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Long-term variability of air temperature and precipitation conditions in the Polish Carpathians

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Abstract: Mountain regions are sensitive to climate changes, which make them good indicators of climate change. The aim of this study is to investigate the spatial and temporal variability of air temperature and precipitation in the Polish Carpathians. This study consists of climatological analyses for the historical period 1851-2010 and future projections for 2021-2100. The results confirm that there has been significant warming of the area and that this warming has been particularly pronounced over the last few decades and will continue in the oncoming years. Climate change is most evident in the foothills; however, these are the highest summits which have experienced the most intensive increases in temperature during the recent period. Precipitation does not demonstrate any substantial trend and has high year-to-year variability. The distribution of the annual temperature contour lines modelled for selected periods provides evidence of the upward shift of vertical climate zones in the Polish Carpathians, which reach approximately 350 meters, on average, what indicates further ecological consequences as ecosystems expand or become extinct and when there are changes in the hydrological cycle.

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Introduction

Mountain regions, especially those at high altitudes, are considered to be among the best indicators of climate change due to the low degree of human impact on these ecosystems and their interactions with general atmospheric circulation, (Barry 1992; Diaz et al. 2003; Beniston 2003; Beniston 2005; Pepin et al. 2015). Additionally, montane ecosystems exhibit a high degree of complexity, which combined with orography (relief, slope, aspect, etc.) and other interrelated factors, also contributes to their role as climate change indicators.

The aforementioned compositeness makes it difficult to assess further impacts of climate change in mountain regions (Beniston 2005; Rangwala and Miller 2012; Kohler et al. 2014). It is worth emphasizing that any environmental modification, especially in air temperature or precipitation, has significant consequences on hydrological, ecological and even societal systems, especially at high altitudes, where direct human-based factors are of minor importance (Rangwala and Miller 2012; Kohler et al. 2014). Nevertheless, boundary-layer processes as well as existing feedbacks lead to enormous differentiation among climate change "fingerprints" (Barry 2008). Therefore, to assess the environmental impacts of climate change, local conditions should be considered as well as the variability of climatic factors (Parmesan and Yohe 2003).

Several studies have confirmed the recent warming of mountain regions at a rate of approximately three times the global average (e.g. Beniston 2005; Lindner et al. 2010; Kohler et al. 2014). This increase has been particularly pronounced since the 1980s and at different vertical zones, but with regionally differentiated intensity. This tendency has resulted in an upward shift of plant species of approximately 6.1 meters per decade followed by the advancement of phenological stages (Parmesan and Yohe 2003; Kelly and Goulden 2008). Pauli et al. (1996) indicate that the rate of ecological expansion is strictly dependent on the features and adaptive ability of species, including drought resistance. Since water availability constrains biomass production and the general state of the ecosystem, water deficits also significantly restrict plant distribution. Despite the intense temperature increase in mountain regions and resultant extension of the growing season, lower elevation foothills as well as dry valleys are exposed to increasing drought stress, a complex factor that slows or even arrests plant shifting (Lindner et al. 2010).

The Carpathians are one of the most important European mountain ranges, holding the tributaries of four main watersheds as well as hosting the largest, unmanaged forests and many endemic species (Björnsen-Gurung et al. 2009). In terms of geographical location, the range also creates a significant climatological barrier that modifies the general atmospheric circulation and results in the formation of a vertically differentiated climate and environmental zone. The need to explore climate variability across the region has been widely articulated (Obrębska-Starkel 1990; Björnsen-Gurung et al. 2009) and was partly addressed by the CARPATCLIM project with its database and resultant publications (e.g. Spinoni et al. 2013; Cheval et al. 2014; Spinoni et al. 2015a, b; Antofie et al. 2015). The results confirm the widespread tendencies of climate change, expressed most notably by the substantial increase in air temperature (Cheval et al. 2014; Spinoni et al. 2015a, b) and drought intensity (Spinoni et al. 2013; Antofie et al. 2015) but with no significant trend in precipitation (Cheval et al. 2014; Spinoni et al. 2015a). The results also indicate the important role of atmospheric circulation, but note that circulation can be considerably modified by local conditions. Therefore, detailed regional studies with finer temporal and spatial scales are needed (Cheval et al. 2014).

This study assesses the variability of air temperature and precipitation across the Carpathian region in Poland (i.e. Western Carpathians) within the past 160 years and future climate projections in the context of ongoing climate change and its possible environmental impact. The magnitude of the changes is established across the region, taking into account its spatial differentiation, as well as its vertical profile.

1 Data and Methods

The study was carried out for the Polish Carpathians located between 49° and 50° N latitude and 18.6° and 22.9° E longitude (Figure 1). The Polish Carpathians cover an area of approximately 20,000 km², including a Piedmont region. The highest peaks exceed 2000 meters above sea level, but the most northern part of the range does not exceed 300 m a.s.l. (Figure 1).

Analyses were conducted for two key study periods, the historical period of 1851-2010 and future projections of 2021-2100. The climatological standard period 1961-1990 was determined as a reference period as being available for all data sources.

1.1 The historical period of 1851-2010

To obtain monthly temperature and precipitation data for the period 1851-2010, three main data sources were incorporated: 1) the CARPATCLIM gridded database (1961-2010) with a spatial resolution of 0.1° (Szalai et al. 2013,

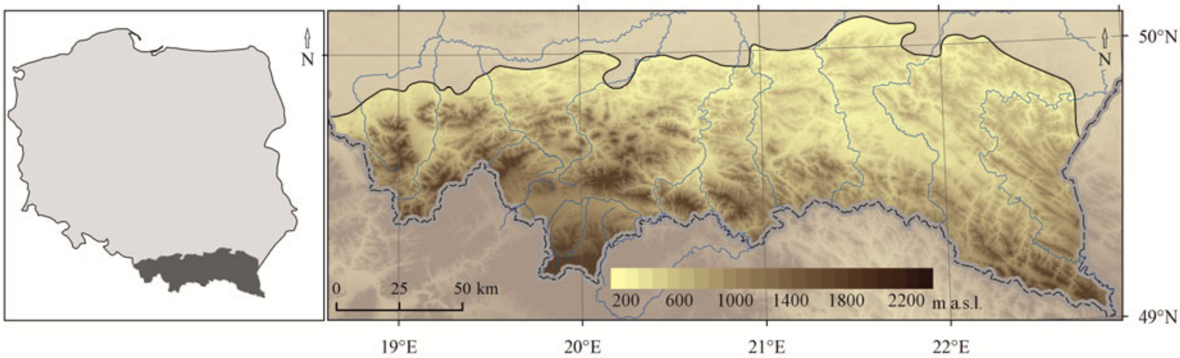

Figure 1 The study area of the Polish Carpathians and its location in Poland.

http://www.carpatclim-eu.org), 2) gridded temperature by Luterbacher and Xoplaki (Luterbacher et al. 2004; Xoplaki et al. 2005) and precipitation by Pauling et al. (2006) both covering the period 1850-1998 and with a 0.5° spatial resolution, and 3) in-situ measurements obtained from the Krakow meteorological station (1851-2010).

Data source 1, the CARPATCLIM database was created to fulfill the lack of a dense dataset over the Carpathians. It is based on long-term in-situ measurements, which were quality controlled, homogenized and interpolated using the MISH method (Meteorological Interpolation based on Surface Homogenized data basis, Szentimrey and Bihari 2007) built on a regression kriging scheme (Szentimrey et al. 2012). The region of the Polish Carpathians was represented by 38 temperature measuring stations and 102 precipitation gauges, supplemented with 12 temperature and 28 precipitation stations from neighboring countries. Cross-validation tests for the Polish Carpathians gridded data reach mean representativity values (REP = 1-RMSE·σ^{-1}) of 0.83 for air temperature and 0.65 for precipitation (Szentimrey et al. 2012).

Data source 2, the gridded reconstructions of monthly temperature and seasonal precipitation fields were based on a large number of homogenized and quality-checked instrumental data series, reconstructed data from documentary records as well as a few other proxies (Luterbacher et al. 2004; Pauling et al. 2006). The reconstructions were performed using principal component regression and show a high accordance with other databases, e.g. R=0.98 for temperature data compared to NOAA for the 1901-1998 period (Luterbacher et al. 2004, supplementary material).

Data source 3, the Krakow meteorological station, situated at the northern edge of the Carpathian foothills, has been operating constantly since 1792 and provides homogenous data series for temperature and precipitation (Trepińska 1971; Twardosz 1997). Therefore this station was chosen as a reference station.

Before combining these data sources a validation procedure was carried out. The grid point values of the reconstructed data and the areal means of the surrounding CARPATCLIM grids (2×2) were compared for the reference period 1961-1990. The areal means confirm a significant correlation between these databases, i.e. R=0.95 for air temperature (Figure 2) and R=0.92 for precipitation (Figure 3B). For only mountainous area the consistency is weaker, i.e. R=0.89 and R=0.62, respectively.

Since the data from station located in Krakow was included to create the historical data series, the representativeness of the reconstructed data was calculated also for the Krakow-nearest grid point. The analyses were performed separately for the reference period and for the historical period and report an accordance of R=0.91 and R=0.85 for air temperature (Figure 4) and 0.65 and 0.71 for precipitation (Figure 3A), respectively.

A multi-stage process had been applied to downscale these data sources of different original spatial resolutions to a very high resolution of 100 m, adopted as applicative for further environmental studies.

In the first step, the monthly mean temperatures and precipitation totals from the CARPATCLIM database were downscaled to 100 meters with SRTM-3 DEM (http://dds.cr.usgs.gov/srtm/). A multiple regression model that used the altitude, latitude and longitude was implemented for temperature downscaling and a bilinear interpolation to obtain high resolution precipitation data for the whole period from 1961-2010.

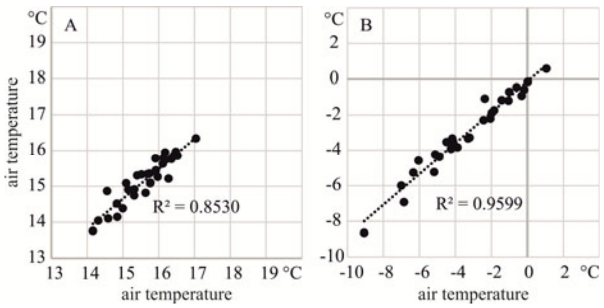

Figure 2 Relationship between areal mean air temperature values from reconstructed grid points (y axis) and related CARPATCLIM grids (x axis); A) summer temperature (JJA), B) winter temperature (DJF) (1961-1990).

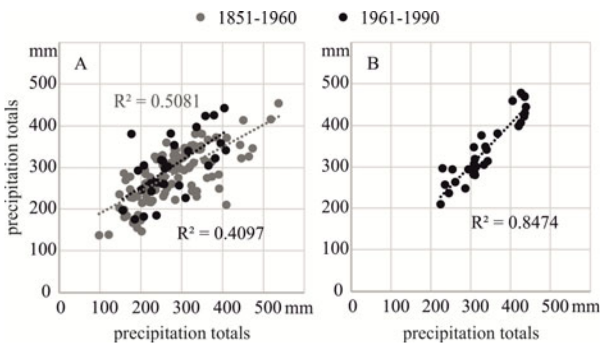

Figure 3 Relationship between seasonal (May-October) precipitation totals: A) from reconstructed grid point (y axis) and Krakow station (x axis), B) areal mean from reconstructed grid points (y axis) and related CARPATCLIM grids (x axis)

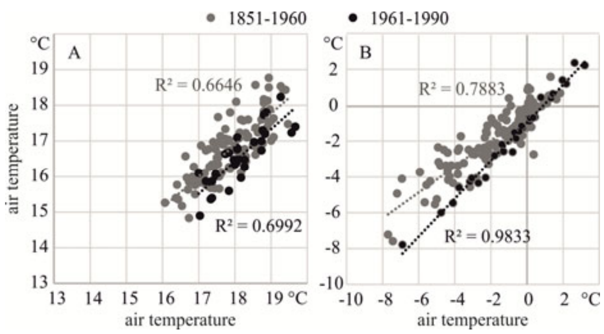

Figure 4 Relationship between air temperature values from reconstructed grid point (y axis) and Krakow station (x axis): A) summer temperature (JJA), B) winter temperature (DJF).

A multivariate regression model applied for air temperature used several geographic parameters, including elevation, latitude, longitude as predictor variables and developed the initial statistical relationship between air temperature and terrain. Elevation played the most important role. The residuals from the regression model were calculated for each CARPATCLIM grid point and spatially interpolated by the ordinary kriging method. The final temperature values are a result of both sub-values summation (compare Eqs. 1-3).

$$Z(s) = \beta_0 + \beta_1 X(s) + \beta_2 Y(s) + \beta_3 H(s) + \varepsilon(s) \quad (1)$$

$$Z^*(s) = \beta_0 + \beta_1 X(s) + \beta_2 Y(s) + \beta_3 H(s) \quad (2)$$

$$\varepsilon^*(s) = Z(s) - Z^*(s) \quad (3)$$

where,

$Z(s)$ – dependant variable
$Z^*(s)$ – modelled value
$X(s)$ – latitude
$Y(s)$ – longitude
$H(s)$ – altitude
$\varepsilon(s)$ – regression residuals
$\varepsilon^*(s)$ – estimated random model residuals

The procedure was repeated for each month separately to obtain annual temperature distribution pattern.

The validation procedure conducted to evaluate the reliability of the final products demonstrated a good adjustment of the re-gridded dataset. Correlation coefficient reached an average of 0.92 for temperature (R=0.95 for summer months and R=0.84 for winter months) and R=0.78 for summer precipitation (JJA). Root-mean-square error ranged between 0.397 (JJA) and 0.514 (DJF) for temperature fields and reached 0.627 for precipitation. Error maps (not presented) demonstrate higher bias values for high mountains which are also a result of the different spatial resolution of digital elevation models used to create CARPATCLIM database and the database created in this study.

In the second step, to obtain fine resolution data for the whole period 1851-2010, the change factor method was implemented (Anandhi et al. 2011). This method was used in many climate change impact assessment studies (e.g. Semadeni-Davies et al. 2008). Monthly means for temperature and seasonal means for precipitation were calculated for the reference period 1961-1990 at the resolution of the downscaled CARPATCLIM (100 m). The same averages were calculated for the

Table 1 Simulations used in the study

Domain	GCM model	RCM model	Modelling group	Model abbreviation*
EUR-11	CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17	CLMcom	CNRM
EUR-11	ICHEC-EC-EARTH	KNMI-RACMO22E	KNMI	KNMI
EUR-11	ICHEC-EC-EARTH	CLMcom-CCLM4-8-17	CLMcom	CCLM
EUR-11	MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17	CLMcom	MPI
EUR-11	ICHEC-EC-EARTH	DMI-HIRHAM5	DMI	DMI

Note: * Used in this study.

reconstructed data set. In the next step, each value of the reconstructed dataset (1851-1960) was expressed as an anomaly relative to the reference period. Difference anomalies were calculated for temperature but relative anomalies were calculated for precipitation to prevent negative values. Finally, the anomalies were bilinearly interpolated to a resolution of 100 m and subsequently combined with the CARPATCLIM reference period to obtain fine scaled maps for all of the years between 1851 and 1960. As reconstructed precipitation was available seasonally, to obtain warm season totals May-October precipitation amount was calculated for CARPATCLIM data and expressed as a percentage of three seasons precipitation MAM, JJA, SON. The derived proportion was applied to reconstructed data. Since differences between the reconstructed data series and in-situ measurements from Krakow were determined (Figure 3A, Figure 4), Krakow data were used for validation purposes. Monthly (temperature) and seasonal (precipitation) correction coefficients, using the differences established for each grid point separately, were adjoined to the already calculated data.

The constructed database was subject to control via the following statistical tests, which were carried out independently to assess the homogeneity of the data: (1) the standard normal homogeneity test (SNHT), (2) the Buishand range test, (3) the Pettit test, and (4) the von Neumann ratio test (Wijngaard et al. 2003). A 1% significance level was used to identify 'breaks'.

1.2 Future climate projections for 2021-2100

Future climate projections were calculated for two greenhouse gas concentration trajectories (Representative Concentration Pathways), RCP 4.5 and RCP 8.5. The monthly mean temperature and precipitation data for the period 2021-2100 at a spatial resolution of 0.11° were obtained from the EURO-CORDEX website (http://www.euro-cordex.net) for five different GCM-RCM model chains (Table 1). Before being effectively used, they all were validated and post-processed due to possible bias and spatial resolution different from the first key study period, i.e. 1851-2010. To downscale the output of RCMs to finer resolution the same statistics-based change factor method as described above was applied. The additive model for temperature and multiplicative for precipitation were chosen as by assumption that GCM-RCMs produce reasonable estimates for the absolute temperature change or relative precipitation change regardless of the accuracy of the absolute climate simulation (Anandhi et al. 2011). The change factor method reduces the impact of model bias on future projection results to a minimum. Final analyses were conducted using model ensembles for each scenario separately, nevertheless the influence of the particular GCM-RCM combination on projected changes is also discussed.

Long-term variability as well as future projections were described according to their mean values and anomalies for the whole area, considering its spatial differentiation, as well as in five distinguished altitudinal zones (Table 2). Trends for the entire 160-year past period and 40-year sub periods (1851-1890, 1891-1930, 1931-1970, 1971-2010) were assessed and subjected to the nonparametric Mann-Kendall test used to measure the statistical significance of changes (von Storch and Zwiers 2003). To assess the intensity of the detected trends, the linear model was implemented

Table 2 Altitudinal structure of the Polish Carpathians

Altitude (m a.s.l.)	Area (%)
≤500	58.93
501-1000	38.33
1001-1500	2.31
1501-2000	0.39
>2000	0.04

and least square linear fitting was used to calculate the trend slopes.

For the vertical profile, the concept of vertical climatological zones in the western Carpathians, formulated by Hess (1965), was also used. Hess delimited the location of six isotherms of annual temperature from -2°C to 8°C, with two degree intervals, and these were marked out for each temporal sub-period separately. As the average annual temperature is one of the most important determinants of regional ecology, detected changes in the temperature distribution, as expressed by the location of the mentioned isotherms, emphasize the environmental consequences of contemporary climate warming.

2 Results

2.1 Climatology of the Polish Carpathians

The mountain climate of the Polish Carpathians is characterized by significant spatial variances due to changes in relief and elevation. It is intensified by latitudinal location of the mountain chain, which modifies also mesoscale atmospheric circulation. According to the long-term averages (1851-2010), summer temperatures vary from more than 16°C in the foothills to less than 8°C at the highest peaks. Winters are characterized by mean temperature below 0°C over the whole area, reaching more than -3°C in the warmest regions to less than -8˚C in the mountains. The 0°C isotherm of the mean annual air temperature runs at an elevation of approximately 1850 m in the Tatra Mountains (highest range) (Figure 5a), whereas the rest of the area demonstrates positive values, up to more than 7°C in the northern most part.

In terms of geographical location, most rainfall is recorded during the warm half of the year across the entire study area, which makes it one of the most important environmental factors. The precipitation totals vary spatially in the region (Figure 5b). The western part of the study area experiences oceanic effects, resulting in higher

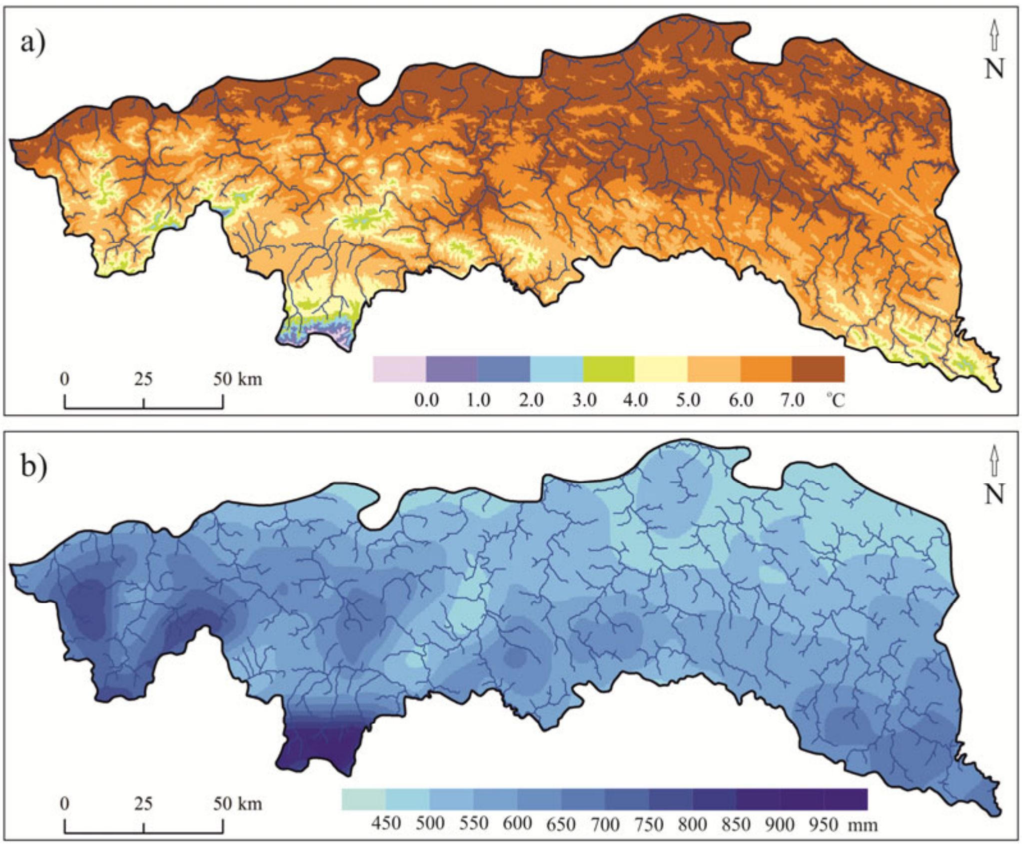

Figure 5 Spatial distribution of the mean a) annual temperature b) seasonal precipitation totals (May-October) in the Polish Carpathians (1851-2010) .

precipitation totals, reaching more than 1000 mm during a year, 700 mm of which appear during the warm season (Figure 5b). This explains why this portion is more prone to precipitation-based natural hazards, such as floods and landslides. The seasonal precipitation totals for the eastern part are approximately 500 mm.

Global climate change tendencies specific to mountain regions (Kohler et al. 2014) are also visible in the Polish Carpathians. Long-term temperature and precipitation data, covering a 160 year historical period and projections for another 80 years, were used to investigate the temporal and spatial tendencies across the region.

2.2 Changes of air temperature conditions

The intensity of the air temperature increase in the mountain region depends on boundary-layer processes, which differ seasonally and spatially according to orographic features and related drivers, e.g. radiation, cloud cover, snow cover or even soil moisture (Beniston 2005; Rangwala and Miller 2012).

The air temperature changes with respect to the 1901-2000 period are higher in the Polish Carpathians than the average of the northern hemisphere during the examined seasons. During the first decades of the examined period (up to 1940), negative anomalies dominated, reaching approximately -1°C for summer annual temperatures and -2°C in winter, but occasionally falling to almost -6°C. Positive anomalies were recorded sporadically, but occurred much more often in winter months (up to 2°C), which explains why Carpathian winters are much warmer and more differentiated than the northern hemisphere average. Global warming has been discernible in the Polish Carpathians, especially over the last few decades of 20th century, and appears to be consistent with results observed in the Alps (Beniston 2005). Although the temperature rise is more consistent during summer, since 1992 only positive anomalies have been recorded. In contrast, during winter, the anomalies reach up to 4°C, more than a two-fold amplification of the northern hemisphere trend. The interannual variability of winter temperatures is much higher than that observed during summer. Cold winters still occur, with anomalies reaching -2°C, synchronous with the northern hemisphere winter temperature and contributing to the lower, but still higher than long-term, annual means (Figure 6a).

These tendencies vary spatially, presenting different magnitudes of the variability in terms of altitude (Table 3). Winter warming with respect to a reference period of 1961-1990 is most significant for the lowest areas, located below 500 m a.s.l., especially for the last study period of 1971-2010. The mean seasonal temperature of the years 1971-2010 was 2.4°C higher than during the period from 1851-1890 and 0.7°C higher than the reference period (Table 3). Winters are also warmer in other vertical zones, but the change intensity is weaker. For the highest peaks (>2000 m a.s.l.), the temperature increase was approximately 0.08°C per 10 years. Although the last several decades have contributed most significantly to the general trend, it must be emphasised that the winter seasons of 1891-1930 were also crucial, as mentioned before (Table 3). The temperature growth over that time reached almost 0.1°C on average, maintaining the vertical intensity pattern, from 0.12°C below 500 m a.s.l. to only 0.04°C at the peaks. All the described tendencies are not statistically significant at a=0.05 (Table 3).

The summer temperature trends show also visible temporal and altitudinal differentiation (Table 3). However, the anomalies are negative for the first two periods (1851-1890, 1891-1930), reaching a maximum of -1.8°C, and positive for the last few decades (up to 0.7°C). The trend, which is only positive for the last time period (1971-2010), is the most intensive at the highest altitudes, as well as more sensitive and prone to variation (Table 3). For all vertical zones the described tendencies are statistically significant at a=0.05 (p <0.0001).

The annual temperature increased by 1.5°C on average from the first study period and is the most noticeable in the lowest parts of the Polish Carpathians (Table 3). However, the last several decades (1971-2010) are characterized by a statistically significant (p=0.001) trend of the same intensity in the highest vertical zones, reaching 0.3°C per 10 years. The spatial distribution of selected isotherms at specific time periods confirms the described tendencies (Figure 7, Table 4). The location of the 0°C isotherm shifted upwards by approximately 160 meters between the years 1851-1970 and disappeared over the last four

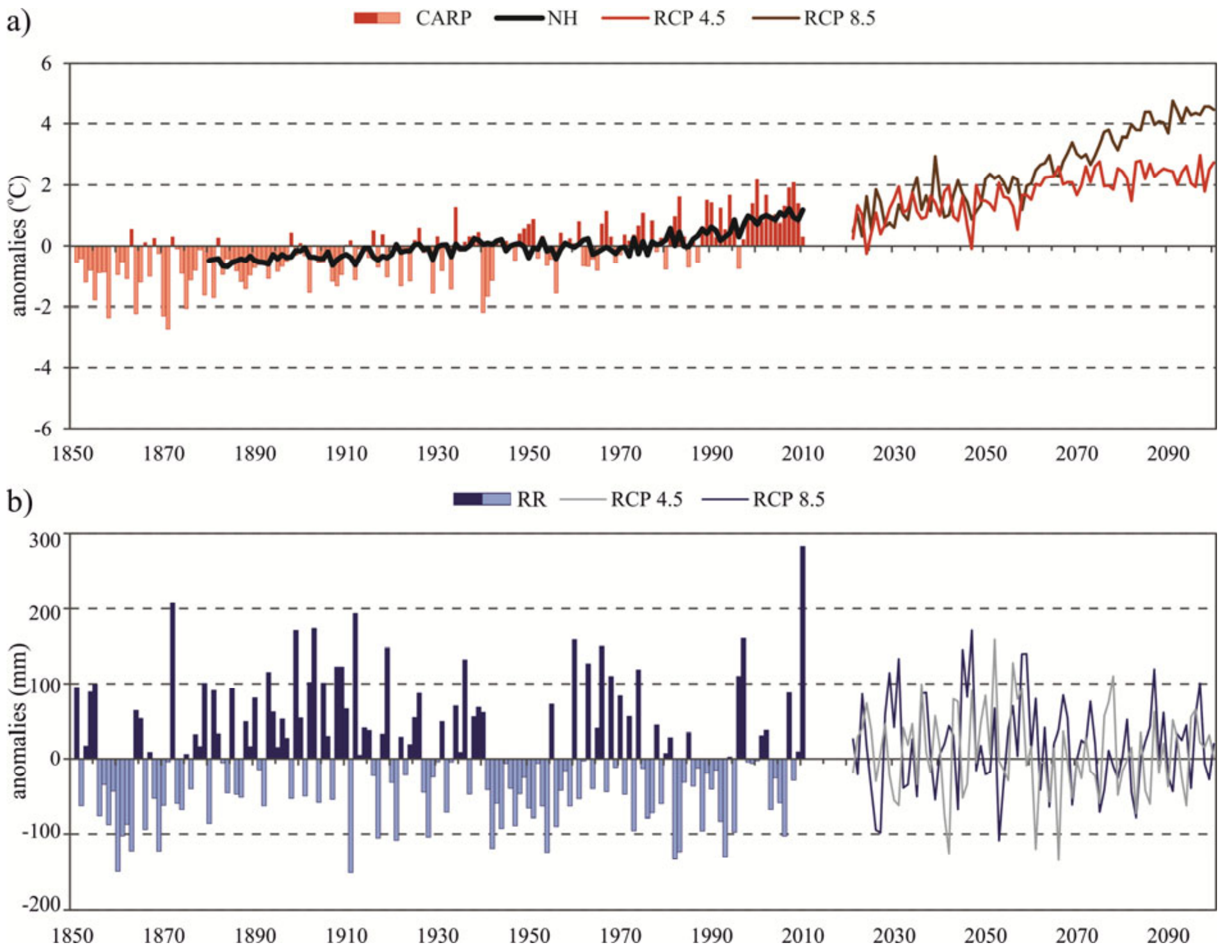

Figure 6 Long-term historical variability and future projections (RCP 4.5, RCP 8.5 - 5 models ensembles) of a) annual temperature (CARP) with the Northern Hemisphere temperature (NH) (http://www.ncdc.noaa.gov/cag /) as the background and b) warm season (May-October) precipitation totals (RR) in the Polish Carpathians), areal mean anomalies with respect to the 1901-2000 period.

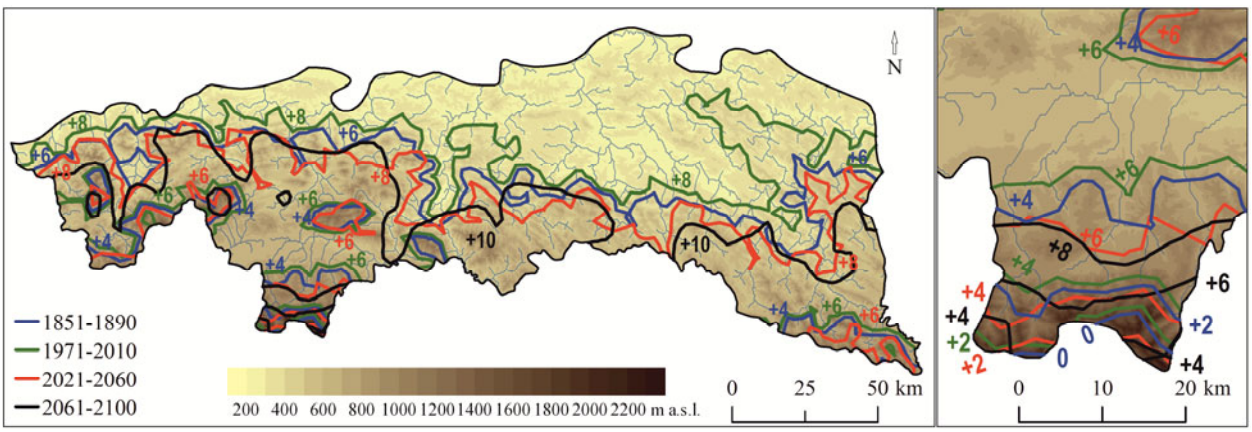

Figure 7 Spatial distribution of selected isotherms (mean annual temperature, °C) in the Polish Carpathians and their highest part in particular time periods (with the elevation as a background).

decades (1971-2010). The other borderlines (+2°, +4°, +6° and +8°C as defined by Hess in 1965) have also shifted over the 160 years under investigation. The highest shift of more than 400 meters upwards on average affected the isotherm +2°C (Table 4). The appearance of the isotherm

Table 3 Areal means of the air temperature in selected 40-year periods in 1851-2010 as well as their anomalies (with respect to the 1961-1990 period) and tendencies in distinguished vertical zones. Statistically significant values in bold.

Altitude (m a.s.l.)	Winter (DJF)				Summer (JJA)				Whole year			
	1851-1890	1891-1930	1931-1970	1971-2010	1851-1890	1891-1930	1931-1970	1971-2010	1851-1890	1891-1930	1931-1970	1971-2010
	Mean temperature (°C)											
≤500	-3.9	-2.9	-3.1	-1.5	16.1	15.9	16.5	17.1	6.4	6.8	7.1	8.0
501-1000	-4.9	-4.0	-4.2	-2.7	14.3	14.1	14.7	15.3	4.9	5.3	5.6	6.4
1001-1500	-6.3	-5.5	-5.7	-4.5	11.7	11.5	12.2	12.8	2.7	3.1	3.5	4.2
1501-2000	-8.1	-7.5	-7.6	-6.7	8.5	8.3	9.0	9.6	0.1	0.4	0.7	1.5
>2000	-9.3	-8.8	-8.9	-8.1	6.5	6.3	7.0	7.6	-1.6	-1.4	-1.0	-0.3
	Temperature anomalies (°C)											
≤500	-1.6	-0.6	-0.9	0.7	-0.3	-0.5	0.2	0.7	-1.2	-0.7	-0.4	0.5
501-1000	-1.6	-0.6	-0.9	0.6	-0.4	-0.6	0.0	0.6	-1.1	-0.7	-0.4	0.5
1001-1500	-1.7	-0.9	-1.1	0.1	-1.1	-1.3	-0.6	0.0	-1.1	-0.7	-0.3	0.4
1501-2000	-0.9	-0.3	-0.4	0.5	-0.4	-0.6	0.1	0.7	-1.0	-0.6	-0.3	0.4
>2000	-1.5	-1.0	-1.1	0.3	-1.6	-1.8	-1.1	0.5	-0.9	-0.7	-0.3	0.4
	Tendency (°C /10 years)											
≤500	0.001	0.030	0.075	0.159	-0.074	-0.040	-0.038	**0.489**	0.013	0.092	**0.083**	**0.297**
501-1000	0.003	0.026	0.067	0.144	-0.077	-0.042	-0.039	**0.504**	0.012	0.083	**0.080**	**0.299**
1001-1500	0.006	0.021	0.056	0.123	-0.081	-0.044	-0.039	**0.526**	0.010	0.071	0.076	**0.301**
1501-2000	0.010	0.014	0.042	0.096	-0.086	-0.046	-0.040	**0.553**	0.009	0.055	0.072	**0.305**
>2000	0.012	0.010	0.033	0.079	-0.089	-0.048	-0.041	**0.570**	0.008	0.045	0.069	**0.307**

Table 4 Average altitude of selected isotherm (mean annual temperature) locations in distinguished periods

Temperature (°C)	Altitude (m a.s.l.)							
	1851-1890	1891-1930	1931-1970	1971-2010	2021-2060 (RCP 4.5)	2021-2060 (RCP 8.5)	2061-2100 (RCP 4.5)	2061-2100 (RCP 8.5)
0.0	1672	1733	1830	-	-	-	-	-
2.0	1278	1384	1452	1704	1735	1748	-	-
4.0	844	904	974	1150	1314	1317	1519	1565
6.0	417	514	579	748	851	912	989	1302
8.0	-	-	-	344	416	480	655	907
10.0	-	-	-	-	-	-	258	532

+8°C in the period 1971-2010 is also worth mentioning as mean annual temperatures of 8°C or more have become a feature throughout most of the Carpathian Foothills (Figure 7).

2.3 Precipitation variations

The precipitation totals are characterized by significant interannual variability (Figure 6b). Warm season anomalies reached from -150 mm in the most dry years to almost +300 mm during a very wet 2010, one of the flood years in the Polish Carpathians. Interspersed dry and wet periods with no discernible long-term tendencies have been found in other European regions as well (Hartmann et al. 2013). Precipitation variability is slightly more visible at lower altitudes. The most significant variabilities are found in the high totals in the years 1891-1930, which were the wettest for the entire analysed period. In all of the vertical zones, the 40-year-mean totals were 30 mm higher on average, constituting an anomaly of a range from 5% to 8% with respect to the 1961-1990 period (Table 5, Figure 6b).

2.4 Future projections

Before accessing the climate change scenario s imulations the representativeness of the five selected GCM-RCM model chains (Table 1) was examined for the reference period 1961-1990. Monthly mean air temperature and precipitation totals of the model simulations were compared to the corresponding values of the CARPACTLIM database, which was taken into account as the ground truth for the Polish Carpathians. Although all GCM-RCM combinations reproduce the basic behaviour of the annual cycle, summer months (JJA) temperatures are overestimated by all the models (up to +3.6° in July by the CRNM model) except for the KNMI simulation while cold half-year temperatures are predominantly underestimated, with the biggest bias of -3.5°C in March by KNMI (Figure 8A). In contrast, cold half-year precipitation is much higher (up to 150%) than the ground truth, while summer precipitation totals are highly underestimated (e.g. only 40% of the observed amount in August simulated by CNRM model) (Figure 8B). Thermal conditions throughout the year are figured out the best by MPI's GCM-RCM model combination with an annual mean bias value of 0.4°C. Precipitation, with high spatial differentiation, is much more difficult to simulate, especially in mountainous region. Significant bias values have been detected in all model simulations, however warm season precipitation, being examined in this study, is the best reproduced by DMI's GCM-RCM combination (Figure 8B).

Since the biases compensate for one another to a large extent, to access climate change scenario simulations for the future periods 2021-2100 five model ensembles have been incorporated. Using the change factor method additionally enabled to reduce described biases by creating future temperature and precipitation projections based on the differences between modelled series and fine scaled current state climatology (baseline) calculated for the reference period.

The results of the future projection model ensembles (the average of five models) calculated for RCP 4.5 and RCP 8.5 up to the year 2100 and averaged for the entire region continue the trend for both the mean temperature and precipitation totals and demonstrate no significant difference between scenarios until 2060 (Figure 6). The

Table 5 Areal means of the warm season (May-October) precipitation totals in selected periods of 1851-2010 and projections for the periods 2021-2060 and 2061-2100 (RCP 4.5 and R CP 8.5) and their anomalies (with respect to the 1961-1990 period) in distinguished vertical zones

Altitude (m a.s.l.)	1851-1890	1891-1930	1931-1970	1971-2010	2021-2060 (RCP 4.5)	2021-2060 (RCP 8.5)	2061-2100 (RCP 4.5)	2061-2100 (RCP 8.5)
	Precipitation totals (mm)							
≤500	529.5	561.0	534.2	526.5	562.3	565.6	564.4	586.4
501-1000	619.3	653.7	624.6	616.3	643.3	648.9	641.4	659.6
1001-1500	736.0	777.0	742.8	732.5	758.3	767.9	755.1	769.0
1501-2000	858.5	905.6	866.3	854.0	864.9	877.8	860.2	865.8
>2000	844.7	890.8	851.9	840.0	841.6	854.2	853.1	856.5
	Anomalies (%)							
≤500	1.8	7.9	2.7	1.2	8.3	8.9	8.7	12.9
501-1000	1.3	7.0	2.2	0.9	5.6	6.5	5.0	8.1
1001-1500	0.2	5.8	1.1	-0.3	4.2	5.4	2.9	4.9
1501-2000	0.8	6.3	1.7	0.2	2.6	4.2	0.9	1.5
>2000	-0.4	5.1	0.5	-0.9	2.1	3.7	0.3	0.6

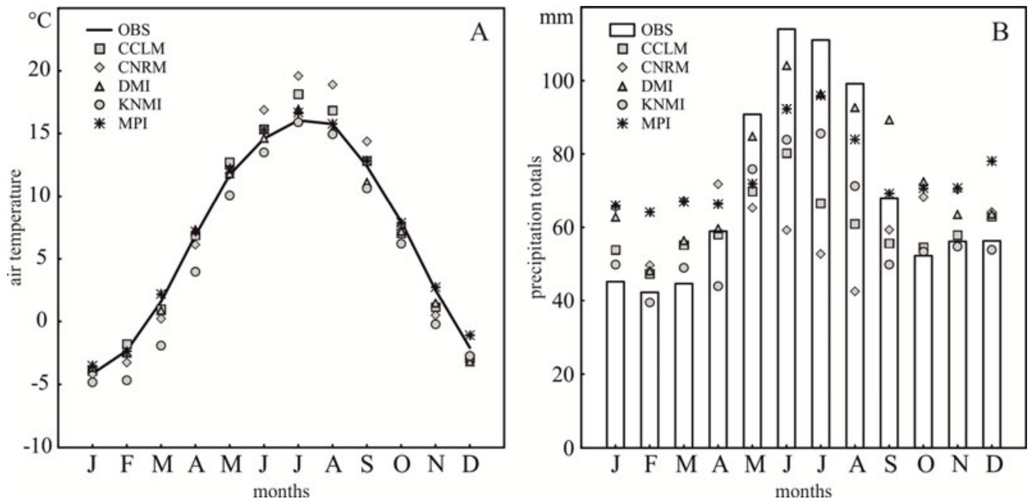

Figure 8 Monthly mean air temperature (A) and precipitation totals (B) by the CARPACTLIM database (OBS) and GCM-RCM simulations (according to Table 1) for the period 1961-1990 averaged across the Polish Carpathians.

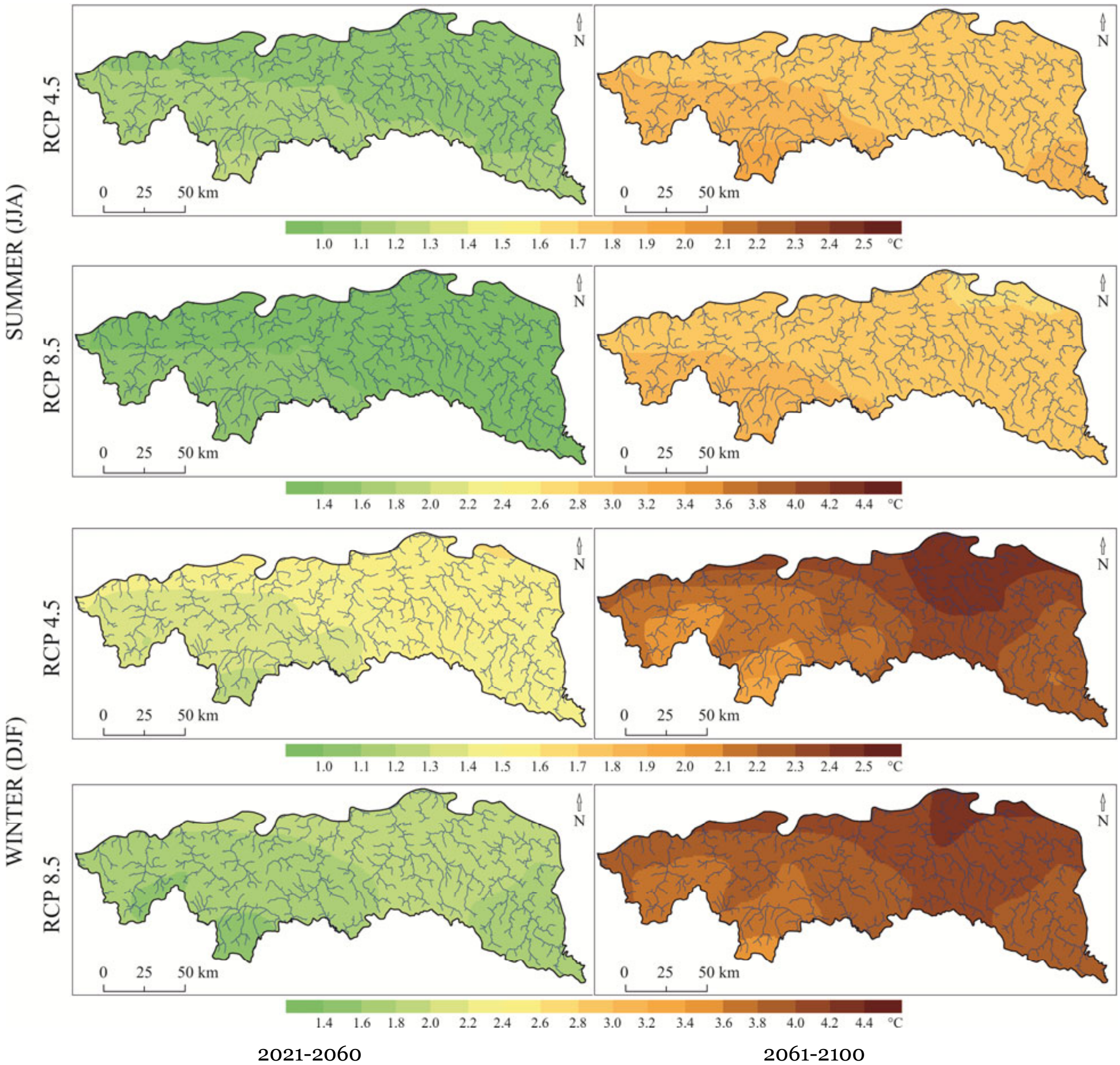

Figure 9 Seasonal temperature anomalies of future projections 2021-2060 and 2061-2100 (5 models ensembles) in the Polish Carpathians with respect to the 1961-1990 period.

annual mean as well as summer temperatures appear to increase by up to 2°C for the RCP 8.5 scenario, whereas the rise in winter temperature is estimated to be approximately 3°C during specific years and of far greater amplitude (Figure 6a). The precipitation totals are expected to oscillate around the long-term mean, with a low frequency of positive anomalies, reaching more than 100 mm (Figure 6b). After 2061 the scenarios show different tendencies. According to RCP 4.5 the temperature in the Polish Carpathians will not exceed the aforementioned 2°C anomaly, whereas RCP 8.5 projects a further increase of up to 4°C in summer and even higher during winter and the whole year (Figure 6a). Precipitation totals are projected to be less variable and not surpass 100 mm anomaly (Figure 6b).

Environmentally important changes are most evident in the spatial distributions of temperature (Figure 9, Table 4, Table 6) and precipitation (Figure 10, Table 5) anomalies with respect to the 1961-1990 period. The Carpathian climate will be characterized by much warmer winters as well as warmer and more humid (up to 12%) summer conditions in the Piedmont area. Temperature anomalies averaged for DJF will vary from 1.4°C

Table 6 Areal means of the projected temperature values for the periods 2021-2060 and 2061-2100 (RCP 4.5 and RCP 8.5) and their anomalies (with respect to the 1961-1990 period) in distinguished vertical zones

Altitude (m a.s.l.)	2021-2060						2061-2100					
	Winter (DJF)		Summer (JJA)		Whole year		Winter (DJF)		Summer (JJA)		Whole year	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
	Mean temperature (˚C)											
≤500	-0.8	-0.4	17.4	17.7	8.3	8.7	0.0	1.8	18.1	19.2	9.5	10.8
501-1000	-2.0	-1.7	15.7	16.0	6.8	7.1	-1.2	0.5	16.5	17.7	8.1	9.4
1001-1500	-3.8	-3.5	13.2	13.5	4.7	5.0	-2.5	-0.9	14.7	15.9	6.4	7.8
1501-2000	-6.0	-5.8	10.1	10.3	2.0	2.3	-5.0	-3.4	11.4	12.6	3.4	4.7
>2000	-7.3	-7.1	8.1	8.4	0.4	0.7	-5.3	-3.7	10.9	12.1	3.0	4.3
	Temperature anomalies (˚C)											
≤500	1.5	1.8	1.1	1.4	0.8	1.2	2.3	4.0	1.8	2.9	2.0	3.3
501-1000	1.4	1.7	1.1	1.4	0.8	1.1	2.2	3.8	1.8	3.0	2.1	3.4
1001-1500	1.3	1.6	1.2	1.4	0.9	1.2	2.1	3.7	1.9	3.1	2.6	4.0
1501-2000	1.3	1.5	1.2	1.5	1.0	1.3	2.0	3.6	2.0	3.2	2.4	3.7
>2000	1.3	1.5	1.2	1.5	1.1	1.4	2.0	3.6	2.0	3.2	3.7	5.0

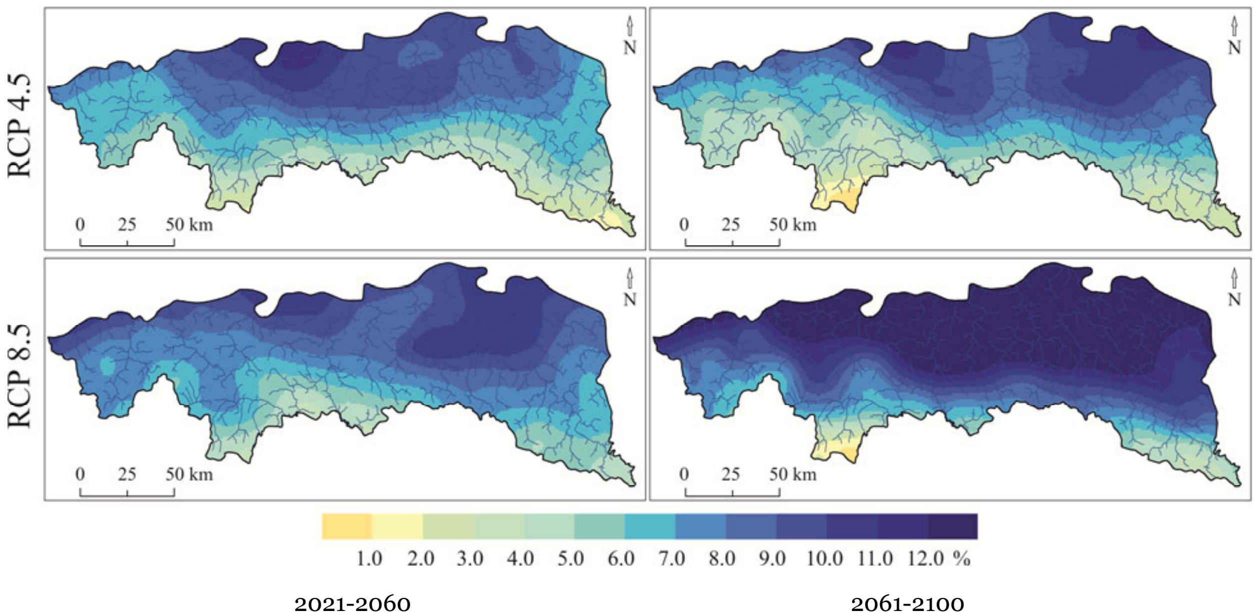

Figure 10 Seasonal precipitation anomalies (May-October) of future projections 2021-2060 and 2061-2100 (5 models ensembles) in the Polish Carpathians with respect to the 1961-1990 period.

(projected by RCP 4.5 for the period 2021-2061) to 4.0°C (projected by RCP 8.5 for the period 2061-2100). Summer (JJA) temperature projections are less differentiated and range from 1.1°C to 3.2°C (Table 6). The study results confirm that the differences between the summer and winter changes are less significant at high altitudes, where the distinction between the RPC 4.5 and 8.5 projections is not as clearly pronounced. The temperature borderlines (indicating climate vertical zones of the lower montane belt, i.e. 4°C or even the submontane belt i.e. 6°C) are anticipated to shift upwards (Table 4, Figure 7), reaching the location of the 1851-1890 isotherms of an annual temperature of 2°C and downwards, i.e. shifting different climatic zones to the area (Figure 7, Table 4) and resulting in potentially severe environmental implications.

All the aforementioned results of projected temperature and precipitation changes are based on model ensemble values. To access the possible uncertainty of projected changes the analyses were repeated for all GCM-RCM combination used in the study. As a result, ten different future projections, presenting the outcomes of five GCM-RCM model chains in RCP 4.5 and 8.5 were obtained to describe the possible temperature and precipitation conditions in the Polish Carpathians (Figure 11, Figure 12). Although the magnitude of temperature changes differ between the individual GCM-RCMs, the tendency towards positive change remains accordable regardless of the model combination used (Figure 11). On the contrary, projected precipitation changes differ significantly (Figure 12). Some combinations, e.g. DMI for both RCP, simulate relatively stable precipitation conditions while the CCLM and KNMI combinations using the same GCM (ICHEC-EC-EARTH) but different RCMs project in general (averaged for the whole period 2021-2100) higher amount of rain in the Polish Carpathians. The extremes (5% and 95% quantiles) are more differentiated indicating dryer minimum and wetter maximum precipitation extremes (Figure 12).

3 Discussion

The results of long-term climate analyses are strongly dependent not only on the location of the site but also on the research period taken into account. The variability of the Carpathian climate in Poland was the subject of studies conducted by, among others, Obrębska-Starkel et al. (1995) for the period 1951-1990, which was extended to 2006 by Bokwa et al. (2013) using in-situ measurements from selected stations. In both cases, the results proved that precipitation does not exhibit any particular trend and indicated the weakening of the mean annual temperature tendencies from the foothills to the ridges. The magnitude of the changes was different when the decades at the turn of the century were taken into account and became statistically significant at the highest altitudes. Similar results were found by Żmudzka (2009, 2011) for the Tatras (the highest massif in the entire Carpathian Mountains ridge).

Though gridded databases are burdened with a spatial smoothing effect, higher for precipitation than for air temperature data and not uniformly distributed (Wibig et al. 2014), the use of high-resolution gridded data for the entire area of the Polish Carpathians and the longest possible data series, covering the whole period of measurements in southern Poland, allows for broader and novel perspectives of climate change and environmental

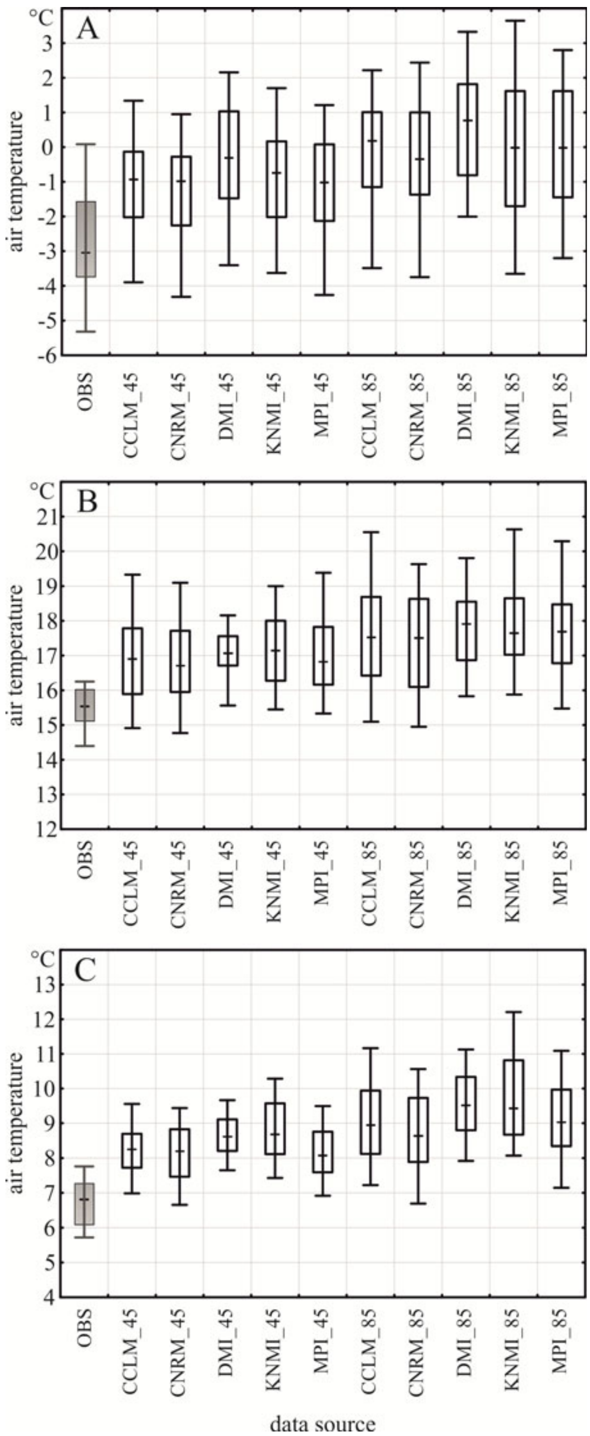

Figure 11 Observed (CARPATCLIM, 1961-1990) and projected air temperature values for the Polish Carpathians using different GCM-RCM (according to Table 1) simulations under RCP 4.5 (_45) and RCP 8.5(_85) for the period 2021-2100; A) winter season (DJF), B) summer season (JJA), C) whole year. The bottom and top of the box are the first and third quartiles, and the point inside the box shows the median. The whiskers represent the 5% and 95% quantiles.

research in region to be developed (Price et al. 2017). The change factor method, which reflects only a shift in the mean and keeps the variability unchanged (Anandhi et al. 2011) and therefore may not be helpful in event frequency analyses, proceeds effectively in comparative studies acknowledging the possibility of relative non-stationarity of overall patterns in highly heterogeneous landscapes at high resolutions.

The results confirm that the noticeable year-to-year precipitation variability has no statistical significance for the entire period under consideration. This is in line with other European studies which prove complex and non-uniform spatial patterns of precipitation changes mainly due to their circulation background. As atmospheric circulation, even variable in time, does not demonstrate any long-term univocal changes no significant trend in precipitation totals is observed (Łupikasza et al. 2011).

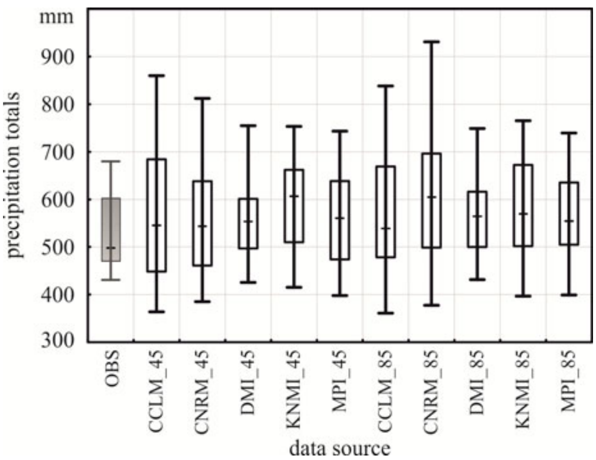

Figure 12 Observed (CARPATCLIM, 1961-1990) and projected warm season (May-October) precipitation totals for the Polish Carpathians using different GCM-RCM simulations (according to Table 1) under RCP 4.5 (_45) and RCP 8.5(_85) for the period 2021-2100. The bottom and top of the box are the first and third quartiles, and the point inside the box shows the median. The whiskers represent the 5% and 95% quantiles.

On the other hand, the research does show significant discrepancies in the air temperature tendencies. The distinct spatial and temporal temperature trend differences between distinguished vertical zones prove that there is sensitivity to temperature changes at high elevations in the Polish Carpathians, which is also confirmed by the upward shift in borderlines, a trend that is reflective of general European long-term temperature variability patterns in mountainous areas (Auer et al. 2007; Kelly and Goulden 2008; Jurkovič et al. 2011; Cheval et al. 2014; Spinoni et al. 2015a, b). The spatial trend of warming intensity increasing with altitude is observed in summer months (JJA). However its magnitude, due to atmospheric instability over the mountains, is modest. In winter, characterized by more significant warming over the whole region, the foothills experience and are projected to be afflicted with a more intense temperature increase. Increasing minimum air temperature confirmed by numerous regional studies (e.g. Wypych et al. 2017a) is reported as a predominant factor.

Progressive shrinking of low-temperature zones in montane ecosystems may destroy high-elevation habitats, as already observed in the Alps (Gottfried et al. 2012), and shift lower elevation belt plant species upward in elevation (Pauli et al. 1996). Research conducted for East-Central Europe (Ponocná et al. 2016) confirms that the impacts of climate variability intensify with increasing elevation. According to Ponocná et al. (2016), Norway spruce, constituting more than 21% of forest area in the Polish Carpathians, is most affected by summer and early growing season temperatures as well as drought episodes. These results can be observed in the intensity of tree growth and are regionally differentiated. This is congruent with the outcomes achieved by Socha and Durło (2012) who observed the deterioration of spruce growing conditions in the western part of the Polish Carpathians. The temperature increase for the entire research area in both summer and spring, as confirmed by the current study, causes the extension of heat resources (Wypych et al. 2017b) and suggests that the climate factor should be taken into consideration in further environmental studies concerning forest cover quality and spread. The future climate projections for the Carpathians, including the air temperature and precipitation totals, sustain the tendencies established by the climatological data. Regardless of the model or even the scenario, the expected conditions will cause a slight deterioration in habitat conditions, especially at lower altitudes, shrinking the spruce forest area (Socha and Durło 2012).

As already demonstrated (Pauli et al. 1996;

Thuiller et al. 2005; Lindner et al. 2010; Milad et al. 2011; Gottfried et al. 2012), the observed rate of upward plant movement as an ecological response to temperature increase includes a significant time lag. Moreover, due to the heterogeneity of the mountain microclimate patterns, which are strongly dependent on local conditions as well as the biodiversity of the mountain ecosystem, the shift is first expressed by a modification in habitat composition. As plant species react individually and adaptation processes differ, climate change may lead to novel species inter-dependencies and competition, which may result in the development of new habitats. These observations suggest that detailed studies on the spatial variability of climate elements, especially temperature and precipitation, should be followed by environmental research, including land cover and, as proved by Hlásny et al. (2016), land use as well as demographical indices. Disturbed ecosystems (e.g. overexploited) are more sensitive to natural hazards and also climate (Theurillat and Guisan 2001); therefore, only multicomplex variables will allow researchers to identify climate-change hot spots.

4 Conclusions

Numerous studies have confirmed that high elevation environments, due to their importance to hydrological processes (glaciers, snow, permafrost, water) as distinguished by the uppermost limits of vegetation, are among the most vulnerable to climatic change (Diaz et al. 2003; Švajda 2008). Land ecosystems are unquestionably climate-dependent. Therefore, any change in climate parameters may lead to either positive (e.g. increasing productivity via air temperature increase) or negative (e.g. decreasing productivity as a result of intensified drought repercussions) changes.

The present study proves that the Western Carpathian region has been warming faster than the global or hemispheric averages; however, it must be noted that the magnitude of these changes, as well as their additional environmental impact, is seasonally and elevation dependent. The foothills have experienced more intensive temperature increases during summer, whereas the winters have warmed more at the summits.

In the succeeding decades, the Carpathian climate overall will be characterized by warmer seasons. The proven upward shift in climatic vertical zones suggests that in the forthcoming time-periods, one can expect temperature-driven changes in the environmental structure. However, since the humidity conditions, as expressed by the precipitation amount, are trendless and highly spatially differentiated, increasing temperature will drive more intense evaporation and might ultimately cause moisture failure. Since the expected feedbacks are mostly connected to the growing season, the possible expansion of thermophilic species might only result in a reduction of hydrophobes. To ensure ecosystem sustainability it appears to be necessary to reintroduce mixed stands in place of the pure spruce stands that are currently prevalent, mostly at the lower altitudes of the range. It also needs to be emphasized that any future planning concerning land use management should consider the complex climate element together with human activity, since this activity represents one of the most important factors influencing land cover in the Carpathians.

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