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Climatic Changes and Their Relation to Weather Types in a Transboundary Mountainous Region in Central Europe

Andreas Hoy [1,2,*], Nils Feske [1], Petr Štěpánek [3,4], Petr Skalák [3,4], Andreas Schmitt [5,6] and Petra Schneider [5,7,*]

1 Saxon State Agency for Environment, Agriculture and Geology, Department of Climate, Air, Noise and Radiation, Pillnitzer Platz 3, D-01326 Dresden, Germany; nils.feske@yahoo.de
2 TU Bergakademie Freiberg, Interdisciplinary Environmental Research Centre, Brennhausgasse 5, D-09599 Freiberg, Germany
3 Global Change Research Centre AS CR, Bělidla 986/4a, 603 00 Brno, Czech Republic; stepanek.p@czechglobe.cz (P.Š.); skalak.p@czechglobe.cz (P.S.)
4 Czech Hydrometeorological Institute, Na Šabatce 17, 143 06 Praha, Czech Republic
5 C&E Consulting und Engineering GmbH, Jagdschänkenstr. 52, D-09117 Chemnitz, Germany; andreas.schmitt@cue-chemnitz.de
6 IAF-Radioökologie GmbH, Wilhelm-Rönsch-Strasse 9, D-01454 Radeberg, Germany
7 Department of Water, Environment, Construction and Safety, University of Applied Sciences Magdeburg-Stendal, Breitscheidtstrasse 2, D-39114 Magdeburg, Germany
* Correspondence: andreas.hoy@ioez.tu-freiberg.de or andreas.hoy@tu-freiberg.de (A.H.); petra.schneider@hs-magdeburg.de (P.S.)

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Abstract: A first-time common cross-border assessment of observed climatic changes in the Saxon–Bohemian region was the aim of the German–Czech climate cooperation INTERKLIM. This paper focuses on the observed changes of temperature and precipitation averages and extremes within the period 1961–2010, investigating how variations of a range of climate indices were regionally shaped by changes in frequency and character of weather types. This investigation serves to enhance our understanding of the regional climate characteristics to develop transboundary adaptation strategies and focuses on the classification of the "Grosswetterlagen" using the parameters of air temperature and precipitation. Climate data were quality controlled and homogenized by a wide range of methods using the ProClimDB software with a subsequent comprehensive regional visualization based on Geographical Information Systems. Trends for the temperature averages showed increasing trend values mainly from January to August, especially for high temperature extremes. Precipitation trends displayed regionally varying signals, but a strong spatially uniform decrease from April to June (early growing season) and a distinctive increase from July to September (late growing season). Climatic changes were supported by frequency changes of weather types, e.g., the drying from April to June was related to a decrease/increase in patterns causing rather wet/dry conditions, while from July to September opposite trends were observed. Our results represent regional climatic changes in a complex topography and their dependency on variations in atmospheric circulation peculiarities.

Keywords: transboundary regional climate change; climate extreme indices; impact of weather types; Grosswetterlagen; ProClimDB; Germany; Czech Republic

1. Introduction

Recent decades have been characterized by increasingly noticeable changes in the global climate system, accompanied by distinct regional anomalies. For instance, the large positive mean temperature anomalies, observed since the 1990s in most areas of mid and high northern latitudes, are unique in their extent and magnitude [1–3]. Such observed climatic changes are no longer explained solely by natural climate variations and are increasingly connected to the human-induced increase of tropospheric greenhouse gas concentrations [1,4], which are projected to accelerate in the coming decades [1].

Future extremes will have much larger impacts than climate variations observed to date due to a higher base-line of temperature averages. Already, the number, frequency and intensity of high temperature extremes are increasing globally, while low temperature extremes are declining [5–7]. The regional expression of climatic changes is strongly related to changes in the frequency and duration of large-scale weather types—within Europe, often assessed through the Grosswetterlagen classification. For instance, they modulate regionally varying patterns of decreasing winter severity and increasing growing season length [8,9], as well as increasing extreme precipitation situations (especially subdaily extreme rainfall) in most parts of Europe [2,7]. Heavy precipitation events specifically increase the vulnerability of society and in particular sensitive infrastructure [10]. Caspary and Hennegriff [11] developed the term "critical Grosswetterlage" to express the increasing risk of that kind of climate impact. To manage the global challenges related to climate impacts, the United Nations developed the Sustainable Development Goals under the Agenda 2030, and particularly Goal 13: Climate Action [12]. The Sustainable Development Goal 13 particularly aims to strengthen resilience and adaptive capacity to climate-related hazards and natural disasters; to integrate climate change measures into national policies, strategies and planning; and to improve education, awareness-raising and human and institutional capacity for climate change mitigation, adaptation, impact reduction and early warning. This study supports the implementation of the SDGs through the provision of information on observed climate trends based on a long-term database to be used for the development of climate adaptation strategies in the region of the Ore Mountains.

Past and present climate variations have been investigated only separately for the orographic and scenic features, thus a climatic diverse area is in focus here, i.e., Saxony and the northern parts of the Czech Republic—located in the heart of Central Europe. For Saxony, Roberts et al. (2004) [13] collected, quality-checked and homogenized a large amount of regional climate data. They reported pronounced climate trends for several meteorological elements (averages and trends) during 1951–2000. Küchler and Sommer (2005) [14] compiled a comprehensive publication about observed and projected climate changes in Saxony, the role of climate change and climate impacts to/adaptation possibilities of various ecosystem services. Specific emphasis was placed on heavy precipitation events, related to the events observed in August 2002 (flooding) and 2003 (drought). Saxon climate characteristics and changes during 1961–2005 were investigated for the publication "Saxony under Climate Change" by the Saxon State Ministry of Environment and Agriculture (2008) [15]. Therein, the spatial climate diversity of the county was shown by an extensive number of maps comparing the two time periods 1961–1990 and 1991–2005. This publication was extended in 2015 by the Saxon State Agency for Environment, Agriculture and Geology [16] to 1961–2010 (comparing 1961–1990 and 1981–2010) and expanded by evaluations based on hourly data for 1991–2010. Besides those comprehensive reports on Saxon climatology, several further publications have focused on specific issues. Enke et al. (2007) [17] and Spekat et al. (2008) [18] analysed blocking situations and pathways of low-pressure areas over Europe with a specific focus on their effects on Saxony. Hoy (2008, 2013) [19,20] investigated observed and projected climate changes in Saxon low mountain ranges, their impacts on regional winter tourism and the touristic adaptation potential. Hänsel (2008) [21] and Hänsel et al. (2009) [22] studied changes in Saxon precipitation characteristics in the 20th and early 21st century with specific emphasis on heavy precipitation events and drought. Hänsel et al. (2015) [23] expanded those approaches by employing additional methods and related observed and modelled precipitation data for 1901–2100. Löser et al. (2011) [24] and Schneider et al. (2011a) [25] investigated the impact of the projected temperature and precipitation change on Saxon water bodies such as rivers, reservoirs and groundwater and suggested options for adaptation. The spatiotemporal characteristics of lightning events were investigated by Schucknecht and Matschullat (2014) [26] for 1999–2012 by means of Siemens BLIDS data, showing a large inter-annual frequency variability and strong links to specific weather types. A climate adaptation program was developed for the Saxon city of Chemnitz by Schneider et al. (2011b) [27], involving climate data for 1961–2010. The REGKLAM project on regional climate change adaptation (www.regklam.de) focused on the region of Dresden in central Saxony. Project publications include a general assessment of climate conditions and trends for 1961–2005 by Bernhofer et al. (2009) [28], as well as investigations of drought, heavy precipitation and atmospheric circulation by Hoy and Hänsel (2009) [29] and Hänsel and Hoy (2013) [30].

The climate of the Czech lands in the 20th century has been described in numerous studies published by the Czech Hydrometeorological Institute (CHMI). The "Climate Atlas of Czechia" [31] describes the characteristic features of the Czech Republic's climate for all available meteorological parameters and observations for 1961–2000 [31]. It follows a series of publications by the National Climate Program on different aspects of the Czech climate for 1961–1990—analysing air temperature [32], air pressure [33], wind speed and direction [34], soil temperature [35] and climate variability in relation to atmospheric circulation [36]. A comprehensive analysis of future climate conditions in the Czech Republic was conducted by [37] in the frame of the project "Specification of existing estimates of climate change impacts in hydrology, water management, agriculture and forestry sectors and proposals for adaptation options". The evaluation of future climatic changes was based on simulations of CMIP4 global circulation models and the regional climate model ALADIN-Climate-CZ [36,37].

Cross-border investigations, combining and harmonizing different approaches, are necessary for the development of regional adaptation strategies, including long-term regional planning. The observations of the last decades show that climate change is already taking place in the cross-border region observed here, and it affects the daily life of the inhabitants [27,29]. While the frequency of extreme heavy rainfall events increases, winter sport areas face an uncertain future [38,39]. As such, a harmonized approach is dearly needed considering the topography of both areas. The German–Czech climate cooperation INTERKLIM addressed the regional transboundary exchange, processing and assessment of observed and projected climate data in the Saxon–Bohemian border area. For the first time, common cross-border regional evaluations of observed climatic changes and climate projections were developed, aiming at the development and evaluation of a cross-border data and knowledge base. Depending on the climatic classification, the investigated Saxon–Czech border region belongs to the climate zone of suboceanic cooling according to Troll and Paffen [40], while, according to Köppen [41] and Geiger [42,43], the area belongs to the beech climate of warm climates. By contrast, the higher elevations of the study area are already attributable to the birch climate of the boreal subarctic climates.

This paper presents selected results of the INTERKLIM project, namely observed changes of temperature and precipitation averages and trends in the period 1961–2010, and how they were regionally modulated by character and variations in the frequency of weather types. A main challenge of the scientific approach was to cope with the complex topography of the study area in the frame of the visualization of regional specifications of certain weather types using Geographical Information Systems. This contribution is organized as follows: Section 2 introduces the study area, climate dataset and methods. Section 3 presents climatic changes within the study region, while Section 4 relates them to regional peculiarities of weather types, followed by the conclusions in Section 5.

2. Data and Methods

2.1. Study Area Characteristics

The study area covers the south of the Federal State of Saxony in Germany and the north of the Bohemian region in the Czech Republic (Figure 1). The northern lowlands (Saxony/Germany) are separated from their southern counterparts (Bohemia/Czech Republic) by a belt of low mountain ranges (Figure 2). Furthermore, pronounced topographic differences shape the Bohemian part of the study area, related to many mountainous formations with volcanic origin.

Figure 1. Location of the study area in Central Europe (map source: National Geographic Society, Atlas of the World).

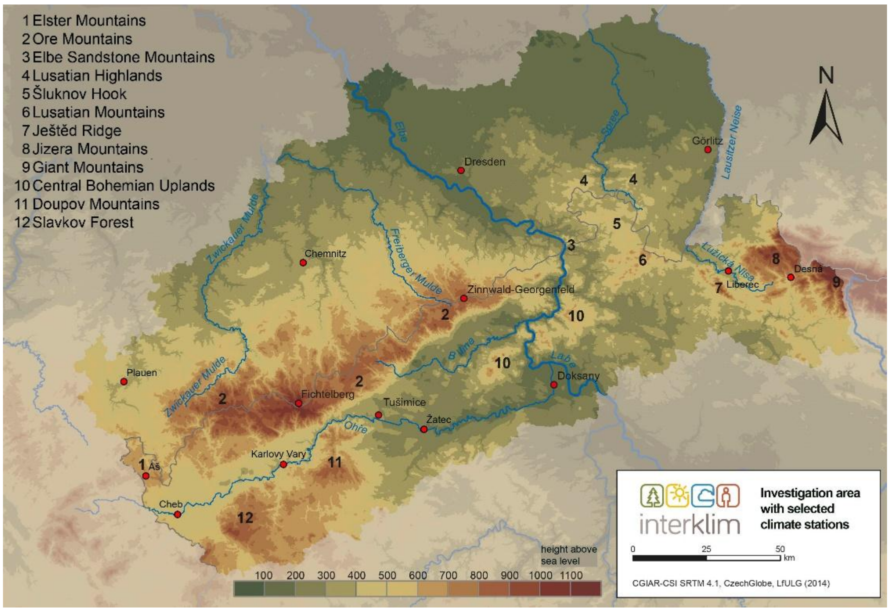


Figure 2. Physical map of the investigation area with selected climate stations and major orographic features; the thin grey line marks the border between Saxony (Germany) in the north and northern Bohemia (Czech Republic) in the south; adapted from LfULG 2014 [44].

The Ore Mountains (called Erzgebirge in Germany or Krušné hory in the Czech Republic) are the most important mountain chain separating both countries (#2 in Figure 2). For around 800 years, they have formed an administrative border between Saxony and Bohemia, and, after World War II, the border between Germany and the Czech Republic was established just north of the main crest of the mountain range. The average height is around 700 m a.s.l., while the highest peaks are Klínovec on the Czech side (1244 m a.s.l.) and Fichtelberg on the German side (1215 m a.s.l.). Since in higher elevations a large part of the precipitation falls as snow, long-lasting snow cover forms during the winter usually lasting until April. Hence, a well-developed winter tourism region has evolved in the region [38,39].

The study area is determined by a gradual shift from the maritime western European climate towards the more continental climate of Eastern Europe. The balancing effect of the Gulf Stream strongly impacts the region, resulting in higher average temperatures (1961–2010 area mean: 7.8 °C; Figure 3 for spatial details) and lower seasonal changes than in regions of similar geographical latitudes in northern America, eastern Europe and northern Asia [15,28]. However, the apparent continental influence results in comparably low precipitation amounts (1961–2010 area mean: 740 mm; Figure 4 for spatial details), despite the hilly character of the study area. The spatial distribution of precipitation is modulated by windward/leeward effects. The largest precipitation amounts are registered in the Ore Mountains and the western Sudetes (Jizera and Giant Mountains) in the east with up to 1600 mm/year. In contrast, the Lowlands of Bohemia in the central southern part of the study area—prone to leeward effects of the mountains in their west and north—only receive between 400 and 500 mm/year. The lowlands in Saxony in the northern part of the study area benefit from a comparably high frequency of moist air masses approaching from north and northwest, leading to larger precipitation amounts than in their southern counterparts.

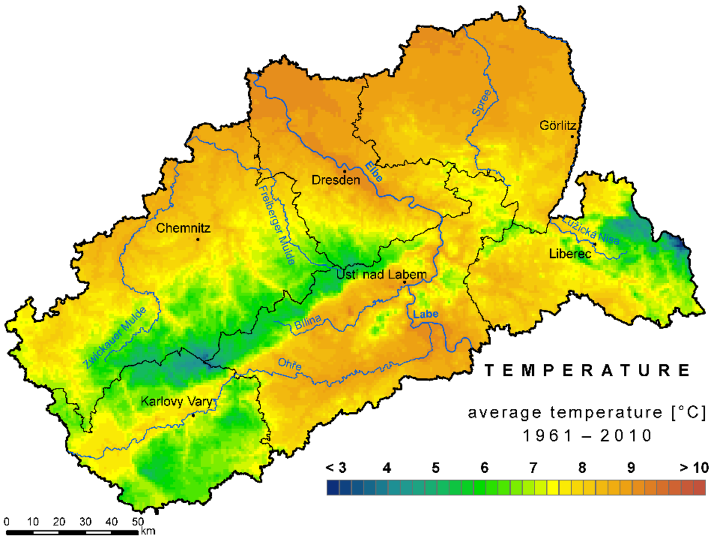


Figure 3. Annual temperature average in the study region in 1961–2010; adapted from LfULG 2014 [44].

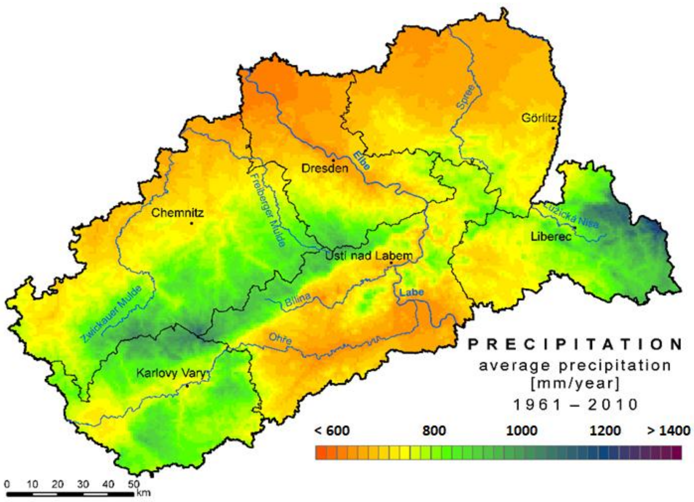


Figure 4. Annual precipitation average in the study region in 1961–2010; adapted from LfULG 2014 [44].

2.2. Climate Data and Processing

Daily air temperature (daily average, minimum and maximum) and precipitation data of 65 meteorological stations (42 in Saxony and 23 in the Czech Republic) were employed in this study for the period 1961–2010, provided by the German Weather Service and the Czech Hydrometeorological Institute (see Excel file as Supplementary Materials). Additionally, the German Weather Service provided 300 stations observing precipitation only for the Saxon part of the study area. The limited number of stations on the Czech side is a consequence of the strict data policy of the Czech Hydrometeorological Institute, demanding payment dependent on the amount of climate data ordered.

The original time series covering the full period 1961–2010 were available for some stations only. Most stations include a certain degree of gaps for one or a period of days or months or sometimes even longer periods. Thus, the following approach was applied to establish time series without missing values at all stations. It consists of three major steps: quality assurance, homogenization and gap filling. The entire process was developed and described in detail by Štěpánek et al. [45–47]; it was carried out using the ProClimDB software package [48] and is summarized in Figure 5.

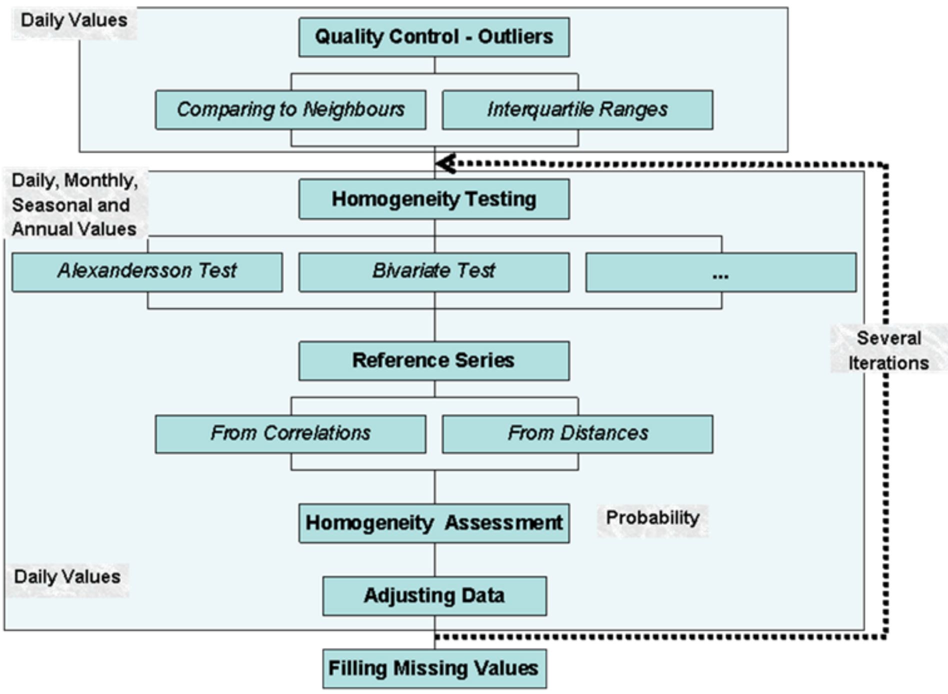


Figure 5. Data processing scheme (Alexandersson and Bivariate Tests are examples of homogeneity testing, " . . . " denotes that a different and/or larger number of tests may be employed).

Data processing started with quality control, aiming at detecting outlier values in the original data. It was carried out by combining the following three methods:

(i) analysing time series of differences between candidate and neighbouring stations (i.e., pair-wise comparisons = individual comparison of candidate (tested) series with neighbours; the number of neighbours determines the number of comparisons);
(ii) applying limits derived from inter-quartile ranges; and
(iii) comparing time series of tested values with "expected" (theoretical) values of "technical" series created by means of statistical methods for spatial data. "Expected" values were estimated as weighted means (IDW method) from values of neighbouring stations, standardized by altitude. The weights are reciprocal values of distances, with a given power (one for temperature, three for

precipitation). "Technical" series are artificial time series of the same station. Compared to raw data, they are homogenized and do not include gaps.

The next step was a homogenisation of daily time series. The following homogeneity tests were applied:

(i) Standard Normal Homogeneity Test [49,50];
(ii) Maronna and Yohai Bivariate Test [51]; and
(iii) Easterling and Peterson Test [52].

Reference series for homogeneity testing were calculated as weighted averages from the six nearest stations (measuring within the same period as candidate series) with statistically significant correlations. By creating reference series as an average of surrounding stations, we suppress the possible effects of inhomogeneous reference series. Weighted averages are used, because the similarity of neighbouring stations with the candidate series decreases with distance.

After an evaluation of detected breaks and their comparison with metadata, a final decision on the correction of inhomogeneities was made. Data were corrected on a daily scale using the distribution fitting method based on percentiles (for more details, see [44]). The described steps (homogeneity testing, evaluation and correction of inhomogeneities) were performed in several iterations, leading to more precise results. Several iterations were conducted because series of neighbouring stations—used to create reference series for homogeneity testing and correction—include inhomogeneities as well. Even if time series of neighbouring stations were averaged, and thus inhomogeneities in individual neighbouring stations were suppressed, such inhomogeneities would still affect our results. Therefore, we ran 3–4 iterations of homogeneity testing and correction to identify a higher number of potential breaks. Therewith, we were able to use identified homogeneous parts of the time series of neighbouring stations only to establish reference series. The following final correction thus included the generated knowledge about the identified breaks.

Finally, individual missing values or time periods were calculated based on statistical relations of the candidate station with gaps compared to neighbouring stations.

2.3. Climate Indices

Rare meteorological events are part of the natural climate variability. They require special attention due to the potential damages they may cause. Changes in their frequency allow us to specify which kinds of climate extremes react most sensitively to general climate change. Therefore, climate indices are used to investigate changes in rare meteorological events. Eleven extreme temperature indices—mainly defined by the World Meteorological Organisation (WMO; [53]) and the European Climate Assessment and Dataset ([54]; see Table 1)—are used in the Section 3, comparing the period 1991–2010 with 1961–1990. The period 1961–1990 is recommended as the base period for climate change investigations by the WMO, while 1991–2010 includes a period already strongly affected by climatic changes in the region [15,16]. The year 1961 was chosen as a start because climate data of the Czech side of the investigation area were not available in a quality-controlled status beforehand. They include five threshold-based and four percentile-based indices on daily basis, plus two percentile-based indices indicating extreme warm/cold periods of at least six days duration. Percentile-based indices allow for a direct comparison between stations independent of their altitude, local-specific peculiarities and the annual temperature cycle. The ones used here include the ten per cent of days with the lowest/highest minima/maxima in the base period 1961–1990. Five meteorological stations are employed, representing the south-western (Karlovy Vary, 603 m), north-western (Chemnitz, 418 m), south-eastern (Görlitz, 238 m) and north-eastern (Liberec, 398 m) parts of the study area, as well as the mountain station Fichtelberg (Section 3.1).

Table 1. List of extreme temperature indices (see [53,54] for additional details; abbreviation SF: definition used in this study).

Abbreviation	Designation	Description
TN10p	cold nights	count of days with a daily minimum temperature < 10th percentile of all days during 1961–1990, after removal of annual cycle
TX10p	cold days	count of days with a daily maximum temperature < 10th percentile of all days during 1961–1990, after removal of annual cycle
CSDI	cold periods	count of days in a span of ≥6 days with a daily minimum temperature < 10th percentile (see TN10p)
FD	frost days	count of days with a daily minimum temperature < 0.0 °C
ID	icing days	count of days with a daily maximum temperature < 0.0 °C
SF	days with severe frost	count of days with a daily minimum temperature ≤ −10.0 °C
TN90p	warm nights	count of days with a daily minimum temperature > 90th percentile of all days during 1961–1990, after removal of annual cycle
TX90p	warm days	count of days with a daily maximum temperature > 90th percentile of all days during 1961–1990, after removal of annual cycle
WSDI	warm periods	count of days in a span of at least six days with a daily maximum temperature > 90th percentile (see TX90p)
SU	summer days	count of days with a daily maximum temperature ≥ 25.0 °C
HD	heat days	count of days with a daily maximum temperature ≥ 30.0 °C

Very high or low precipitation amounts affect sectors such as agriculture, forestry, urban planning and others. Heavy precipitation events may last from only a few minutes up to a couple of days, while precipitation deficits accumulate over longer time periods from weeks to years. To evaluate changes in the frequency of precipitation or drought days, eight heavy precipitation indices and two indices showing drought conditions are used (Table 2), comparing frequencies in 1991–2010 with 1961–1990. Three indices representing heavy precipitation are percentile-based daily indices (R75/95/99p) and three are threshold-based (RR1/10/30), representing moderate to extreme precipitation events. CWD-a and RRX (CDD-a and TRK) comprise periods of wet (dry) conditions with a certain duration or minimum duration (Section 3.2).

Table 2. List of extreme precipitation indices (see [39,40] for additional details; CWD-a/CDD-a: adapted to annual maximum; RRX/TRK: based on/adapted from [41]).

Abbreviation	Designation	Description
R75p	moderate wet days	count of days with precipitation sum on a wet day (RR1) > 75th percentile of daily amounts during 1961–1990
R95p	very wet days	count of days with precipitation sum on a wet day (RR1) > 95th percentile of daily amounts during 1961–1990
R99p	extremely wet days	count of days with precipitation sum on a wet day (RR1) > 99th percentile of daily amounts during 1961–1990
RR1	wet days	count of days with precipitation sum ≥ 1 mm
R10mm	heavy precipitation days	count of days with precipitation sum ≥ 10 mm
R30mm	extremely heavy precipitation days	count of days with precipitation sum ≥ 30 mm
CWD-a	consecutive wet days	annual maximum length of wet spell (count of days with precipitation sum ≥ 1.0 mm)
RRX	wet periods	count of days in a span of ≥ 3 days with daily precipitation sum ≥ 5.0 mm
CDD-a	consecutive dry days	annual maximum length of dry spell (count of days with precipitation sum < 1.0 mm)
TRK	drought periods	count of days in a span of ≥ 10 days with daily precipitation sum ≤ 0.5 mm

2.4. Weather Types

The Grosswetterlagen classification of large-scale weather patterns is used in this study, initially established by the German meteorologist Franz Baur [55–57] and further refined by Paul Hess and Helmut Brezowsky [58,59]. This classification was developed specifically for Central Europe and can be seen as one of the most appropriate tools to analyse atmospheric circulation impacts on regional climate variability in the study region. The Grosswetterlagen classification performs excellently in a comparative study with 73 different classifications by Huth [60] in Central Europe as well as the whole European region in describing surface temperature variations. James et al. [61] evaluated the Grosswetterlagen classification as "the best conceptual system currently available" for the North Atlantic-European region. Automated versions of the Grosswetterlagen classification may, dependent on the concept, differ in weather pattern frequencies, but they give similar results in terms of the regional expression of their relation to climate elements [20].

"Grosswetterlagen" (weather types) define atmospheric processes grouped into weather types including days with similar characteristics lasting from at least three days up to several weeks. They are determined by: (1) similar geographical distributions and spatial movements of steering pressure areas, i.e., anticyclones and cyclones, troughs and ridges; (2) comparable directions of air mass inflow; and (3) similar attributes of air masses. The Grosswetterlagen classification employs 29 Grosswetterlagen, which may be combined to more general types, e.g., ten "Grosswettertypen" (major types; see Table 3 and Werner and Gerstengarbe 2010). In [20], a comprehensive discussion about: (a) the historical development of the Grosswetterlagen classification; (b) occurrence, frequency variability and trends of circulation types; and (c) relations to sea level pressure, temperature and precipitation in the North Atlantic-European area can be found.

Table 3. Weather types (Grosswetterlagen) and major types (Grosswettertypen) of the Grosswetterlagen classification (after [62]); their average frequencies are given for 1961–2010 in winter half year (October to March) and summer half year (April to September); the most frequent Grosswetterlagen are marked in italic.

Großwettertypen (GWT)		**Frequency [%]**		**Großwetterlagen (GWL)**		**Frequency [%]**	
		WHY	**SHY**			**WHY**	**SHY**
W	West	30	22	***WA***	*Anticyclonic Westerly*	5,1	5,4
				WZ	*Cyclonic Westerly*	18,5	13,9
				WS	South-Shifted Westerly	3,7	1,6
				WW	Westerly, Block Eastern Europe	3,0	1,4
SW	Southwest	8	7	**SWA**	Anticyclonic South-Westerly	3,6	2,5
				SWZ	*Cyclonic South-Westerly*	4,6	4,7
NW	Northwest	8	6	**NWA**	Anticyclonic North-Westerly	2,2	2,2
				NWZ	*Cyclonic North-Westerly*	6,3	4,2
HME	Anticyclone over Central Europe	16	17	***HM***	*High over Central Europe*	6,7	5,3
				BM	*Zonal Ridge across Central Europe*	9,4	11,9
TME		1	3	**TM**	Low (Cut-Off) over Central Europe	1,3	2,6
N	North	14	17	**NA**	Anticyclonic Northerly	0,4	0,9
				NZ	Cyclonic Northerly	2,5	2,3
				HNA	Icelandic High, Ridge Central Europe	1,5	2,6
				HNZ	Icelandic High, Trough Central Europe	1,3	2,2
				HB	High over the British Isles	3,0	3,4
				TRM	*Trough over Central Europe*	5,3	5,8
NE	Northeast	1	4	**NEA**	Anticyclonic North-Easterly	0,5	1,8
				NEZ	Cyclonic North-Easterly	0,8	2,0
E	East	7	9	**HFA**	Scandinavian High, Ridge Central Europe	2,5	3,2
				HFZ	Scandinavian High, Trough Central Europe	1,3	1,8
				HNFA	High Scandinavia-Iceland, Ridge C. Europe	1,0	1,9
				HNFZ	High Scandinavia-Iceland, Trough C. Europe	1,9	2,4
SE	Southeast	5	2	**SEA**	Anticyclonic South-Easterly	2,8	1,1
				SEZ	Cyclonic South-Easterly	1,8	0,7
S	South	8	12	**SA**	Anticyclonic Southerly	2,0	1,1
				SZ	Cyclonic Southerly	1,3	0,3
				TB	Low over the British Isles	1,5	2,8
				TRW	*Trough over Western Europe*	3,3	7,5

2.5. Spatial Visualisation of the Results

Spatial maps of: (a) mean temperature and precipitation conditions; (b) change signals comparing the time frames 1961–1990 and 1991–2010; and (c) anomalies of weather types from long-term climate averages have been created for different periods (e.g., yearly, half-yearly, growing periods, etc.), using the software ArcGIS 9.3.1 (ESRI, Redlands, CA, USA). The interpolated maps of temperature and precipitation values were created by using interpolation modules of the water balance model WaSiM-ETH [63,64]. A combination of elevation-dependent regression (EDR) and inverse-distance-weighting (IDW) was applied as the interpolation method. The EDR was conducted using the WaSiM-ETH module REGRESS to assess the elevation-dependent changes of the climate parameters while taking into account observed latitudinal and longitudinal gradients. Combining equidistant weighting with IDW then allowed us to calculate the weighted mean of both interpolation methods [65]. The weighting factor was determined by the magnitude of the elevation dependency of the respective climate parameter [63,64].

3. Observed Climate Changes

This section discusses the observed temperature and precipitation variability in the study area for 1961–2010. Relations to variations in weather types are examined in Section 4.

3.1. Temperature

The seasonal temperature cycle of the study region is characterized by lowest temperatures in January and highest in July [15]. Annual temperature variations of the city of Dresden (Saxony) in the past 200 years are displayed based on [28] in Figure 6—those variations are typical for lower elevations in the study area. Variations are shown as an anomaly to the period 1961–1990, which corresponds almost exactly to the mean of the complete 20th century. The first period used in this publication (1961–1990) therefore includes temperature conditions characteristic of the 20th century. A considerably higher temperature level dominates since 1988, so the second time slice (1991–2010) used in this paper represents the recent remarkable temperature increase.

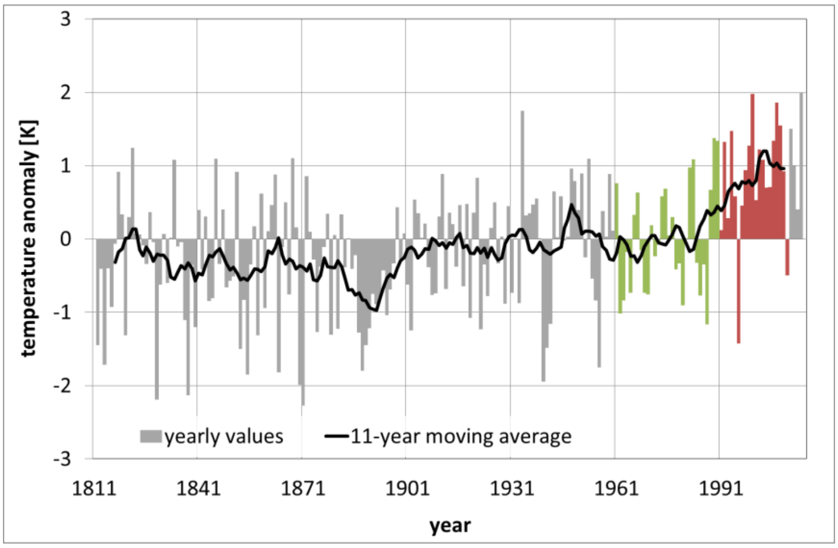


Figure 6. Time series (1812–2014) of annual temperature deviations of the 1961–1990 mean for Dresden (227 m)—the two time periods 1961–1990 (green) and 1991–2010 (red) are emphasized; adapted from LfULG 2014 [44], data based on [28].

Figure 7 shows the monthly low-pass-filtered time series and trends between 1961 and 2010 of one lowland station (Dresden) and the mountain station Fichtelberg in the Ore Mountains (1213 m; at the Saxon–Czech border). A similar temporal variability is visible between time series of both stations in most months, with few exceptions. Similarly, the trend magnitude and direction generally harmonize between both stations, but different magnitudes (e.g., June and December) and even directions (September) sometimes appear. The annual warming trend between 1961 and 2010, apparent in the study area, is mainly caused by increasing temperatures between January and August, while none or only weak warming signals are present in the last third of the year (Figure 7). The most pronounced warming took place in the middle of January and the end of April, comparing 1991–2010 with 1961–1990 (not shown).

Figure 8 shows change signals of temperature indices (defined in Table 1) for five meteorological stations (for their location, see Figure 2) located in the four corners of the study area. Both warm (increasing frequency) and cold extremes (decreasing frequency) indicate warming. Much larger signals for warm (TN90p and TX90p—about 20 days increase) than cold percentile-based indices (TN10p and TX10p—about five days decrease) indicate a stronger warming effect on warm than cold extremes. A stronger decrease of cold and a weaker increase of warm extremes at Fichtelberg, compared to the other stations, represent the generally colder conditions prevailing at higher altitudes.

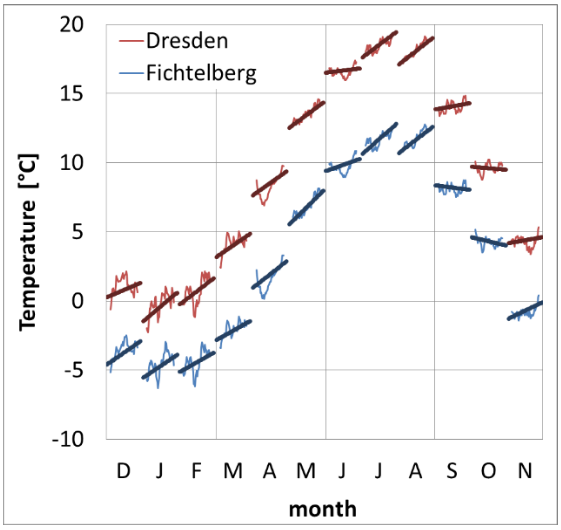


Figure 7. Monthly temperature variability (11-year mean) and linear trend for every month during 1961–2010 for Dresden (Saxony; 227 m) and Fichtelberg (Saxon–Czech border; 1.213 m). Trends are indicated as thick blue and red lines, from D = December to N = November; adapted from LfULG 2014 [44].

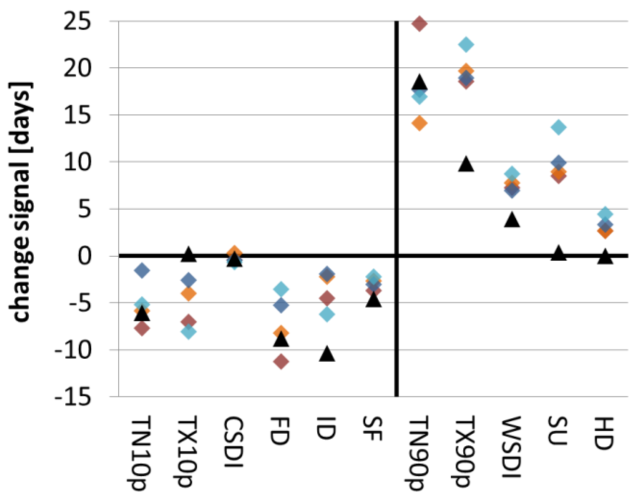


Figure 8. Change signal (1991–2010 vs. 1961–1990) of selected cold (left) and warm (right) temperature indices of five meteorological stations; four are located in low and hilly lands in the southwest (Karlovy Vary, 603 m), northwest (Chemnitz, 418 m), southeast (Görlitz, 238 m) and northeast (Liberec, 398 m) of the study area; additionally, one mountain station (Fichtelberg, 1213 m); adapted from LfULG 2014 [44].

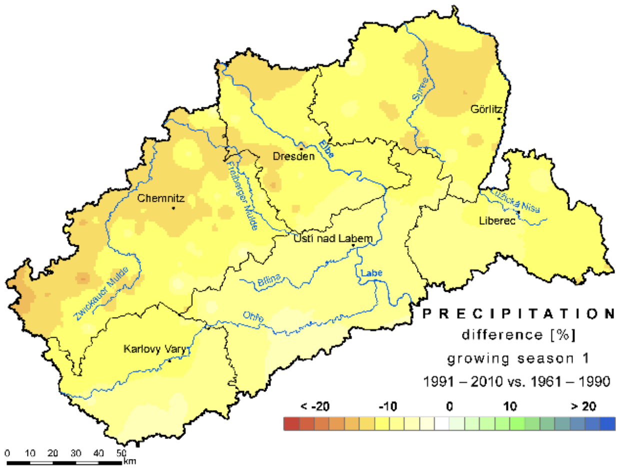
The strongest decreases of cold extremes (TN and TX10p) occurred in April and July/August (indicating warming), while they increased in autumn, especially October (indicating cooling). Warm extremes (TX and TN90p) increased most in January/February and July/August, while October and December exhibited a decrease at some stations. An increasing amplification of differences in the level of continentality between eastern and western areas is made visible by the smaller decrease of indices representing cold minima (TN10p, FD) and the larger increase of indices representing warm maxima (SU, HD) in the east than in the west. Periods with extremely low minima (CSDI) and extremely high maxima (WSDI) occurred, on average, at about five days/year at most stations in

1961–1990. The frequency of warm spells (WSDI) doubled or tripled throughout the study area in 1991–2010 to about 13 days/year. Warm spells occurred only every two to three years before 1988. Afterwards, at least one warm spell appeared most of the years and, on average, with a longer duration. On the contrary, cold spells (CSDI) remained constant (5 days/year) in 1991–2010. In summary, warm extremes increased more during the recent warming than cold extremes decreased in the study area, comparing 1961–1990 with 1991–2010. Changes towards warming were more pronounced in the summer than winter half year.

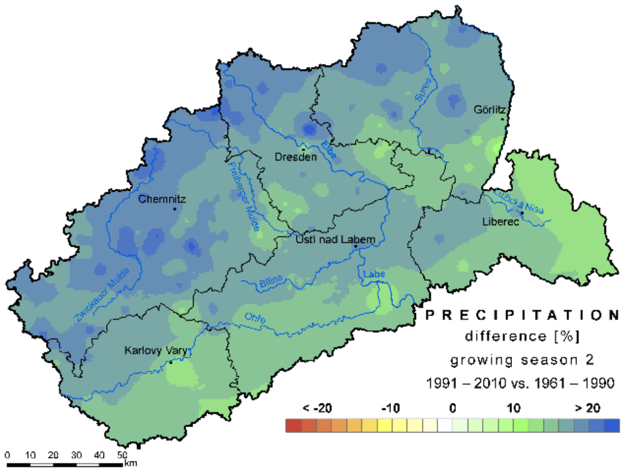
3.2. Precipitation

This paragraph is based on our own data treatment, without visual support. The study area is characterized by a precipitation maximum in July and August, connected to the annual maximum of convectional activity, and a minimum at the end of winter in February. In mountainous areas, the seasonal cycle is softened by windward-effects. Here, the second maximum is often observed in December connected to frontal activity, while the (second) minimum in October relates to often steady anti-cyclonic conditions during that time. Precipitation amounts are characterized by a large variability within and between the years. In certain years, the maximal annual precipitation may well exceed the long-term average by more than 50% at some stations (e.g., in 2010), while a precipitation lack of 40% or more has been observed as well (e.g., in 2003). Most of the study area was characterized by higher precipitation amounts in 1991–2010 compared to 1961–1990. A pronounced increasing trend has been detected at most stations between 1961 and 2010, which should not be over-interpreted considering the large year-to-year variability. Shifts of even a few years may already lead to distinctive changes of trend values, especially when considering seasons or months. For instance, shifting precipitation data on the German side of the study area during summer by one decade backwards (from 1961–2010 to 1951–2000) clearly changes the direction of precipitation trends from positive to negative, connected to a replacement of the rather wet 2000s with the similarly wet 1950s [23].

Inner-annually, the largest changes in precipitation amounts in 1991–2010 compared to 1961–1990 appeared in the growing season from April to September (Figure 9). Its division into two parts relates to agricultural needs. The early growing season lasts from April to June and represents the time of sowing and early growth. The late growing season lasts from July to September and comprises the time of late growth and harvest. Both growing seasons show very different change signals (Figure 9). They may be problematic for agriculture. Precipitation strongly decreased from April to June, when rain is greatly needed for growth. The largest changes occurred in April, when the average precipitation amounts decreased equally by about 2030 per cent at all stations. Congruously for 1991–2010, April replaced February as the driest month of the year at many stations. On the contrary, precipitation largely increased from July to September, the time of harvest, accelerated by a couple of very strong precipitation events in the 2000s.



(**a**)



(**b**)

Figure 9. Change signal (1991–2010 vs. 1961–1990) of precipitation amounts in the two growing seasons: (**a**) early growing season (April to June); and (**b**) late growing season (July to September); adapted from LfULG 2014 [44].

Figure 10 compares the frequency of precipitation indices between 1991–2010 and 1961–1990. Observed change signals are weak compared to those observed for temperature indices. Additionally, their spatial consistency over the project area is low. Days with high to extreme precipitation amounts (R95p, R99p, RR10, and RR30) increased in their frequency at most locations, with a spatially quite high consistency. Change signals of days with very high precipitation amounts (R99p and RR30) are—related to their rarity—hardly visible in Figure 10. However, to stay consistent between the indices shown in this paper, they are still given in days (and not percentages). A stronger increase of heavy precipitation events with altitude is linked to the generally larger precipitation amounts there. Wet periods (CWD and RRX) show a different development; especially, the area-wide flood-triggering three-day events (RRX) decreased in frequency. The extreme precipitation events in the central parts of the project area in August 2002 and in its eastern parts in August 2010, for instance, were associated with 24- to 48-h heavy precipitation. Those events exceeded the criteria for extremely wet days (R99p) at many stations and were embedded into periods with generally high precipitation amounts, but did not fulfil the criteria of CWD or RRX at most stations.

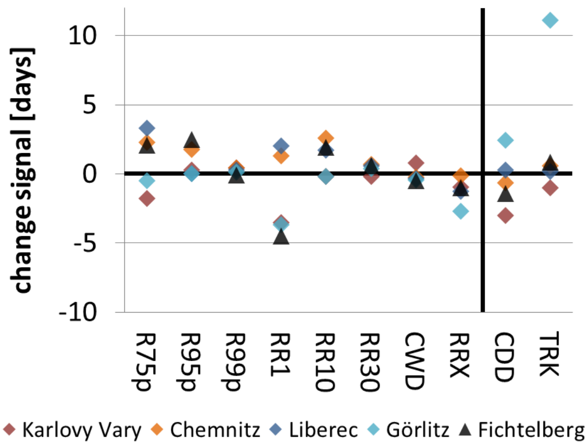


Figure 10. Change signal (average frequencies 1991–2010 vs. 1961–1990) of selected wet (left) and dry (right) precipitation indices of five meteorological stations (see Figure 8); adapted from LfULG 2014 [44].

Change signals for periods with distinctive precipitation deficits exhibit a pronounced slope from west to east. Analogous to annual precipitation increases, long dry periods (CDD, Figure 11) occurred less often in the western and central parts of the study area. Nonetheless, they remained constant or occurred slightly more often in the east (despite the observed precipitation increase). The intensification of drought periods (TRK) in Görlitz in the north-eastern part of the study area is particularly striking (Figure 10). Here, TRK increased by 11 days in their annual mean in 1991–2010 compared to 1961–1990. This rise mainly took place in the growing season with the largest increase in April (from a mean of four to eight days) as well as in August and September. While the April increase is consistent with decreasing precipitation amounts and was similarly observed in the rest of the project area, the increase in August and September occurred despite higher precipitation amounts (which, in turn, resulted from increasing heavy precipitation events).

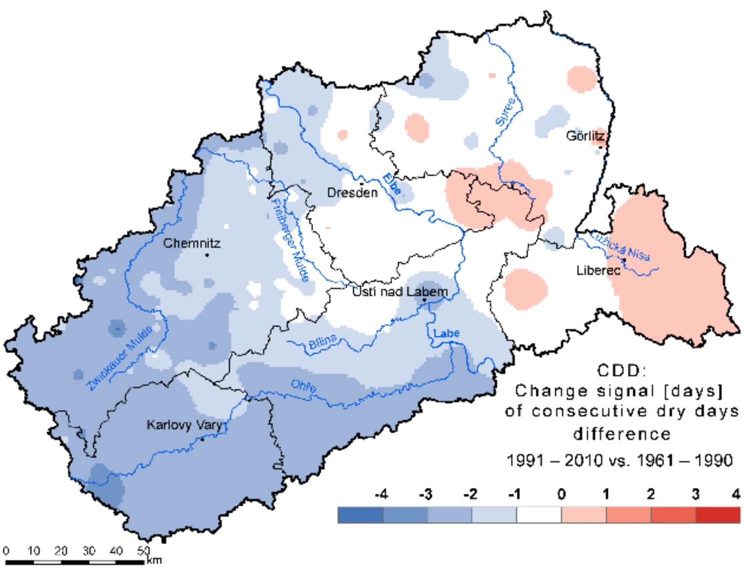


Figure 11. Change signal of average annual frequency of consecutive dry days (CDD); adapted from LfULG 2014 [44].

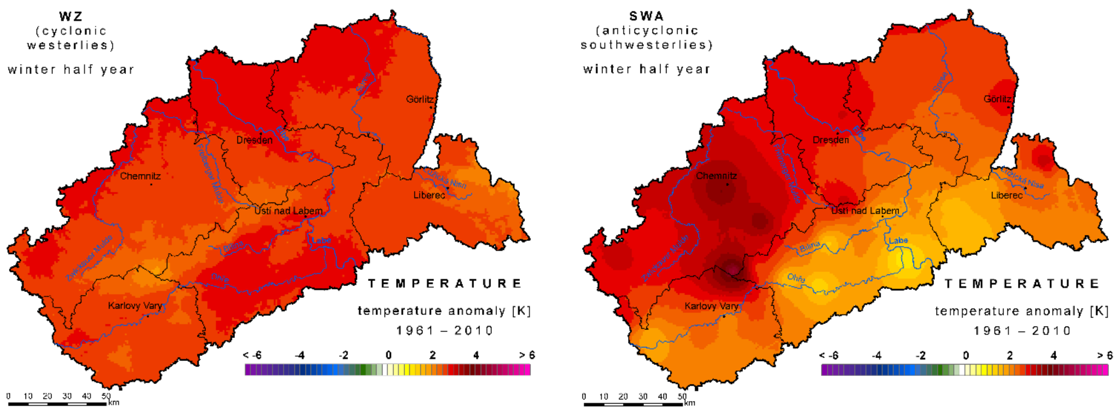
4. Relation of Climatic Changes to Weather Types

The character and frequency of large-scale weather types are important for analysing long-term climate fluctuations in the study region, on top of global processes such as increasing climate-relevant tropospheric greenhouse gas emissions and concentrations. In addition to shorter periods such as weeks or seasons, also longer-term climatic changes of averages, variability and extremes are quite well explained by frequency fluctuations of certain weather types, if their regional peculiarities are known. Hence, detailed maps of temperature and precipitation anomalies of all 29 weather types (Section 2.4) have been created. They help to describe the influence of atmospheric circulation within the study area, and how it affected recent climatic changes (such as the precipitation decline in growing season 1 and increase in growing season 2) illustrated in the previous section.

The study region is determined by fluctuations of maritime Atlantic and continental air masses approaching from northern, eastern or southern directions. The most frequent weather types are marked by grey background colour in Table 3. The Atlantic impact is distinctively stronger during the winter half year than the summer half year. Atlantic air mass inflow from the southwest, west and northwest—responsible for a variable weather character—dominates, on average, every second day during the winter half year, compared to every third day during the summer half year. During the latter, local and regional convection plays an important role, while synoptic-scale circulation—largely steered by the fluctuations of Icelandic Low and Azores High—is most important during the winter half year. Section 4.1 evaluates the character of weather types important for the climate of the study area, while Section 4.2 relates their frequency changes to climate fluctuations observed in the study region.

4.1. Character of Important Weather Types

Cyclonic westerly (WZ): The most common weather type is characterized by intensive cyclonal activity, impacting the study area by frequently passing weather fronts. Related to frequency and moisture content, WZ is an important supplier of precipitation. However, extreme precipitation events occur rather seldom compared to its frequency, since the weather fronts usually pass the study region quickly from west to east. The regional precipitation distribution is similar between seasons with the highest values in the mountains and lowest in the Bohemian Basin. Comparably warm temperatures dominate during the winter half year, and cold ones during the summer half year. The positive wintery thermal anomaly is more visible in the lowlands than in mountainous areas, associated with rarely observed temperature inversions (characterized by cooler temperatures in the lowlands than in the mountains) and windward-effects (cooling) in the mountains (Figure 12a).



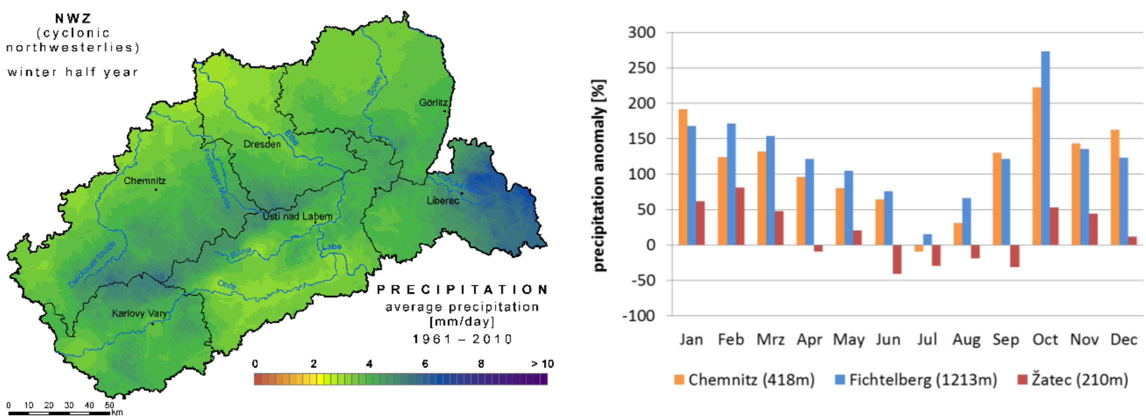
(**a**) (**b**)

Figure 12. Spatial distribution of temperature anomalies (in K) during the winter half year for: (**a**) WZ (cyclonic westerlies); and (**b**) SWA (anticyclonic south-westerlies); adapted from LfULG 2014 [44].

South-westerlies (SW): They are responsible for strong positive thermal anomalies year-round, coupled to the advection of warm/hot air masses from south-western Europe and north-western Africa. Prominent regional differences characterize anticyclonic south-westerlies (SWA) during the winter half year, linked to differences in the occurrence of temperature inversions (Figure 12b). Hence, western and central Saxony is usually characterized by rather high temperatures of 4–5 K larger than the long-term average, with a locally even stronger amplification by lee-effects. In contrast, often cold and foggy/cloudy conditions dominate in the Bohemian Basin, linked to the often low wind speeds during SWA, so that mean temperatures are only 2 K higher than the long-term average. The smaller thermal anomaly in the eastern Saxon border area is linked to the colder conditions in the Bohemian Basin. Air masses from those areas reach the German parts of the study area during inflow from southwest, south and southeast (the so-called "Bohemian Wind").

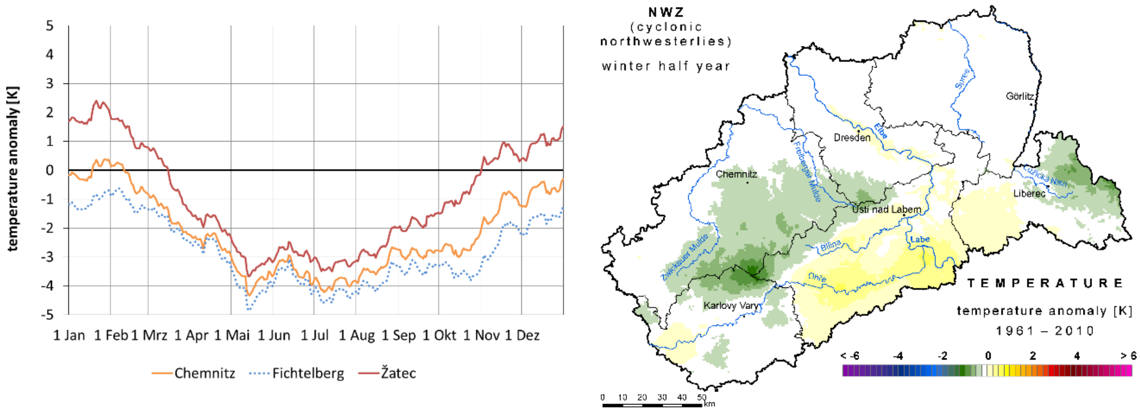
Cyclonic north-westerly (NWZ): Moist air masses from the North Atlantic stream against the Saxon–Czech border mountains and are forced to ascend, wherefore the NWZ is responsible for the largest precipitation amounts along the northern mountain ranges (Figure 13a). This topographically induced amplification is most relevant during the winter half year, where synoptic-scale circulations dominate over convective elements. About 20%–25% of moderately wet days (R75p), 25%–30% of very wet days (R95p) and up to 40% of extremely wet days (R99p) are connected to north-westerlies during the winter half year in the fore- and highlands of the border mountains, with greater values in higher elevations. On the contrary, NWZ´s relevance for summery heavy precipitation events is much lower (5%–10% for R75p, declining to 0%–5% for R99p). The leeward-orientated areas of northern Bohemia receive much less precipitation during NWZ (e.g., Žatec, Figure 13b).

Pronounced negative temperature anomalies dominate during the summer half year, while they are quite moderate during the winter half year (Figure 14a). Comparing north-westerlies and south-westerlies reveals astonishing regional phenomena. Marked windward-effects arise during NWZ in the western and central ranges of the Saxon Ore Mountains and the Ore Mountains forelands, leading to a strong temperature gradient between lowlands and mountains. In contrast, the wintery temperature inversion breaks up during the windy NWZ in the Bohemian Basin (contrarily to the calmer south-westerlies, Figure 12b), additionally causing leeward-effects. Both effects lead to warming, resulting in a similar temperature range during north-westerlies than south-westerlies in the Bohemian Basin (e.g., the January average in Žatec (201 m) is ca. 1 K higher during NWZ than during SWA)—in contrast to all other locations of the study region, where north-westerlies are always colder than south-westerlies year-round (Figure 14b).



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

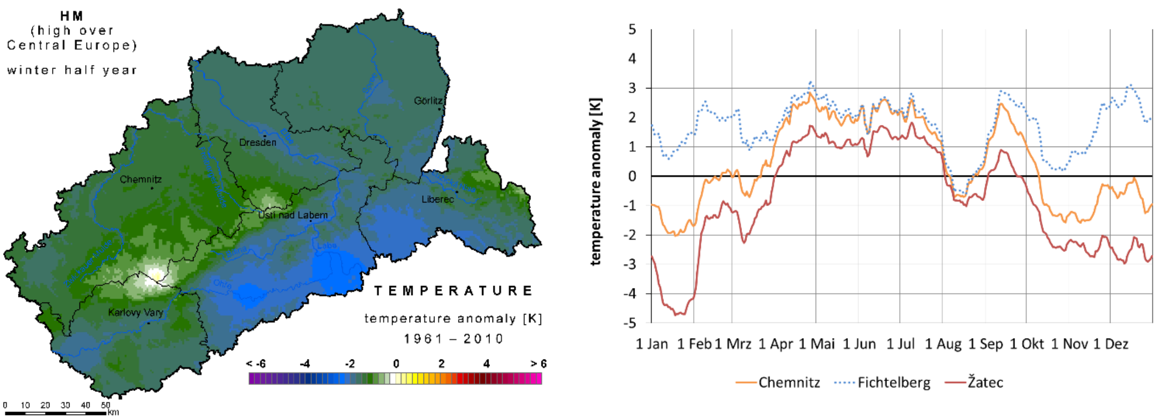
Figure 13. (**a**) Spatial distribution of precipitation anomalies (in percentage) during the winter half year; and (**b**) seasonal cycle of average precipitation anomalies (in percentage; from 1961–2010) for NWZ (cyclonic north-westerlies); adapted from LfULG 2014 [44].



(a) (b)

Figure 14. (**a**) Spatial distribution of temperature anomalies (in K) during the winter half year; and (**b**) seasonal cycle of average air temperature anomalies (in K; from 1961–2010) for NWZ (cyclonic north-westerlies); adapted from LfULG 2014 [44].

Anti-cyclonic conditions over Central Europe (HM): They are characterized by year-round dry and calm weather conditions and positive temperature anomalies, at least at higher altitudes. So-called Omega situations are often linked to HM, characterized by long and stable phases of blocking high-pressure areas. None or very little precipitation is observed in this context for weeks. Such weather situations were responsible for major drought events in the past. Spatially comparable positive temperature anomalies prevail during the summer half year independent of the altitude, while large differences appear during the winter half year. Here, sunny conditions prevail at the ridges of Ore Mountains and the Jizera and Giant Mountains in the east. These locations reside above the inversion layer, fostering positive temperature deviations there. In contrast, the Saxon lowlands and—more pronounced—the Bohemian Valley are characterized by negative temperature deviations (Figure 15a). The annual cycle of thermal anomalies from the long-term mean is shown in Figure 15b for three meteorological sites. The mountain station Fichtelberg displays positive temperature deviations year-round, while Chemnitz in the northern Ore Mountains foreland, and especially Zatec in the Bohemian Basin, observe a distinctive seasonal cycle connected to the prevailing temperature inversions.



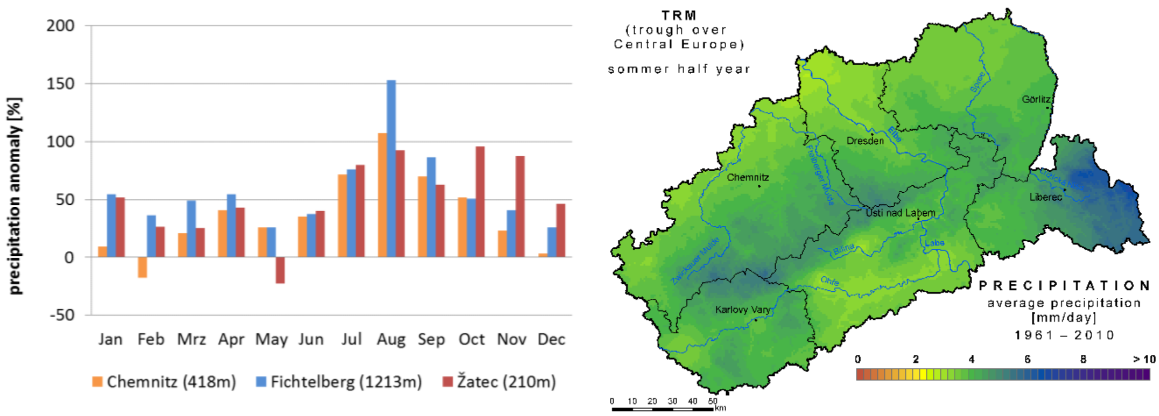
(a) (b)

Figure 15. (**a**) Spatial distribution of temperature anomalies (in K) during the winter half yea;r and (**b**) seasonal cycle of average air temperature anomalies (in K; from 1961–2010) for anticyclonic conditions over Central Europe (HM); adapted from LfULG 2014 [44].

Trough over Central Europe (TRM): The most severe floods and the largest flooding potential connect with this weather pattern. During TRM, a trough extends from northern to southern Europe across the study area. It blocks the usual path for Atlantic low-pressure systems from west to east through northern Europe. In some cases, low-pressure areas therefore move southwards towards the Mediterranean, receive abundant humidity over the Mediterranean Sea and wander back northwards towards the study area or passing it eastwards (so-called Vb-track; after [66]). Most of the largest 24-h precipitation amounts ever registered in the study area (and the eastern parts of central Europe in general) are related to Vb-situations. They may occur during cyclonic northerlies (NZ) or north-easterlies (NEZ) as well, but are mostly connected to TRM (Section 5).

Average daily precipitation amounts are above average during TRM year-round, but largest during the late growing season from July to September (Figure 16a). The majority of the largest spatially widespread precipitation events in the study area occurred in the first part of August during 1961–2010 (e.g., 8 August 1978, 12 August 2002, and 7 August 2010). Here, the water holding capacity (and therefore the potential precipitation amount) of the air masses transported northwards from the Mediterranean along the eastern side of the trough over Eastern Europe towards the study area, reaches its annual maximum, due to the combination of high water temperatures in the Mediterranean Sea and high-summery conditions in Central Europe.

Mean precipitation amounts increase from west to east in the study area, connected to the average trough position over eastern Europe and the increasing impact of Vb-tracks towards central-eastern Europe—opposite of the usual precipitation decline from west to east (Figure 16b). Extremely wet days (R99p) are connected to TRM in every 5th case in the eastern parts of the study area during the summer half year, compared to about every 10th case in its western parts. Every 4th heavy precipitation event (R95p, R99p) occurring within the study area is connected to trough situations (TRM, TRW) during the summer half year, as "trough over western Europe" (TRW) is more relevant for heavy precipitation events in the western study area.



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

Figure 16. (**a**) Seasonal cycle of average precipitation anomalies (in percentage from 1961–2010); and (**b**) spatial distribution of precipitation anomalies (in percentage) during the summer half year for TRM (trough over Central Europe); adapted from LfULG 2014 [44].

4.2. Frequency Changes of Weather Patterns

The occurrence frequency of weather types varies on different time scales. The period 1961–2010 was characterized by considerable changes in the frequency of certain Grosswetterlagen, comparing the two sub-periods 1991–2010 and 1961–1990. For example, changes in precipitation amounts described in Section 3.2 were strongly affected by inner-annual changes in the share of cyclonic and anti-cyclonic weather types (Figure 17). Strongly increasing anti-cyclonic conditions from mid-March to mid-May explain the dramatic precipitation decline in April and generally during the early growing season from

April to June. Typical Central European "April weather"—changeable and cool weather with frequent showers due to labile maritime air masses—became much rarer, while sunny and dry conditions became more frequent. On the other hand, the precipitation increase in the late growing season from July to September was accompanied by increasing cyclonic conditions.

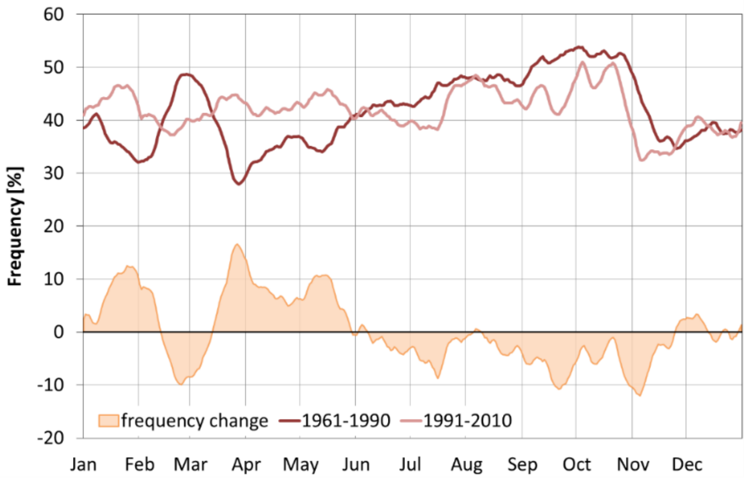


Figure 17. Frequency share of anti-cyclonic weather patterns, comparing 1991–2010 with 1961–1990 (31-day moving average); adapted from LfULG 2014 [44].

4.2.1. Winter Half Year

Figure 18 shows the average frequencies (bubble size) and climatic characteristics (spatial position) of the 29 Grosswetterlagen for temperature and precipitation anomalies within the winter half year during 1961–2010. Red (increase) and blue (decrease) colours mark prominent changes in Grosswetterlagen frequencies in 1991–2010, compared to 1961–1990. Strong positive temperature anomalies during the winter half year mostly connect with intensive Atlantic cyclonic activities. Anomalies of, on average, >2 K were linked to only four weather types (WA, WZ, SWA, and SWZ), occurring every third day on average. Southern weather types (SA, SZ, TB, and TRW), in contrast, were only marginally warmer (or even cooler) than long-term averages in many areas, due to their weaker atmospheric dynamics and resulting inversion conditions in the lowlands. They, however, belong to the warmest weather types on the mountaintops. The lowest temperatures prevail during inflow from north, northeast or east. Eleven weather types lead to thermal anomalies of <-2 K (yet they occur, on average, less than every sixth day). On average, one-third of the average area precipitation amount is connected to cyclonic westerlies (WZ)—this signal is spatially quite equally distributed over the study area. With an occurrence frequency of only 6%, cyclonic north-westerlies (NWZ) bring 15% of the area averaged precipitation—more in Saxony, less in the northern Czech Republic. Central anticyclones and inflow from east to south lead to dry conditions.

Comparing 1991–2010 with 1961–1990, two Grosswetterlagen with high precipitation potential strongly increased in their frequency, especially from January to March: NWZ (from 5% to 8%) and trough conditions over central Europe (TRM; from 4% to 7%). A very strong increase in NWZ during the end of winter/beginning of spring (Figure 19) was the main reason for the observed precipitation increase in March in the 1990s and early 2000s. Increasing NWZ also buffered the general snow height decline observed during this time, which negatively affected winter tourism in the study area. Westerlies (especially WA and WS) generally declined in their frequency, but not in high winter (January and February). Very cold Grosswetterlagen with air mass inflow from northeast, east and southeast occurred less often, especially in February and March.

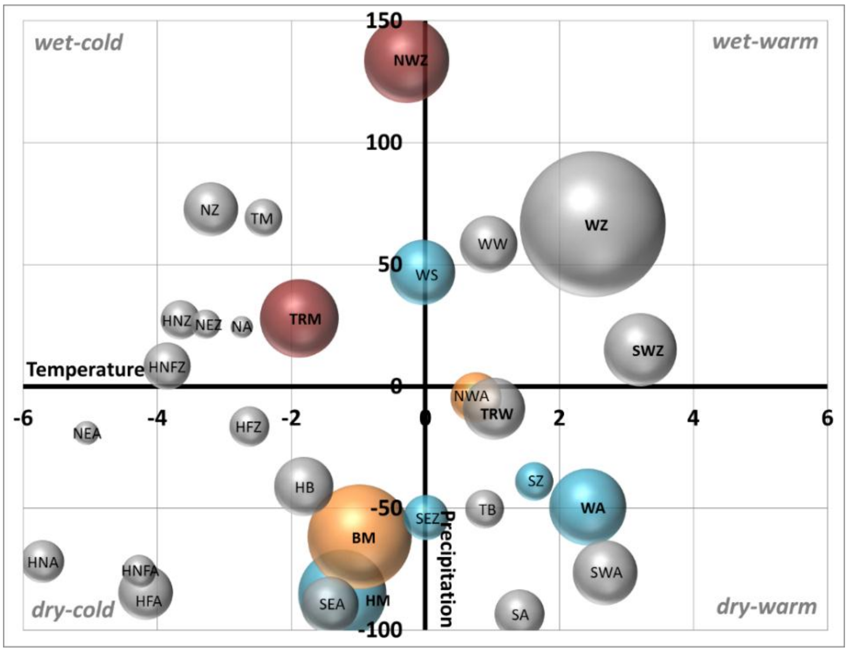


Figure 18. Relative frequency (bubble size), frequency changes in 1991–2010 vs. 1961–1990 (bubble colour) and temperature [K]/precipitation anomalies [%] (position within the thermopluviogram) of the 29 weather patterns (see Table 3 for description) during the winter half year (data: 1961–2010); adapted from LfULG 2014 [44]. Details: temperature: anomalies of daily averages from the long-term five-day-centred mean values of 1961–2010, averaged by weather pattern; precipitation: proportional deviation of daily mean precipitation during a weather pattern from the long-term daily precipitation average of 1961–2010; frequency changes: increases of ≥3% (≥1%) depicted in red (orange) and frequency decreases of ≤3% (≤1%) in blue (light blue); station average of 12 stations: from west to east (1) four Saxon low and hilly land stations (Plauen, Chemnitz, Dresden, Görlitz) in the northern project area; (2) four Bohemian low and hilly land stations (Cheb, Tušimice, Doksany, Liberec) in the southern project area; and (3) four centrally located mountain stations >600 m a.s.l. (Aš, Fichtelberg, Zinnwald, Desná).

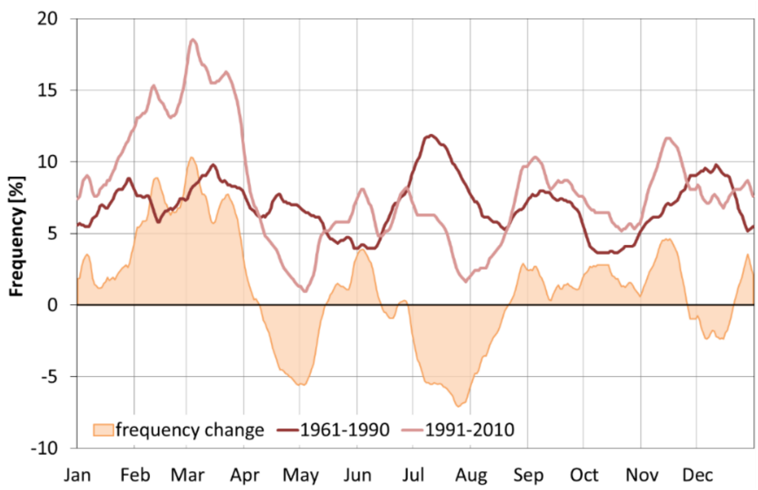


Figure 19. Frequency of weather pattern NWZ, comparing 1991–2010 with 1961–1990 (31-day moving average); adapted from LfULG 2014 [44].

4.2.2. Summer Half Year

Figure 20 depicts the frequency and characteristics of the 29 Grosswetterlagen for the summer half year. In contrast to the winter half year, highest temperatures with average anomalies of >4 K, occurred during continental southerlies (SA, SZ), since their thermal characteristics are not dampened by inversion conditions during the summer half year. South-easterlies and south-westerlies are also considerably warmer than the long-term study area temperature average, with an anomaly of >2 K. Easterlies and central anticyclones lead to moderate positive temperature anomalies. North-westerlies, northerlies and north-easterlies bring low temperatures, connected to air masses of Arctic origin. The distribution of precipitation is more balanced compared to the winter half year among the 29 Grosswetterlagen. The impact of cyclonicity now dominates over the air mass origin. About 15% of precipitation within the study area is linked to cyclonic westerlies (WZ) and 10% to trough conditions (TRM, TRW). Moist (dry) weather patterns are often colder (warmer) than usual—a pattern less apparent in the winter half year.

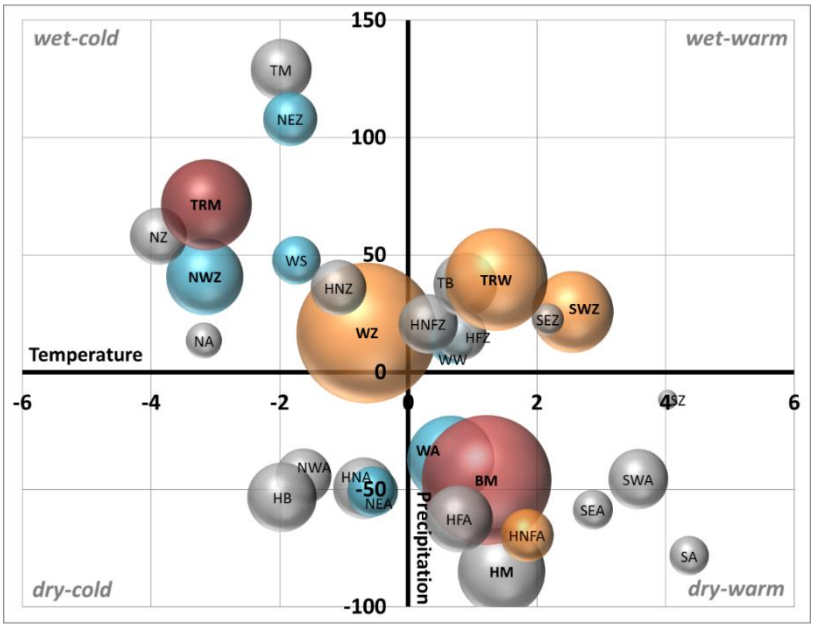


Figure 20. Like Figure 19, but for the summer half year; adapted from LfULG 2014 [44].

Grosswetterlagen frequency changes in 1991–2010 compared to 1961–1990 differed largely within the summer half year. They relate to the observed precipitation changes (Section 3.2): rather dry or only moderately wet Grosswetterlagen showed frequency increases during the early growing season from April to June (e.g., HM, BM, SWA, and NWA), and very wet Grosswetterlagen a decline (e.g., NWZ, NZ, NEZ, and TM). During the late growing season from July to September, the opposite tendencies were observed.

The by far largest temperature increase in 1991–2010, compared to 1961–1990, occurred in the last ten days of April. During this period, temperatures amplified area-wide by about 4 K, while sunshine duration showed its largest annual rise and precipitation showed its largest annual decrease. Those changes connect to an increase in warm and dry weather types (SW, SE, and HME), and a decline of cool and moist weather types (NW, N, NE, and TME). The climate characteristics of those two groups are shown in Figure 21 using a selection of rather moderate climate indices.

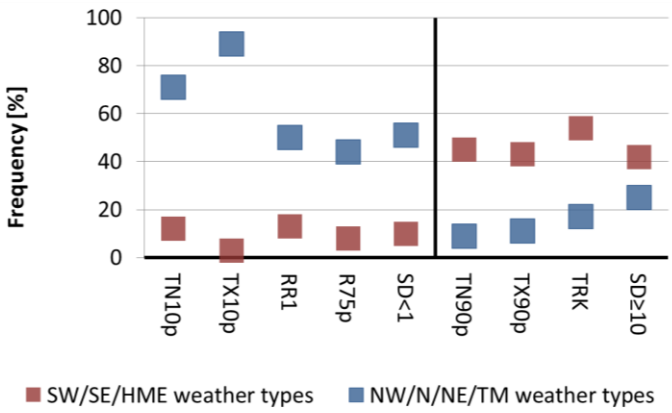


Figure 21. Distribution of weather types for a selection of extreme climate indices during April. Two groups of weather types are selected: (1) Grosswetterlagen representing warm, dry and sunny conditions (red); and (2) Grosswetterlagen with cold, wet and cloudy conditions (blue). Indices represent temperature (low: TN10p, TX10p; high: TN90p, TX90p; see Table 1), precipitation (high: RR1, R75p; low: TRK; see Table 2) and sunshine duration (low: SD < 1 = daily sunshine duration <1 h; high: SD ≥ 10 = daily sunshine duration ≥10 h); adapted from LfULG 2014 [44].

The main findings of the investigations can be summarized as follows:

- The average annual temperature rose by 0.7 °C in the period 1991–2010 compared to 1961–1990. The last decade of the study period (2001–2010) was the warmest at 8.3 °C, the first (1961–1970) the coldest at 7.3 °C, while a stronger warming effect on warm than cold extremes was observed.
- Especially in the spring and in the summer, a steady increase of the mean temperatures was observed, both decadically and in the comparison of both investigation periods.
- The warming in the spring led to a premature start of vegetation by about 8 days, while the end of the vegetation period in autumn had no relevant changes.
- The average annual precipitation in the project area was about 766 mm in the period 1991–2010 and is thus about 7% higher than 1961–1990 (715 mm).
- Comparing 1991–2010 to 1961–1990, two Grosswetterlagen with high precipitation potential strongly increased in their frequency: NWZ and TRM.

5. Discussion

Our results highlight the strong temperature increase in the Saxon–Bohemian region during 1961–2010, as well as the observed climate variability and its connection to large-scale weather types. These facts connect to atmospheric circulation changes over time, as also observed in [9]. For example, the increase in westerly weather conditions from the late 1980s, with a simultaneous decrease in weather conditions with easterly inflow, resulted in comparatively milder winters. During the summer, the incidence of weather conditions characterized by extensive areas of low atmospheric pressure above or near the project area (central low and trough weather conditions) increased strongly in the late 1990s, resulting in severe flood events in the project area.

In most of Europe, cold winter and hot summer extremes rank among the largest observed seasonal climate impacts within the annual cycle, requiring large resources to manage the consequences of frost and heat which claim many lives [8,67–72]. With a higher base line of temperature averages, the number, frequency and intensity of high temperature extremes increase globally, while the number, frequency and intensity of low temperature extremes decline [4–6]. This leads to significant impacts on the natural and built environment, due to a decreasing number of frost days in the mountains [73], increasing temperatures of rivers [24,25], and heat periods in cities [26,74–77].

In Germany, the increase in air temperature since the 20th century was least in the flat coastal regions impacted by maritime air masses, but most in the eastern and southern regions, as well as the low mountain regions there, where continental air masses are more prevalent [78]. Within the Saxon–Bohemian study area, the average annual temperature strongly rose by 0.7 °C in 1991–2010 compared to 1961–1990. Changes in mountainous regions of the study area were comparable with those of other German low mountain ranges such as Harz Mountains [79] and the Black Forest [80]. The greatest changes were seen between January and August. While annual warming is consistent with other European regions [1,20], inner-annual deviations are best explained by changes in weather types (Section 4), as was also described by Lhotka [81]. The observed warming not only led to a shift in the total spectrum of the daytime temperature, but also to a widening of the temperature distribution: the increase in warm extremes in the study area was stronger than the decrease in cold extremes. That shift is accompanied by an increase in heat waves in the study region (as expressed by the WSDI). As such, the problem is not only the general warming causing the decrease in cold conditions, but particularly the related heating of urban areas, causing Urban Heat Islands [26,74–77].

Precipitation patterns experienced marked changes as well. In the present study, the average annual precipitation amount in the project area was about 7% higher during 1991–2010 than 1961–1990. One reason for this increase is the rise in large-scale extreme precipitation events. Of great importance for the water balance is, in this context, the distinctive increase of weather types with a trough over western (TRW) or central Europe (TRM; Section 4.1)—especially of the TRM (from 4% to 9%). Here, a meridional-directed trough influences parts of Europe, while anticyclonic conditions prevail to the west and east of it. The recently increased flood risk in and around the study area is connected to an increasing frequency of trough conditions, since they support strong and long-lasting precipitation events [14,15,28]. The largest 24-h precipitation amount ever registered in Germany and the third-largest in the entire Central Europe [82] was observed in the study area on 12 August 2002, connected to a Vb-situation during TRM. This value was measured in Zinnwald on the Saxon–Czech border at the eastern Ore Mountains ridge, 312 mm from 6 to 6 UTC, which is four times higher than the previous extreme value there. Synoptically, a low pressure system moved from the Mediterranean to western Poland and became stationary, leading to a very long-lasting and stationary windward-situation (northern inflow) towards the eastern and central regions of the Saxon mountains, especially the Ore Mountains. Here, precipitation amounts of more than 200 mm were recorded in 24 h, and even the central-northern Saxon lowlands received considerably more than 100 mm. One of the most severe Central European flooding events of recent centuries followed at the river Elbe and smaller tributaries, especially in the northern part of the Ore Mountains [83–85]. During the past 20 years, record-high water levels were also observed at the river Oder in 1997 [83,86–89] and again (together with the Neisse river) in 2010 [90,91], and again at Elbe and Mulde in 2013 [92–94], connected to intense and long-lasting trough conditions impacting Central Europe.

Our results show that the eastern part of the study area faces both an increased flooding risk as well as an increase in dry conditions. At first glance, such contrasting findings are in line with the results of a multi-model study by Pendergrass et al. [95]. They demonstrate that warmer temperatures lead to increasing precipitation variability worldwide—temporal scales are used from 24 h to a few decades.

Important weather types account for very different local climate effects on both sides of the border, connected to luv and lee effects and variations in elevation. For instance, during anti-cyclonic conditions, a cold wind leading to cold and foggy/cloudy conditions—in Saxony called the "Bohemian Wind"—often blows from the Bohemian Basin through the Elbe valley and over the mountains into the (south-eastern) Saxon border areas, if a south-easterly, southerly and south-westerly wind direction arises. In contrast, western Saxony, which is sheltered by higher mountains than Saxony´s eastern part, experiences rather warm and sunny conditions. The main reason for the "Bohemian wind" is an accumulation of cold air masses within the Bohemian Basin, resulting in a high-reaching temperature inversion filling the complete basin. It forms during calm, clear and long nights from October to March (often when an anticyclone is located directly over Central Europe). The visualisation of temperature and precipitation characteristics of the weather patterns connected to the "Bohemian wind" (compare Figure 12b in Section 4.1) helps to develop a better understanding of observed meteorological phenomena on both sides of the border. Hence, cross-border investigations including this study are needed to integrally assess climate characteristics and changes on both sides of the dividing border.

6. Conclusions

Climate change studies developed during the past decades often focussed on large-scale regional patterns, while the influence of weather types on small-scale climate variations has received less attention in international publications. The INTERKLIM project represents the first cross-border investigation on observed and projected climate variability specifically directed towards the Saxon–Bohemian region, located in Germany and the Czech Republic. This paper focusses on regional climatic changes in a complex topography and their dependency on variations in atmospheric circulation peculiarities within the past 50 years (1961–2010).

Changes in temperature and precipitation characteristics are presented in Section 3, while characteristics and frequency changes of weather types, and their impacts on observed climatic changes, are presented in Section 4. Within this section, spatial maps are of great importance to visualise their spatially diverse (sometimes in their signal even inverse) characteristics. We could reveal that frequency changes of weather types impact the peculiarities of warming patterns (Sections 3.1 and 4.2). Moreover, precipitation changes, e.g., the striking precipitation decline from April to June, and the large increase from July to September, correlate with the observed changes in the frequency of weather types (Sections 3.2 and 4.2).

Regional climate projections targeted at the study region, as also presented by LfULG [44], support cross-border climate adaptation and sustainable development approaches. Projections of regional precipitation development in the project area are subject to great uncertainties. However, at the end of the century, a decrease in summer precipitation is likely [44]. In view of the combined effects of temperature and precipitation on the water balance, tense water balance situations are likely to occur more frequently in the future, especially in the lowlands and during the summer months.

The presented results reveal great potential for future applications in the study region and adjacent areas, e.g., local-climatic investigations, impact studies and the development of concrete adaptation projects. Additionally, a transferability of ideas, methods and approaches to other areas (e.g., the Bavarian–Bohemian, Silesian–Moravian and Silesian–Slovakian border regions) is given and encouraged. Further, the results have a strong practical implication for cross-border regional planning, including long-term economic alternatives for the winter tourism value chain. In parallel, the need for adaptation solutions in urban areas is increased, particularly mitigation strategies for urban heat phenomena. A very important element that can support mitigation strategies is green infrastructure. The European Strategy on Green Infrastructure defines green infrastructure as "*a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings*" [96]. In Germany, implementing green infrastructure is supported by the "Federal Green Infrastructure Concept-Nature Conservation Foundations for Plans Adopted by the German Federation" [97], which aims—through the development of biodiversity networks and the implementation of nature-based solutions—at a better adaptation to more frequent extreme weather events.

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