. Annual and seasonal mean wind speeds dropped by 0.1–0.3 m s^{-1} in 1991–2020 compared to the preceding 30 years, and all of these differences were statistically significant (Table 8). While in 1961–1990, none of the calculated annual and seasonal linear trends were statistically significant at the 0.05 significance level, in the second 30-year period, all except DJF were decreasing and statistically significant (c. 0.1 m s^{-1}/10 years). Similarly, differences in trend slopes were significant for all series with the exception of DJF. Variability characterised by the coefficient of variation (Table 8) significantly increased for the annual and MAM series in the second period and the same two series indicated a significant change in asymmetry as the skewness increased from negative values to positive ones. This means a tendency toward a longer and fatter tail on the right side of the distribution where the extremely large values of mean wind speed may occur. Differences in the distribution of mean wind speeds are quite substantial. Except for DJF, the annual and remaining seasonal series show important declines in percentile values (Figure 11b). For example, the values of the upper quartile during 1991–2020 are close to or deeply below the values of lower quartiles over the preceding 30 years. It is a clear indication of important changes in the character of the distribution of annual and seasonal mean wind speeds that a shift is shown to lower values in density functions. This is remarkable, particularly for the annual and MAM series (Figure 11c). Differences in density functions were significant for all series.

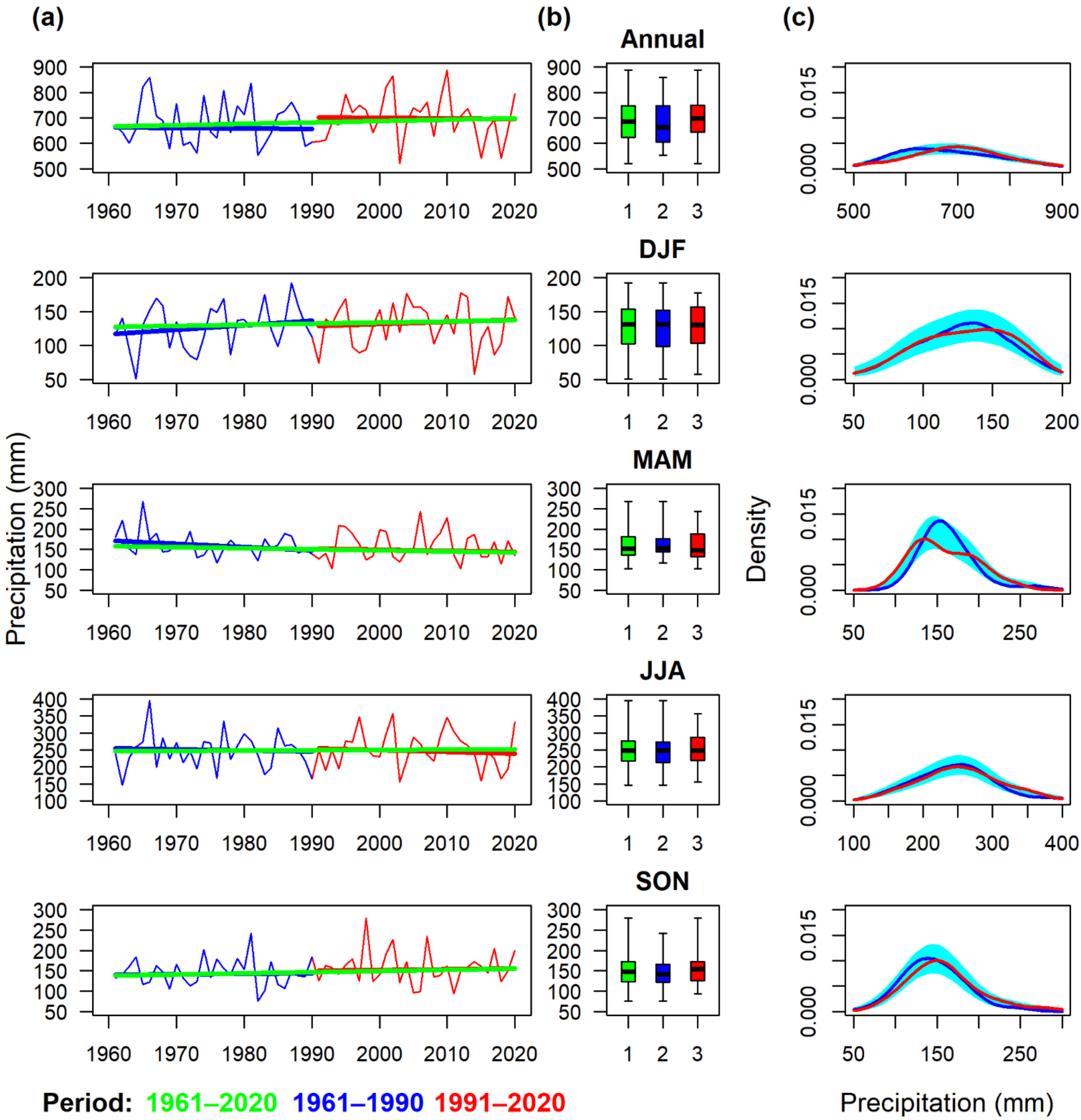

Figure 10. Annual and seasonal series of mean precipitation totals for the territory of the Czech Republic in the 1961–2020 period: (**a**) fluctuations with linear trends in the entire period, 1961–1990 and 1991–2020; (**b**) box plots (median, lower and upper quartile, minimum, and maximum) for 1961–2020 (1), 1961–1990 (2), and 1991–2020 (3); (**c**) the density distribution of the series in 1961–1990 and 1991–2020. The density curves outside the reference band (green–blue) indicate a significant difference in the two distributions (and vice versa).

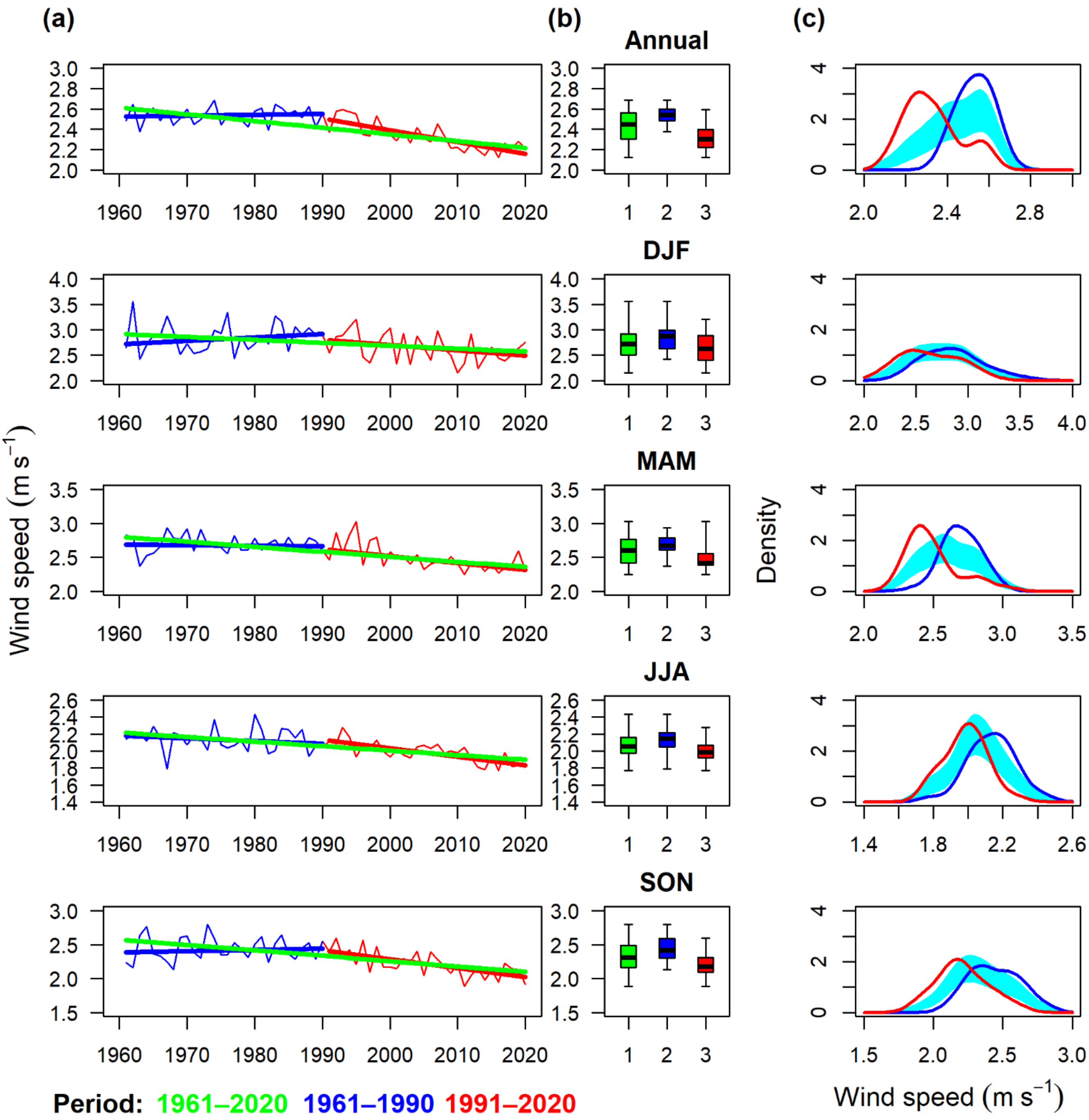

Figure 11. Annual and seasonal series of mean wind speed for the territory of the Czech Republic in the 1961–2020 period: (**a**) fluctuations with linear trends in the entire period, 1961–1990 and 1991–2020; (**b**) box plots (median, lower and upper quartile, minimum, and maximum) for 1961–2020 (1), 1961–1990 (2) and 1991–2020 (3); (**c**) the density distribution of the series in 1961–1990 and 1991–2020. The density curves outside the reference band (green–blue) indicate a significant difference in the two distributions (and vice versa).

3.7. Spatial Patterns

While preceding sections demonstrated differences in climate variables between two 30-year periods averaged for the whole CR territory, Figure 12 shows spatial patterns of differences between 1991–2020 and 1961–1990 for their annual series. Positive differences indicate increases in 1991–2020 compared to the preceding 30 years, and negative ones indicate decreases. As for the three temperature variables, they show very consistent spatial patterns with only positive differences, confirming important increases in temperatures during the last 30 years. In the case of mean temperatures, the highest increases appeared in central Bohemia and the lowest, especially in northern Moravia and Silesia (M&S), and in northern and southern Bohemia (Figure 12b). For maximum temperatures, the highest positive differences occurred in the northern half of the CR territory (Figure 12c), while in the case of minimum temperatures, the highest increases created a belt in the southern part of the CR territory, extending partly to central Bohemia and central M&S (Figure 12d). Compared with temperatures, the spatial distribution of other climate variables shows slightly complicated patterns. While an increase in sunshine duration in the last 30 years prevails over the CR territory (particularly in northwestern Bohemia stretching to the south, with other spots in eastern Bohemia and M&S), some border areas show decreases in sunshine duration (particularly in western Bohemia and southeastern M&S (Figure 12a). In the case of relative humidity, its decreases occurred over the whole CR territory except for a few small areas with positive differences (Figure 12e). The highest decreases appear in two larger areas in Bohemia and one in M&S. Precipitation totals exhibit prevailingly positive differences, however, with a belt of negative differences stretching from central to eastern Bohemia and further to M&S (Figure 12f). In the case of wind speed, a belt of increasing values in a south-north direction in the eastern part of Bohemia is interesting; it separates the CR territory into two parts with decreasing wind speeds (Figure 12g).

Table 8. Selected statistical characteristics of mean annual (Ann) and seasonal (DJF, MAM, JJA, and SON) wind speed series in the Czech Republic in the 1961–1990 (A) and 1991–2020 (B) periods: means are in m s^{-1}, coefficients of variation (CV) in %, linear trends in m s^{-1}/10 years (in bold statistically significant at the 0.05 significance level). An asterisk * indicates statistically significant differences of a given characteristic between two 30-year periods.

Season	Period	Mean		CV		Skewness		Kurtosis	Slope	
Ann	A	2.5	*	3.2	*	−0.15	*	−0.83	0.01	*
	B	2.3	*	5.7	*	0.62	*	−0.46	**−0.12**	*
DJF	A	2.9	*	9.7		0.52		−0.02	0.07	
	B	2.6	*	10.4		0.22		−0.95	−0.10	
MAM	A	2.7	*	4.7	*	−0.13	*	0.20	−0.01	*
	B	2.5	*	7.6	*	1.26	*	1.17	**−0.10**	*
JJA	A	2.1	*	6.3		−0.17		0.63	−0.03	*
	B	2.0	*	6.0		0.07		0.06	**−0.10**	*
SON	A	2.4	*	7.1		0.22		−0.76	0.02	*
	B	2.2	*	8.2		0.32		−0.22	**−0.13**	*

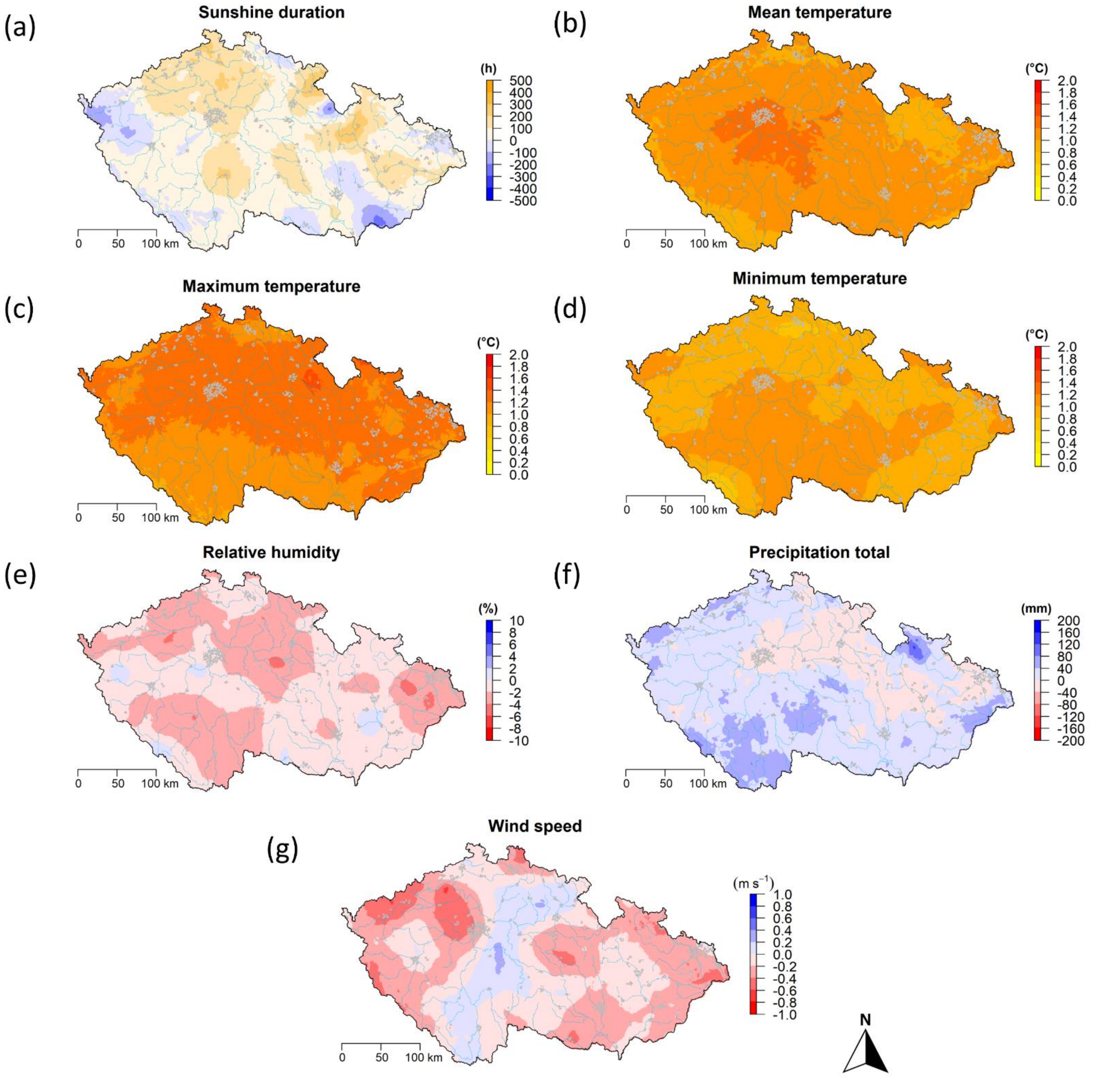

Figure 12. Spatial distribution of differences between the 1991–2020 and 1961–1990 periods over the territory of the Czech Republic for the annual series of selected climate variables: (**a**) sunshine duration, (**b**) mean temperature, (**c**) maximum temperature, (**d**) minimum temperature, (**e**) relative humidity, (**f**) precipitation total, and (**g**) wind speed. The individual maps were created based on the number of stations specified in Section 2.2.

4. Discussion

While neither 30-year sub-period indicated significant changes in the frequencies of days with the occurrence of the directional circulation types (according to the objective classification, Section 3.1), significant differences appeared for the other two groups of circulation types. Mean frequencies of days with anticyclonic types between both sub-periods increased significantly in the annual and seasonal series except SON and experienced statistically significant increasing linear trends in JJA and the annual series during 1961–1990. In the case of cyclonic types, the related changes were opposite and significant in terms of corresponding means for MAM, JJA, and the annual series, and with decreasing linear trends in JJA, SON, and annual frequencies. This is consistent with Trnka et al. [33], who analysed long-term circulation patterns in central Europe based on "Grosswetterlagen" (GWL) of the Hess–Brezowsky classification in the 1881–2005 period. Dividing the GWL types into dry and wet, they discovered a steady increase in the April–June frequency of dry types since 1940 from c. 30% to c. 50% after 1980. The increment of anticyclonic types in JJA over central Europe based on the Hess-Brezowsky catalogue was also reported by Cahynová and Huth [34]. Lhotka et al. [35] used the same objective classification as in the present study to analyse circulation patterns in the CR in relation to drought indices. By dividing the circulation types only into dry types (all anticyclonic together with E, SE, and S) and wet types (all cyclonic together with N, NE, SW, W, NW, and U), they found a statistically significant increasing trend in the frequency of dry types for the vegetation period (April–September) in the 1948–2018 period.

From this analysis, it follows that while the first normal period 1961–1990 was relatively stable, as it was characterised by statistically non-significant linear trends of climatic variables, the situation has changed in the last 30 years. In terms of sunshine duration (Section 3.2), its increase was associated with a heightened frequency of anticyclonic circulation types. The prolonged sunshine duration during 1991–2020 compared to the preceding 30 years in the CR was detected in all series (statistically significant for the annual, MAM, and JJA) except SON, when a decrease in the frequency of anticyclonic types was observed. However, all annual and seasonal linear trends in both the 30-year periods were non-significant. The sunshine duration changes between the two 30-year periods were influenced by a dimming period located by Wild [36] between the 1950s and the 1980s, with a decline in solar radiation (primarily due to a heightened presence of anthropogenic aerosols in the atmosphere), and by a brightening starting afterward with an increase in solar radiation. Observed trends in the CR are in general agreement with other European studies (e.g., [37–41]).

Increasing linear trends for mean, maximum, and minimum temperatures (Section 3.3) during 1961–1990 became statistically significant in the following 30 years, particularly pronounced in JJA and SON, which was also reflected in the annual series. DJF trends remained statistically non-significant, and for MAM, only an increase in the maximum temperature was statistically significant. This is in clear agreement with advanced global warming (e.g., [5–8]) and temperature increases observed everywhere in Europe (e.g., [11,40,42–45]). Despite the changes in the character of the distribution (density curves, percentiles, skewness, kurtosis), these growing trends were not reflected in significant increases in temperature variability as expressed by the standard deviation.

The comparison of mean, maximum, and minimum temperatures in two 30-year normal periods (see Section 3.3) can be complemented by 13 characteristics of temperature extremes analysed by Zahradníček et al. [12]. The "warmer" temperature extremes were generally higher and more frequent in 1991–2020, while for 1961–1990, this was valid for "cold" temperature extremes. Statistically, significant higher means in 1991–2020 were recorded for absolute maximum temperatures, numbers of summer and tropical days, days with tropical nights, days of heatwaves and warm anomalies, and day-to-day changes in minimum temperatures, while statistically significant lower means in 1961–1990 concerning numbers of frost and ice days and days of cold anomalies. As for series variability expressed by the standard deviation, it was significantly higher in 1991–2020 for numbers of tropical days, days with tropical nights, days of heatwaves, and warm anomalies; the opposite case was seen only for the days of cold anomalies.

Connections between temperature and circulation patterns in (central) Europe were broadly studied (e.g., [46–48]). However, the link between temperature and atmospheric circulation is strongest in DJF, when more than half of the warming was attributable to changes in circulation [34]. Combined with a strong dependence of precipitation totals on circulation types in the CR (e.g., [17,49–51]), changes in atmospheric circulation can even affect complex events such as severe soil drought periods (e.g., [18,33]). Therefore, long-term changes in circulation may influence the course of climate change in central Europe and propagate to other related variables, such as relative humidity.

Although annual and seasonal series of mean relative humidity (Section 3.4) showed decreasing trends in both 30-year periods, they were non-significant except MAM and annual values in the first period. However, differences in two 30-year means were all statistically significant except SON. The variability of mean relative humidity grew statistically significant only for the annual and MAM series in 1991–2020. While the box plots and the density functions demonstrate a clear shift of the relative humidity to lower values (significant except SON), no significant differences appeared in any of the skewness or kurtosis coefficients. Decreasing trends in the relative humidity of both 30-year normal periods appearing in the CR are in solid agreement with similar prevailing trends reported in many European studies (e.g., [52–57]) and are also reflected in projected future changes [58].

A closer relationship of some variables expressed by Pearson correlation coefficients in 1991–2020 compared to 1961–1990 (Table 9) is an interesting aspect of comparing these two 30-year normal periods. Comparing sunshine duration and mean maximum temperatures, an existing relationship is evident in the annual, MAM, JJA, and SON series. A significant correlation between mean temperature and relative humidity appears in the annual, MAM, and JJA series, while in DJF and SON, the correlation coefficients are non-significant.

Table 9. Pearson correlation coefficients of annual (Ann) and seasonal (DJF, MAM, JJA, and SON) series between sunshine duration (SD) and mean maximum temperatures (TMAX) and between mean air temperature (TAVG) and relative humidity (RH) in the CR during the 1961–2020, 1991–1990, and 1991–2020 periods. Statistically significant correlation coefficients at the 0.05 significance level are in bold.

Period	Ann	DJF	MAM	JJA	SON
		SD versus TMAX			
1961–2020	**0.58**	0.11	**0.70**	**0.80**	**0.46**
1961–1990	**0.55**	0.18	**0.51**	**0.75**	**0.47**
1991–2020	**0.52**	0.08	**0.78**	**0.80**	**0.55**
		TAVG versus RH			
1961–2020	**−0.67**	**−0.28**	**−0.57**	**−0.77**	−0.04
1961–1990	**−0.39**	−0.12	−0.27	**−0.54**	0.11
1991–2020	**−0.62**	−0.22	**−0.58**	**−0.84**	−0.22

Both 30-year normal periods can be considered representative of precipitation totals. As shown in Section 3.5, differences in mean annual and seasonal totals are not statistically significant. Moreover, statistically non-significant are linear trends calculated for the annual and seasonal precipitation series in both normal periods. Generally, statistically non-significant trends and those significant only limited to fewer analysed stations in precipitation totals are confirmed by many European papers (e.g., [10,59–62]).

Statistically significant decreases in the mean annual and seasonal wind-speed series in 1991–2020, compared with non-significant trends in the preceding 30-year period (Section 3.6), agree with the concept of (wind) "stilling". This refers to observed decreases in wind speed recognised in the last 30–50 years in mid-latitudes over land worldwide, attributed to different factors, in particular to increasing land-surface roughness (e.g., [63–68]).

Besides the evident effects of changes in the frequency of anticyclonic and cyclonic circulation types on climate variables in both 30-year periods, the direction of airflow influencing its temperature and humidity and contributing to regional differences within the CR [17] is very important. Grouping circulation types regardless of their (anti-)cyclonality and excluding types A, C, and U, there appear to be annually statistically significant increases in types with southwestern airflow and significant decreases in those with northeast and southeastern airflow during the 1961–2020 period (not shown). As for individual seasons, DJF was characterised by significant increases in types with western airflow and significant decreases in those with southeastern and southern airflow. Significant increases also appeared in types with northern airflow in MAM and with southwestern airflow in JJA.

Despite a careful homogenisation of all the series of the analysed climate variables, we should be aware of potential effects in meteorological measurements connected with the change from standard instruments to automatic sensors, as was documented for several variables in the CR. For example, Valík et al. [69] showed that the "standard" Stoke–Campbell sunshine recorder at five meteorological stations measured higher sunshine duration totals than the automatic sensors activated in the mid-1990s. Mozny et al. [70] brought attention to the change from standard thermometer screens (TS) to the multiplate radiation shields (MRS) used in automatic measurements, when the mean temperature differences on radiative days could vary between 0.3 °C and 2.8 °C. Measurements from MRS yielded the mean and minimum temperatures lower in DJF and higher in JJA compared to TS, while maximum temperatures were lower throughout the year. Valík et al. [71] showed for two rain-gauge stations that precipitation totals measured by new tipping-bucket rain-gauges were lower than those measured by a "standard" METRA 886 rain-gauge. Brázdil et al. [68] analysed two meteorological stations and concluded that wind stilling could not be attributed only to the massive involvement of automatic wind-speed measurements in the past two decades compared to the preceding manual measurements with "standard" anemographs.

Linear trends derived for two 30-year normal periods may sometimes differ from the trend for the whole 60-year period 1961–2020 (Table 10). This is evident especially for JJA sunshine duration when trends for both sub-periods are negative, but the trend for the whole period is significantly positive. Similarly, negative trends of both normal periods in annual and JJA precipitation totals are changed to positive trends for the whole 60-year period. There is an agreement in the sign of trends in only one of two 30-year periods with resulting trends appearing for annual, DJF, and SON sunshine duration; mean maximum and minimum SON temperatures; and annual, DJF, and SON wind speeds. On the other hand, in the case of annual and seasonal series of relative humidity, all trends are negative independently from 30-year or 60-year periods. In the case of frequencies of circulation types, positive trends in both 30-year periods agree with 60-year trends for anticyclonic circulation types in all series except DJF, while for cyclonic circulation types, such agreement appears only in MAM, but with a negative sign of trends.

The opposite linear trends are obviously related to the relatively short series of analysed sub-periods. For them, the trend estimates must be considered less stable in spite of the fact that we applied a non-parametric Theil–Sen estimator that should be more robust regarding the outliers and also to the limited length of the series. Thus the trend slope of the 30-year sub-periods is used here primarily as an indicator of differences between them. The overall tendencies in the development of the analysed variables are evident from the linear trend estimates for the 60-year period 1961–2020. In this sense, the three temperature variables particularly show significant increases in all seasons and in the annual series (Table 10). Similarly, the wind speed and relative humidity series (except SON) show significant decreases in all series. On the other hand, none of the precipitation series show significant linear trends. Clear seasonality is evident in the case of the sunshine duration series. Significant increases were found for the MAM and JJA series, while insignificant decreases were typical for DJF and SON values. As for circulation types, they naturally show opposite tendencies for anticyclonic and cyclonic types. While for the anticyclonic types, the overall trends are significantly increasing in MAM, JJA, and the annual series, they are significantly decreasing in the same series for cyclonic circulation types.

The synergy effect of significantly increasing annual and seasonal temperatures with decreases in relative humidity and wind speed, together with non-significant changes in precipitation totals in 1991–2020, can be considered as the main triggers of the meteorological drought. This drought intensified over the territory of central Europe (e.g., [72,73]) and of the CR in the last decades (e.g., [74]), particularly in the 2010s (e.g., [75,76]). It resulted in several serious impacts, including an increased mortality during more frequent and severe heat-waves (e.g., [77,78]), increased soil-droughts (e.g., [18,74,76,79]), increasing risk of wildfire occurrence (e.g., [80]), and disastrous bark-beetle infestations devastating large forest areas (e.g., [73,81]). Moreover, it seems that the intensity of drought was exceptional not only in the context of the instrumental period (e.g., [72,82,83]) but also over much longer time scales (e.g., [84–86]).

Table 10. Linear trends of selected annual (Ann) and seasonal (DJF, MAM, JJA, and SON) series of circulation types and climatic variables (Var.) in 1961–2020 (a) in comparison with signs of linear trends (+ positive, − negative, 0 no trend) in two 30-year normal periods, 1961–1990 and 1991–2020 (b): ACT—anticyclonic circulation types (days/10 years), CCT—cyclonic circulation types (days/10 years), DCT—directional circulation types (days/10 years), SD—sunshine duration (hours/10 years), TAVG—mean temperature (°C/10 years), TMAX—mean maximum temperature (°C/10 years), TMIN—mean minimum temperature (°C/10 years), RH—relative humidity (%/10 years), P—precipitation (mm/10 years), WS—wind speed (m s^{-1}/10 years). Bold figures and signs with an asterisk * indicate statistically significant trends at the 0.05 significance level.

Var.	**Ann**		**DJF**		**MAM**		**JJA**		**SON**	
	a	**b**	**a**	**b**	**a**	**b**	**a**	**b**	**a**	**b**
ACT	**6.8**	+ */+	1.7	+/−	**1.9**	+/+	**2.8**	+ */+	0.0	+/+
CCT	**−4.3**	− */0	−0.6	−/+	**−2.1**	−/−	**−1.4**	− */+	0.0	−/0
DCT	−1.7	0/−	−0.9	−/+	0.0	+/−	**−0.9**	0/−	0.0	−/−
SD	16.8	−/+	−1.2	+/−	**14.0**	+/+	**10.5**	−/−	−7.1	−/+
TAVG	**0.37**	+/+ *	**0.36**	+/+	**0.36**	+/+	**0.45**	+/+ *	**0.23**	−/+ *
TMAX	**0.42**	+/+ *	**0.39**	+/+	**0.49**	+/+ *	**0.52**	+/+ *	**0.21**	−/+*
TMIN	**0.35**	+/+ *	**0.38**	+/+	**0.25**	+/+	**0.40**	+/+ *	**0.27**	0/+ *
RH	**−0.6**	−/− *	**−0.5**	−/−	**−1.2**	− */− *	**−0.9**	−/−	0.0	−/−
P	5.5	−/−	1.6	+/+	−2.6	−/−	1.0	−/−	2.8	+/+
WS	**−0.07**	+/− *	**−0.06**	+/−	**−0.07**	−/− *	**−0.05**	−/− *	**−0.08**	+/− *

The importance of 30-year periods in climatological studies can be enhanced by the fact that they may represent two parts of a 60-year cycle recognised in several papers (e.g., [87–89]). For example, Courtillot et al. [90] showed that a 60-year oscillation in global surface temperatures in 1850–2010 is precisely expressed by ~30-year long linear segments with several slope breaks in ~1904, ~1940, and ~1974 (±3 years) and near the turn of the 20th–21st centuries. These breaks roughly correspond to major changes in the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO). The last break may indicate that the Earth's climate entered a new mode (expressed again by a ~30-year period).

5. Conclusions

From a comparison of circulation types and several climatic variables of the CR for two 30-year normal periods of the 1961–2020 period, the following conclusions can be shortly summarised:

(i) Mean frequencies of anticyclonic and cyclonic circulation types according to the objective classification express generally significant changes between both 30-year normal sub-periods. Significant increases in their 30-year means appear for frequencies of days with the occurrence of anticyclonic types and decreases for cyclonic types in the 1991–2020 period compared to 1961–1990. Directional circulation types exhibit relatively stable patterns in both periods analysed;

(ii) Annual and seasonal sunshine duration series do not express significant changes between two 30-year normal periods in terms of their variability, characteristics of

distribution, density functions, or linear trends. Only an increase in annual, MAM, and JJA means in 1991–2020 compared to the preceding period was statistically significant;
(iii) Mean, maximum, and minimum temperatures display different patterns in two 30-year normal periods in accord with recent warming. They are reflected in statistically significant differences in means, characteristics of distribution, density functions, and significant linear trends through 1991–2020 (annual, JJA, SON). This is particularly pronounced for the JJA series;
(iv) Statistically significant decreases in means of relative humidity between two 30-year normal periods (except SON) are reflected in a significant shift of density functions to lower values. However, decreasing linear trends were significant only for MAM. Increasing variability in relative humidity was significant for the annual and MAM series.
(v) Precipitation totals of both 30-year periods are represented well by non-significant linear trends. There are no substantial changes in mean and variability nor in the character of their distributions represented by the density functions;
(vi) Wind speed in two 30-year normal periods represents quite different patterns expressed by statistically significant decreasing linear trends over 1991–2020, significant differences in means (partly in variability and skewness, both annual and MAM), and in density functions;
(vii) The recent 30-year normal 1991–2020 period is strongly influenced by recent climate change. This is reflected in statistically significant changes in means, variability, characteristics of distribution, density functions, and linear trends compared to the preceding 30-year normal of 1961–1990. These features have already become typical for many climatic variables;
(viii) Spatial patterns of differences between two 30-year periods for annual series of climate variables generally confirm knowledge obtained from the mean series for the whole CR. Spatial differences for temperature characteristics are territorially the most consistent, while for other climate variables, spatial patterns are slightly complicated;
(ix) All the above knowledge has to be considered when selecting a proper "baseline" or reference period for climate change impact and adaptation studies.

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Appendix A

An explanation of abbreviations for circulation types:

(i) Anticyclonic circulation types

A—centered anticyclone; AN—anticyclonic northern; ANE—anticyclonic northeastern; AE—anticyclonic eastern; ASE—anticyclonic southeastern; AS—anticyclonic southern; ASW—anticyclonic southwestern; AW—anticyclonic western; ANW—anticyclonic northwestern.

(ii) Cyclonic circulation types

C—centered cyclone; CN—cyclonic northern; CNE—cyclonic northeastern; CE—cyclonic eastern; CSE—cyclonic southeastern; CS—cyclonic southern; CSW—cyclonic southwestern; CW—cyclonic western; CNW—cyclonic northwestern.

(iii) Directional circulation types

N—directional northern; NE—directional northeastern; E—directional eastern; SE—directional southeastern; S—directional southern; SW—directional southwestern; W—directional western; NW—directional northwestern.

Appendix B

The values of climatological time series can sometimes be autocorrelated when a significant positive serial correlation may violate the assumptions for the application of the Mann–Kendall test. Therefore, the autocorrelation function was first calculated for all analysed series. However, significant autocorrelation was identified quite rarely. It occurred in the DJF mean, maximum, and minimum temperature series for the 1961–1990 period. For the following 1991–2020 period, significant autocorrelation was identified in annual minimum temperature series and especially in the annual, MAM, and JJA wind speed series. More frequent significant serial correlations were identified in the 60-year long series over the whole 1961–2020 period for annual and JJA mean, maximum, and minimum temperatures, for annual, DJF, and MAM relative humidity, and for all wind speed series except DJF.

For these series, a modified Mann–Kendall test for autocorrelated data was applied. The test uses the non-parametric block bootstrap technique that is based on resampling the original time series to randomly selected blocks of the pre-defined lengths. Repeatedly calculating test statistics for these blocks enabled a 95% confidence interval for the empirical bootstrapped distribution. If the value of the test statistic falls inside the tail of this distribution, then there is likely a trend in the data.

For all series that indicated the existence of a significant linear trend in the two analyzed 30-year normal periods (Tables 1–8, last column) and also in the whole 1961–2020 period (Table 10), the same results were confirmed using the modified Mann–Kendall test, which considered adjustments for positive autocorrelations.

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