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CLIMATE CLASSIFICATION OF SLOVENIA BASED ON DATA FROM THE PERIOD 1991–2020

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Abstract

This article presents a climate classification for Slovenia for the climatological period 1991–2020. It is based on the Köppen-Geiger classification, but this classification is too coarse-grained to show all the specific climatic features of Slovenia. Taking into account additional temperature and precipitation criteria, we divided the Slovenian climate into four basic types with nine subtypes: moderate Mediterranean (coastal and inland), moderate continental (of northeast, east and southeast, and central Slovenia), mountain (of higher and lower mountains) and submontane climates (very humid and humid).

Keywords: climate geography, climate classification, Köppen-Geiger climate classification, climate types, Slovenia

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1 INTRODUCTION

Slovenia is small in scale geographically, but its climate is highly diverse due to its location at mid-latitudes where the Mediterranean, the Pannonian Basin, the Alps and the Dinarides come together, and the varied topography associated with this junction. The general features of a moderate warm and humid climate are blended with the characteristics of Mediterranean, mountain and continental climates, which at the local level are strongly influenced by topography.

A multitude of climate regionalizations and classifications have been made at the global and macro levels. Classifications are mainly divided into two groups: causal (genetic) and consequential (effective). Among the genetic ones, which try to explain the causes of the formation of a certain climate, is Strahler's classification (Strahler, 2013). Of the genetic ones, which explain the influence of climate on natural conditions, especially on natural vegetation (and also certain characteristics of the cultural use of the landscape), the most well-known in climatological circles and beyond is the Köppen classification (also called the Köppen-Geiger climate classification). It was created at the beginning of the 20th century (Köppen, 1918) and has undergone several additions and revisions over the century of its existence (e.g. Cui et al., 2021; Geiger, Pohl, 1954; Köppen, 1936; Peel et al., 2007; Strässer, 1998). These classifications provide a good insight into the global climate system and a system of larger spatial units, but for spatial units of Slovenian dimensions, they are not sufficiently fine-grained and do not reflect all of the important climatic features.

Over the past 100 years, several climate classifications and regionalizations have been developed for the territory of Slovenia. The first classification scheme of climate types was created by Melik (1935). He noted that the Mediterranean, Pannonian and Central European Alpine climates intersect on Slovenian territory, and that the boundaries between particular climate types are constantly changing. Furlan (1960) analysed climate of Slovenia based on data for the period 1925–1956. With respect to temperatures, he distinguished marine, transitional and inland zones, and with respect to precipitation, areas with a modified Mediterranean and Central European regime. He did not elaborate a comprehensive classification. Ilešič (1970) analysed Slovenia within Yugoslavia on the basis of temperature and precipitation regimes. He distinguished two main climate zones: Adriatic and moderate continental. As part of the first, the northern Adriatic area extends into Slovenia. In the second, within the framework of the western Pannonian continental zone, he divided Slovenia into two subzones: the true Pannonian continental zone and the transitional Pannonian-Adriatic zone.

Gams (1972) classified Slovenia into different zones based on the relationship between monthly temperatures and precipitation in the growing season, or moisture surplus and deficit, temperatures and the length of the growing season. By selecting these criteria, he primarily wanted to explain the differences in natural vegetation and the cultivation of crops. He classified the main climatic zones (littoral, central Slovenia and sub-Pannonian) into several climatic provinces and districts. Gams (1996) also produced a bioclimatic classification of Slovenia. Based on how arid or humid the climate, he distinguished two climatic zones with several subzones. He divided the coastal region and its hinterland into the following climate zones: the Koper littoral, the climate of the hinterland of the Gulf of Trieste, and the transitional climate of Brkini. He divided the climate of continental Slovenia into the very humid climate of the Alpine and Dinaric mountains, the humid climate of central Slovenia, the moderately humid climate in the transition zone to the sub-Pannonian climate, and the sub-Pannonian climate with semi-arid to semi-humid summers. Both of Gams's classifications are also presented in maps.

D. Ogrin (1996) classified the climate in Slovenia based on data for the period 1961–1990. As a starting point for the classification, he used the Köppen-Geiger criteria, according to which most of Slovenia has a moderate warm, humid climate with warm summers (Cfb), the highest elevation areas have a mountain climate (H), and the southwestern parts along the Gulf of Trieste have a moderate warm, humid climate with hot summers (Cfa). The basic types were then subdivided into nine subtypes based on the precipitation regime, the average temperature of the coldest and warmest months, and the ratio between October and April temperatures. In 2009, this classification was updated based on data for the period 1971–2000 (Ogrin, 2009), which maintained the starting points and criteria of the earlier classification. It reflects well the regional responses to global climate change that accelerated after 1980: the spread of the moderate Mediterranean climate towards the interior of Slovenia, the shift of the climate of lower-elevation mountain areas to higher elevations, the mitigation of the continental temperature regime due to the rise in winter temperatures, and as regards precipitation a shift of the moderate Mediterranean precipitation regime towards the eastern part of the country.

The classifications presented have in common that they are made on the basis of point data from relatively sparse networks of weather stations in Slovenia, which is especially true for air temperature measurements. The boundaries between climatic units are largely determined subjectively, taking into account the influence of the topography on the spatial distribution of particular climatic elements and the researcher's familiarity with local and regional climatic conditions. The spatial distribution of natural vegetation and the characteristics of the cultural use of the land are also taken into account. Since in recent years, data in a kilometre grid for the most important climatic elements have also become available (Dolinar, 2016), Kozjek et al. (2017) produced what they call an objective definition of the climatic regions of Slovenia for the period 1981–2010. Using factor analysis and classification based on cluster analysis, they found that the climate of Slovenia can be most logically and representatively classified into six zones or types: the littoral zone (moderate Mediterranean climate), the very wet zone of the northwestern part of the Alpine-Dinaric barrier (humid climate of lower mountains), the higher elevation zone of the Dinarides and Alps (moderate mountain climate), the high elevation zone (mountain climate), the dry zone of the lowlands of eastern and central Slovenia (moderate continental climate) and the higher and slightly wetter region of central

Slovenia (moderate climate of highland areas). The spatial distribution of the climatic zones and types presented does not differ significantly from Ogrin's classifications.

With the aim of determining reference climate stations that would be representative of the wider area and at the same time describe climate changes in recent decades as accurately as possible, Kozjek et al. (2016a; 2016b) built on the original classification by calculating the measures of variability of the most important climatic elements for the period 1961–2011. Taking into account all the selected measures of variability (trends, interyear and interday variability), they divided Slovenia into four zones that have similar climate characteristics. The zones were not specifically named, but they coincide with the Mediterranean areas, the highest parts of the Alpine-Dinaric barrier, the wider area of the Alpine-Dinaric barrier and the area of eastern Slovenia with more continental climatic features.

The year 2020 marked the end of the standard climatological period 1991–2020, which dictates the creation of a climate classification for this time. This is all the more indicated since it is widely known and thoroughly supported in the literature that the climate at all spatial levels, including in Slovenia (Bertalanič et al., 2010; Climate change..., 2021; Dolinar, Vertačnik, 2010; Ogrin, 2003; 2014; 2015; Vertačnik et al., 2013), has been changing very rapidly in recent decades. Due to changes in the values of climate elements and the boundaries between climatic types and subtypes, climate classifications created on the basis of data for previous periods are of limited usefulness. The main purpose of this paper is therefore to show the characteristics of climatic types in Slovenia and the characteristics of their spatial distribution for the period 1991–2020. In addition to point data, we also used data in the spatial grid since these are available. In their processing, spatial interpolation and displays, we used GIS tools (ArcGIS Pro 3.1 and QGIS software tools). In order to maintain basic comparability with the last two classifications that were created at the Department of Geography of the Faculty of Arts of the University of Ljubljana for the period 1961–1990 (Ogrin, 1996) and 1971–2000 (Ogrin, 2009), we proceeded from the same methodological starting points. However, a full comparison is not possible because in the previous classifications we used controlled but not homogenized point data, and the spatial interpolation of point data and the boundaries between individual climate types were determined by expert assessment.

2 METHODS

Point (62 temperature stations, 174 precipitation stations) and spatial data for the period 1991–2020 were obtained from the Slovenian Environment Agency (ARSO). The data were first checked and homogenized at ARSO using modern software tools, and changes that were not the result of climatic events were removed (Vertačnik et al., 2016). The homogenized data formed the basis for conversion into a kilometre grid. The optimal spatial interpolation method, which takes into account the dependence of the climatic variable on geographical factors, was used to calculate the values of the climatic variables in the grid. At each grid point, the value of the variable was calculated on the basis of the values at the surrounding meteorological stations (including stations near the border in Italy, Austria and Croatia), elevation, geographic longitude and latitude of the grid point, and in some cases also other derived geographical variables (e.g. relative elevation of the orographic barrier to the northeast for precipitation). Due to the smaller number of meteorological stations, the data are less reliable for areas with an elevation above 1000 m (Dolinar, 2016; Kozjek et al., 2017).

The starting point for the climate classification of Slovenia was the Köppen-Geiger definition of climate types and their criteria (Peel et al., 2007). According to Köppen, each climate is defined by a certain value of average monthly and annual temperatures and precipitation. In mapping particular temperature thresholds or climate classes and types, we relied on the location of isotherms derived from the Köppen classification: the January isotherm of –3 °C (boundary between moderate warm and humid climates and snow-forest climates), the July isotherm of 22 °C (boundary between climates with hot or warm summers), and the July isotherm of 10 °C (boundary between snow-forest and snow climates). The interpolation of climate variables and all further calculation operations, as well as the Köppen climate classification of Slovenia itself, were carried out in the R programming language, and the maps were drawn with the QGIS program. Since the Köppen-Geiger classification is too coarse-grained to show all the specific climatic features of Slovenia, we took additional temperature criteria into account: January isotherms of 0 and 3 °C, July isotherms of 15 and 20 °C, and the average annual temperature amplitude. If the average annual temperature amplitude is above 20 °C, this is an indicator of the continental character of the temperature regime, if it is below 15 °C it indicates marine characteristics, and if it is between 15 and 20 °C, it is a transitional temperature regime (Supan, 1921, p. 110; Šegota, Filipčić, 1996, p. 71). The values were calculated from the kilometre grid of temperature data, and the vertical temperature gradients and average heights of particular isotherms were calculated using a digital elevation model (GURS, 2021). In defining the continental character of the temperature regime, we also looked at a comparison of average April and October temperatures (Tokt. > Tapr.: marine features of the temperature regime; Tokt. < Tapr.: continental features of the precipitation regime). Higher temperatures in October compared to April are considered to be the result of the influence of a warm sea and sea air masses, as the sea cools down more slowly in autumn and warms up more slowly in spring. Therefore, in areas far from the sea, April is generally warmer than October.

Previous classifications of the Slovenian climate, especially the classification by Kozjek et al. (2016a; 2016b; 2017), indicated the great importance of precipitation and related humidity conditions. To make it easier to differentiate Slovenia with regard to this factor, together with the amount of precipitation, we also took into account Lang's rain factor, which includes the average annual amount of precipitation and the average annual air temperature and climate elements according to the degree of humidity or aridity (Žiberna, 1992, p. 76):

$$L = \frac{RR_l}{T_e}$$

L – Lang's rain factor
RR_l – average annual amount of precipitation
Te –average annual air temperature

In determining the degree of humidity or aridity of the climate, we took into account the standard division into classes (Žiberna, 1992, p. 76):

L	
0–40	arid climate
41–60	semi-arid climate
61–100	semi-humid climate
101–160	humid climate
above 160	perhumid climate

In defining the precipitation regime, we started from Köppen's criteria, which we slightly adapted for the needs of Slovenia, denoting with w' the precipitation regime with peak precipitation in one of the autumn months and the least precipitation in one of the winter months (sometimes in March or in one of the summer months), and with x' the regime with peak precipitation in one of the summer months (in some places also in May) and the least precipitation in one of the winter months. The precipitation regime was further defined using the Mediterranean precipitation index (Koppany, Unger, 1992), which compares the average amount in October and November (peak precipitation in the Mediterranean precipitation regime) with the amount of rainfall in May and June (peak rainfall in the continental precipitation regime) and the annual amount of precipitation. Positive values of the index indicate Mediterranean features of the precipitation regime, while negative values indicate continental features. Since in Slovenia the autumn peak of precipitation also occurs in September, and the summer peak also occurs in July, we modified the index slightly:

$$MI = \frac{\left(P_{sep-nov} - P_{may-july}\right) \cdot 100}{P_l}$$

MI – Mediterranean precipitation index
Psep–nov – amount of precipitation in the period September-November
Pmay–july – amount of precipitation in the period May-July
Pl – average annual precipitation

The continental or marine (Mediterranean) character of the precipitation regime was also determined by comparing the amount of precipitation in the warmer half of the year (April–September) and the colder half of the year (October–March). A larger proportion of precipitation in the warmer half of the year indicates a continental character of the precipitation regime, while in the colder half it is marine (Mediterranean).

Since Köppen was also a phytogeographer, he chose the threshold values between particular climate classes and types in such a way that he could also at least approximately determine the main vegetation types coinciding with them. For the needs of a more detailed climate classification of Slovenia, we also extended this starting point to some characteristics of the cultural landscape, which depend in large extent on thermal conditions (olive growing and viticulture region). We adapted the original Köppen terms for particular climate types to Slovenian conditions.

3 RESULTS

3.1 Köppen-Geiger climatic classification of Slovenia 1991–2020

Three climate classes in the Köppen-Geiger system are represented in Slovenia:

- **C (moderate warm climate):** average temperature of the coldest month (usually February in the mountains and January in the lowlands) above –3 °C, at least one month with an average temperature above 10 °C;
- **D (snow-forest climate):** average temperature of the coldest month below –3 °C, average temperature of the warmest month (July in the lowlands, usually August in the mountains) above 10 °C;
- **E (snow climate):** average temperature of the warmest month below 10 °C.

D and E climate classes in Slovenia are limited to mountain areas, all of the rest of Slovenia is in class C.

By taking into account additional criteria, we can distinguish six basic climate types in Slovenia with greater spatial extent, and another six with smaller spatial representation. We added the following to the basic types (Figure 1):

- **ET; mountain tundra climate:**
  - average temperature of the warmest month between 0 and 10 °C;
  - this climate covers 0.2% of Slovenia, in the high mountain areas of the Julian and Kamnik-Savinja Alps at elevations of about 2200 m.
- **Dfcw‘ (Dfbw‘, Cfcw‘); snow-forest humid climate with warm or cold summers and peak precipitation in one of the autumn months (moderate warm humid climate with cool summers and peak precipitation in autumn):**
  - there is no dry period – the average rainfall of the driest month in the warmer half of the year is over 40 mm;
  - average temperature of the warmest month below 22 °C, and at least four months with an average temperature above 10 °C (warm summer);
  - one to four months with an average temperature above 10 °C, the coldest month above –3 °C (cold summer);
  - the month with the most precipitation in autumn, with the least precipitation in winter;

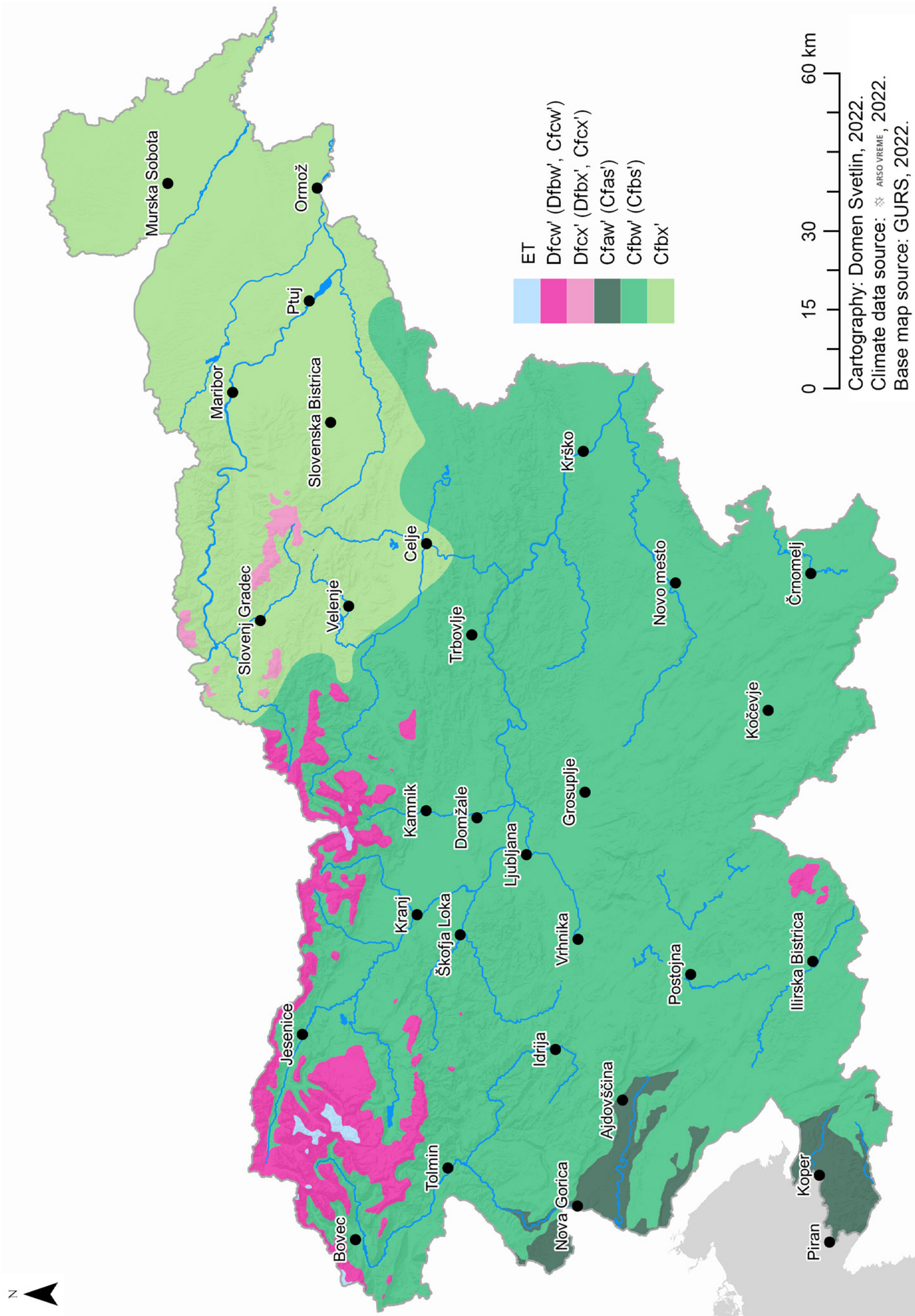
- this climate covers 5.1% of Slovenia, represented in the Julian Alps, the Karawanks and the Kamnik-Savinja Alps including mountain valleys, and outside the Alpine regions on the Menina planina Plateau, on some peaks of the western Prealps and on Mt. Snežnik and Trnovski gozd Plateau (Golak Peaks).

- **Dfcx' (Dfbx', Cfcx'); snow-forest humid climate with warm or cold summers and peak precipitation in one of the summer months or May (moderate warm humid climate with cold summers and peak precipitation in summer or May):**
  - as for Dfcw' (Dfbw', Cfcw'), except that peak precipitation is in one of the summer months and in some places
  - in May, lowest amount of precipitation in winter;
  - this climate covers 0.5% of Slovenia and is found on Pohorje, Košenjak, Strojna and Uršlja Gora.

Climate types ET and Dfcw' and Dfcx' with associated types of smaller extent, which taken together cover only 5.8% of the surface of Slovenia, can be grouped into a mosaic represented by a **mountain climate** based on versions of the Köppen-Geiger classification (e.g. Ahrens, 2005; Henderson-Sellers, 1999) which introduce a special **class H** for higher-elevation areas of our planet, where climate changes rapidly with altitude and the demarcation between climate types is difficult.

- **Cfaw'; moderate warm humid climate with hot summers and peak precipitation in one of the autumn months:**
  - no dry period, average temperature of the warmest month above 22 °C;
  - peak precipitation in autumn, month with the least precipitation in winter, in some places summer (Cfas');
  - this climate covers 2.8% Slovenia, found in Slovenian Istria, the northwestern part of the Karst, the Vipava Valley, the Gorizia Hills, and the Soča Valley as far as Kanal.
- **Cfbw'; moderate warm humid climate with warm summers and peak precipitation in one of the autumn months:**
  - no dry period, average temperature of the warmest month above 22 °C, at least four months with an average temperature above 10 °C;
  - peak precipitation in autumn, month with the least precipitation in winter (rarely March), in some places in southern Slovenia also summer (Cfbs');
  - this climate covers most of Slovenia (66.6 %) apart from mountain areas, lower-lying parts of regions near the Mediterranean and northeastern Slovenia.
- **Cfbx'; moderate warm humid climate with warm summers and peak precipitation in one of the summer months or May:**
  - peak precipitation in summer (in some places in late spring, May), least precipitation in winter;
  - this climate covers just under a quarter of Slovenia (24.8 %) and can be found in northeastern Slovenia east of Peca, Golte and Dobrovlje and north of the Sava Hills, Boč and Haloze.

Figure 1: Köppen-Geiger climatic classification of Slovenia for the period 1991–2020.



3.2 Temperature regime

The classification of the Slovenian climate based on the Köppen criteria results in a picture that is too coarse-grained and does not adequately reflect all the special features of the Slovenian climate. In order to further analyse the extensive area with Cfb climate, we have also considered the characteristics of the temperature regime based on January isotherms of 0 and 3 °C and July isotherms of 20 and 22 °C. Using the **average annual temperature amplitude** and the **ratio between the average April and October temperatures**, we wanted to demarcate the areas of Slovenia having continental features of the temperature regime from the areas where the influence of the sea is greater. Considering the range of the average annual temperature amplitude (between 16 and 22 °C), we can conclude that the temperature regime in Slovenia does not have distinct continental or marine features, but represents a transition zone. The lower-lying areas in the north, east and southeast of Slovenia, the low-lying Dolenjska Karst and the Ljubljana Basin have an average annual temperature amplitude of more than 20 °C and thus a moderate continental temperature regime. In terms of the highest average annual temperature amplitude (more than 21 °C), the lowlands in the northeast of Slovenia, the lower part of the Mežica and Mislinja valleys, and the Drava Valley between Dravograd and Radlje ob Drava stand out. The most marine features, if we exclude the hilly and mountainous areas, where the amplitude is lower due to the higher altitude (Kredarica, 15.4 °C; Rogla, 16.5 °C; Krvavec, 16.7 °C), are seen in slightly higher lying areas in the hinterland of the Gulf of Trieste, where the average annual temperature amplitude is less than 18 °C (Figure 2, Table 1). In most of Slovenia, the amplitude is between 18 and 20 °C.

That the lower-lying areas in the east of Slovenia and parts of the Ljubljana Basin have moderate features of a continental temperature regime can also be concluded from the higher average temperatures in April compared to October. In continental areas, the air warms up faster in spring (and cools down faster in autumn) compared to areas near the sea or under the greater influence of sea air masses, because the sea has a mitigating effect on the warming or cooling of the atmosphere. In the east of Slovenia, April temperatures are up to 0.8 °C higher than October temperatures, and in western and central Slovenia, October temperatures are higher than April ones by up to 2 °C, mostly in the mountains (Table 1, Figure 3). The colder spring in the mountains is also the result of weaker warming of the upper layers of the atmosphere compared to autumn.

The area of Slovenia that shows continental features of the temperature regime in terms of the average annual temperature amplitude (Figure 2, Table 1) overlaps well with the area that has higher temperatures in April than in October (Figure 3). The overlapping is strong in the lower-lying regions in the east of Slovenia, and somewhat less in the Ljubljana Basin.

Figure 2: Average annual temperature amplitude 1991–2020.

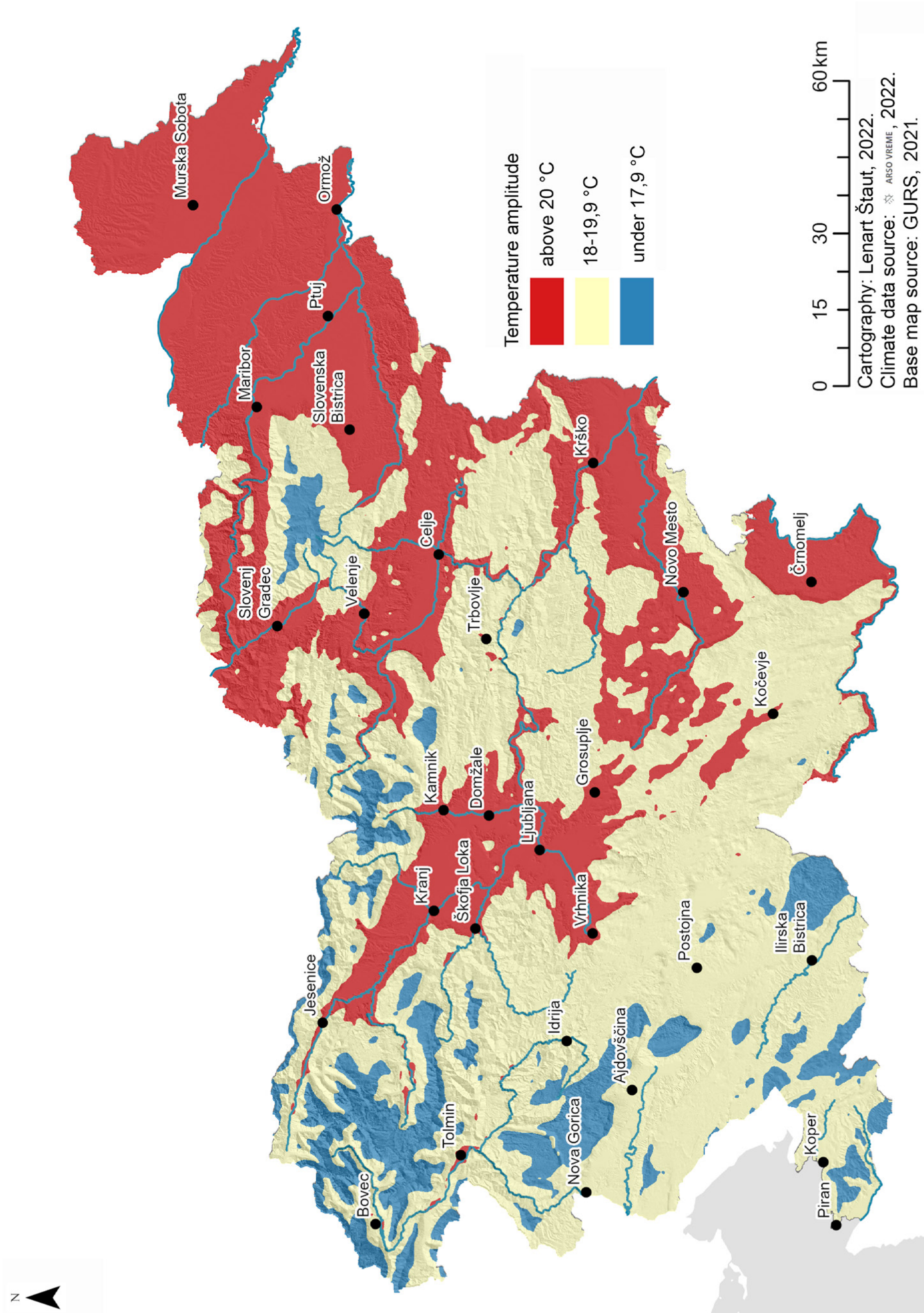


Table 1: Difference between average April and October temperatures (D) and average annual temperature amplitude (A) in the period 1991–2020.

Meteorological station	D (°C)	A (°C)	Meteorological station	D (°C)	A (°C)
Krvavec	–2.7	16.7	Miklavž na Gorjancih	–1.2	18.3
Jezersko	–0.7	18.7	Trojane-Limovce	–0.5	19.2
Planina pod Golico	–1.3	17.9	Gornji Grad	–0.3	19.1
Rateče	–0.5	19.8	Malkovec	0.1	19.8
Kredarica	–2.2	15.4	Airport J.P. Brnik	0.0	20.4
Rudno polje	–2.3	18.1	Ljubljana-Bežigrad	–0.1	20.8
Bohinjska Češnjica	–0.8	19.4	Vrhnika	–0.6	19.7
Vogel	–2.2	17.1	Kranj	0.3	21.0
Zgornja Sorica	–1.0	17.8	Lesce-airport	0.0	20.4
Krn	–1.0	17.9	Ravne na Koroškem	0.6	22.0
Tolmin-Volče	–0.4	19.2	Šmartno pri Sl. Gradcu	0.0	20.9
Vojsko	–0.9	18.6	Velenje	0.1	20.1
Vedrijan	–1.1	18.5	Celje-Medlog	0.1	20.2
Bilje	–0.8	19.0	Slovenske Konjice	0.0	19.5
Podnanos	–1.3	18.6	Črnomelj-Dobliče	0.3	20.4
Godnje	–1.0	19.0	Metlika	0.4	20.4
Ilirska Bistrica	–0.7	18.3	Novo mesto	0.5	20.4
Kubed	–1.4	18.2	Cerklje-airport	0.4	20.9
Portorož-airport	–1.5	18.4	Trebnje	0.1	20.3
Babno Polje	–1.1	19.4	Bizeljsko	0.6	20.8
Kočevje	–0.5	19.1	Rogaška Slatina	0.4	19.8
Nova vas-Bloke	–1.1	19.2	Airport E.R. Maribor	0.3	21.0
Postojna	–1.1	18.8	Polički vrh	0.6	21.0
Logatec	–0.9	19.5	Jeruzalem	0.1	20.2
Litija	–0.3	19.4	M. Sobota-Rakičan	0.8	21.1
Rogla	–2.0	16.5	Ptuj	0.4	20.4
Sevno	–0.2	19.4	Maribor-Vrbanski plato	0.3	20.3
Lisca	–0.8	18.6	Lendava	0.7	21.2

Note: D > 0 – April warmer than October.

Figure 3: Marine or continental character of the temperature regime based on a comparison of average April and October temperatures (1991–2020).

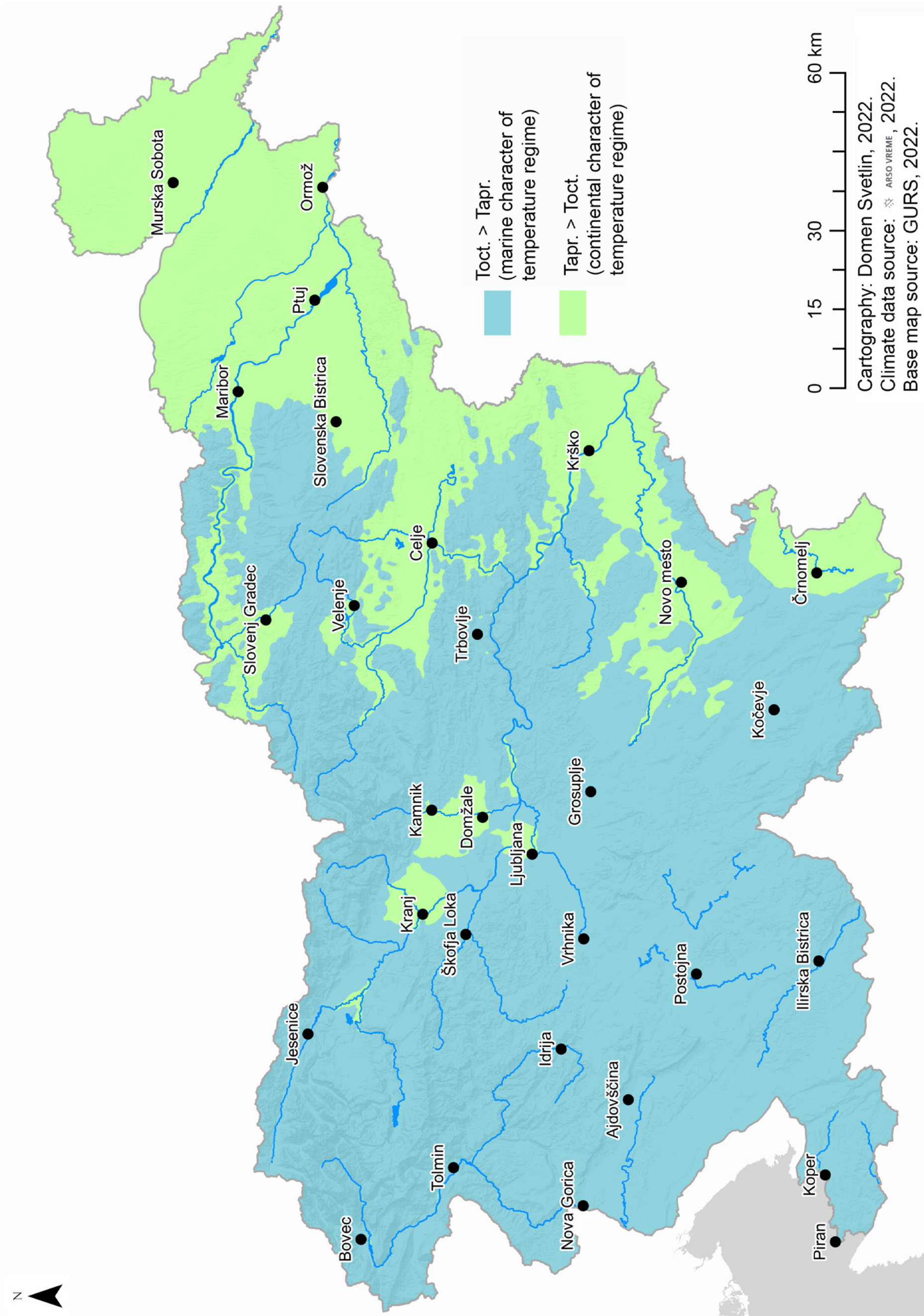


Figure 4: Mediterranean precipitation index (MI) in Slovenia (1991–2020).

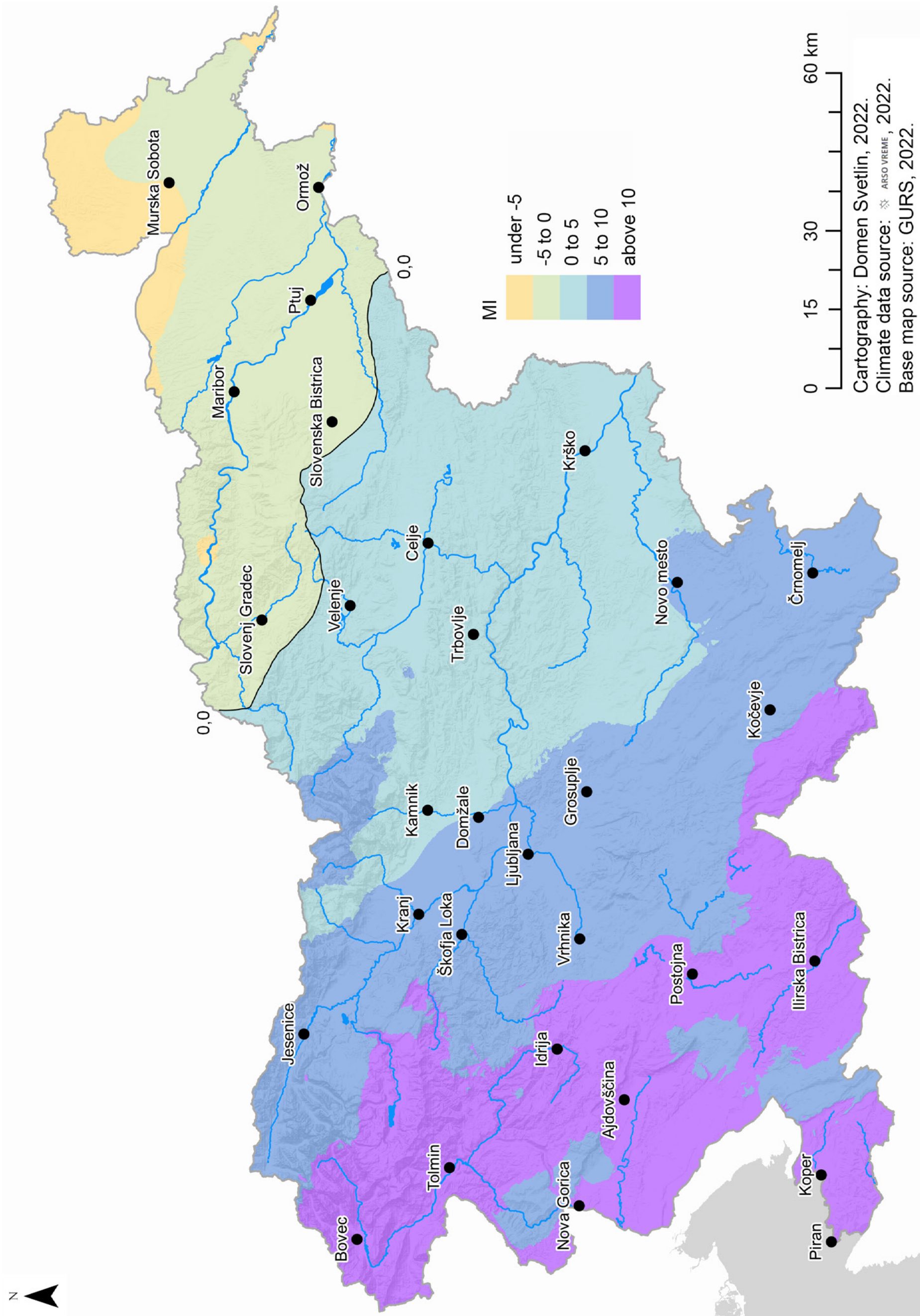
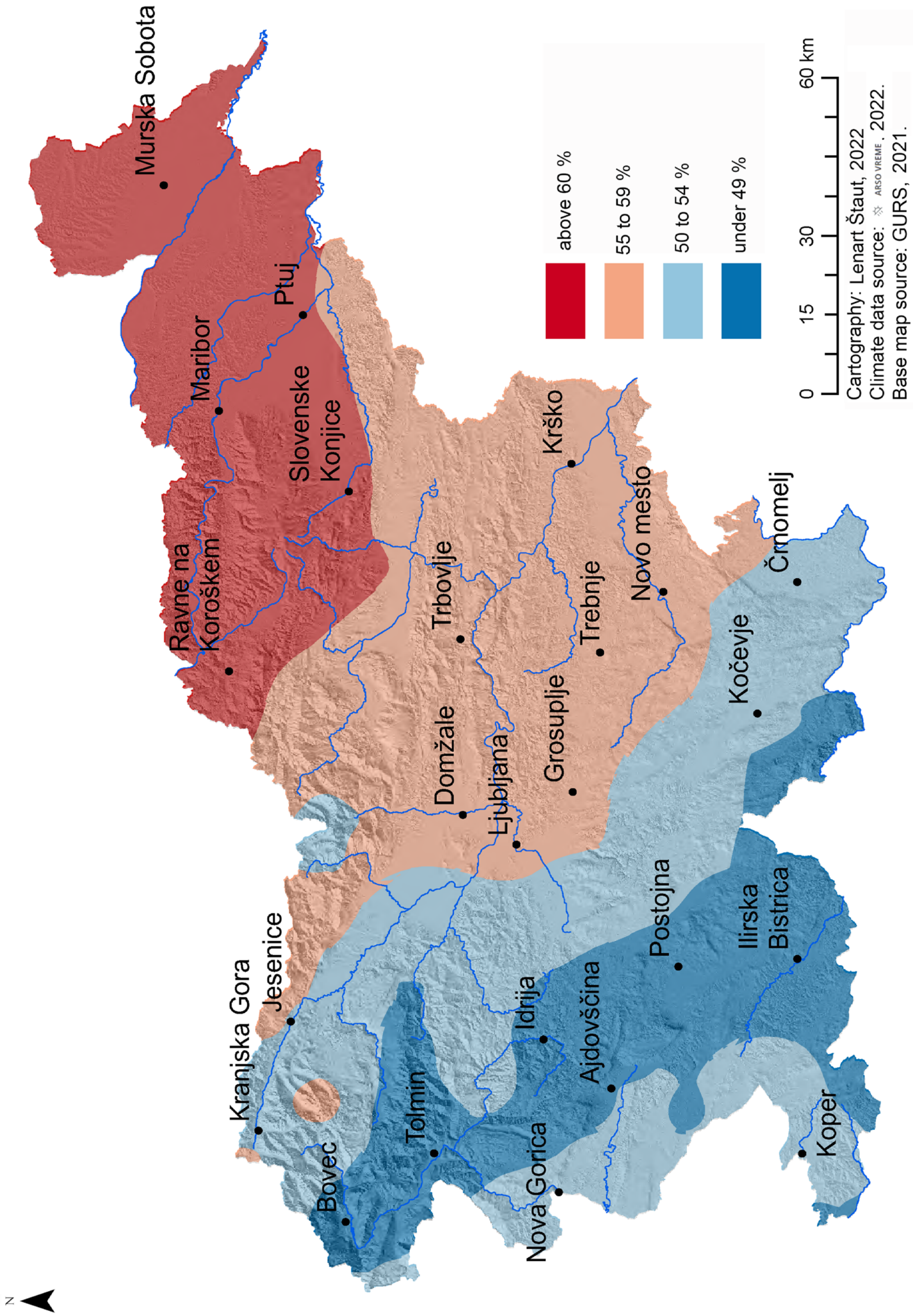


Figure 5: Proportion of precipitation in the warmer half of the year (1991–2020).



3.3 Precipitation regime

Along with the Köppen criteria for the spatial differentiation of the precipitation regime in Slovenia, we also took into account the Mediterranean precipitation index (MI) and the ratio between the amount of precipitation in the warmer and colder halves of the year. These give a similar spatial picture. Northeastern Slovenia has the most continental features (the share of precipitation in the warmer half of the year is over 60%, negative MI values, which means that peak summer precipitation is greater than that of autumn) (Figures 4 and 5). Towards the west and southwest, the proportion of precipitation in the warmer half of the year decreases, and the main peak precipitation shifts to the autumn months.

Slovenia is also a transition zone between moderate Mediterranean (marine) and moderate continental features with respect to the precipitation regime. Western, southern and central Slovenia have moderate Mediterranean features of the precipitation regime with a peak in the autumn months and the least rainfall in the second half of winter, including March, and July and August. The northeastern part, however, has moderate continental features with peak precipitation in summer and minimum precipitation in winter. The MI changes from positive to negative values going in this direction. It is highest in western Slovenia, where it is between 15 and 18 (Dražgoše 17.5; Bovec 16.2; Vogel 15.7; Strunjan 15.4; Seča 15.2), and the lowest in the extreme northeast between –5 and –8 (Šentilj in the Slovenian Hills –5.4; Mačkovci –5.6; Cankova –6.1; Podgorje in the Slovenian Hills –6.2; Jeruzalem –6.9; Martinje –7.1). For Europe, for which Koppany and Unger (1992) calculated the MI for the period 1901–1950, these values ranged between 22 and –16. The difference between the share of precipitation in the warmer and colder halves of the year between western and southwestern and northeastern Slovenia is also not extreme. The highest percentages of precipitation in the warmer half of the year in northern and northeastern Slovenia are mostly between 60 and 65% while the highest percentages in the colder half in the southern and southwestern parts of the country are between 51 and 57%.

The precipitation regime is highly variable from year to year and from period to period and we cannot rely on with certainty the peaks or minimums as determined by the averages. The average annual and seasonal variability of precipitation is between 20 and 30%, and the usual monthly averages can be exceeded by even more than 100% or (even in the wettest months on average) there may be virtually no precipitation. The Mediterranean precipitation index enables the calculation of the theoretical boundary between moderate Mediterranean and moderate continental precipitation regimes (MI = 0.0). According to data for the period 1961–1990, this boundary ran along the line Solčava–Ljubljana–Suha Krajina–Gorjanci (Ogrin, 1996), in the period 1971–2000 it moved east to the line Strojna-western Celje Basin-Suha Krajina-Gorjanci (Ogrin, 2009), and for the period 1991–2020 it ran from Mežica along the Vitanje Lowlands to Slovenske Konjice and beneath under Boč and Haloze to the border with Croatia. This means that the area with peak precipitation in autumn has expanded towards the east of Slovenia, and the area with peak precipitation in summer has shrunk significantly in the last 60 years. At the same time, the summer precipitation peak weakened in the northeast of Slovenia at the expense of an increase in autumn precipitation. It is also noticeable that autumn peak precipitation in the western parts of Slovenia mostly occurs in November or October, while towards the east and northeast it is more frequent in September or in some places in October, i.e. the autumn and summer peaks are becoming more and more equal.

Table 2: Mediterranean precipitation index (MI) and the proportion of precipitation in the warmer half of the year (DT) at selected precipitation stations in Slovenia in the period 1991–2020.

Precipitation station	MI	DT (%)	Precipitation station	MI	DT (%)
Ambrož po Krvavcem	3.9	55	Brod v Podbočju	4.2	55
Zgornje Jezersko	7.2	52	Moravče	3.3	57
Planina pod Golico	7.2	54	Gornji Grad	5.7	54
Rateče	7.9	54	Airport J.P. Brnik	5.6	54
Kredarica	4.9	57	Ljubljana-Bežigrad	3.1	56
Zgornja Radovna	10.4	51	Vrhnika	7.5	50
Bohinjska Bistrica	13.3	48	Škofja loka	8.9	50
Vogel	15.7	46	Javorniški rovt	7.6	54
Zgornja Sorica	11.2	47	Črnomelj-Dobliče	7.9	52
Kneške Ravne	12.0	46	Metlika	5.9	55
Tolmin-Volče	11.1	47	Novo mesto	5.4	56
Vojsko	12.2	46	Cerklje-airport	3.4	58
Vedrijan	10.1	51	Mokronog	2.6	57
Bilje	11.9	50	Bizeljsko	3.0	55
Razdrto	9.5	48	Velenje	0.4	59
Godnje	11.2	48	Celje-Medlog	0.5	59
Ilirska Bistrica	13.7	46	Slovenske Konjice	0.6	60
Movraž	6.7	48	Rogaška Slatina	0.5	58
Portorož-airport	14.8	49	Ravne na Koroškem	−3.2	63
Babno Polje	12.6	47	Šmartno pri Sl. Gradcu	−2.3	62
Kočevje	7.4	52	Ribnica na Pohorju	−2.6	61
Nova vas-Bloke	7.9	52	Airport E.R. Maribor	−2.7	62
Planina-Rakek	11.6	47	Polički vrh	−3.8	63

Precipitation station	MI	DT (%)	Precipitation station	MI	DT (%)
Logatec	10.8	47	Jeruzalem	–6.9	61
Litija	4.3	57	M. Sobota-Rakičan	–4.8	64
Malkovec	2.8	57	Ptuj	–1.9	60
Sevno	3.6	56	Maribor-Vrbanski plato	–1.7	62
Lisca	1.8	59	Lendava	–1.8	60

3.4 Humidity of the climate

On average, about 1450 mm of precipitation falls in Slovenia annually, which makes it one of the wettest countries in Europe, but precipitation is spatially very unevenly distributed. Most of it falls on the Alpine-Dinaric barrier, more than 2000 mm annually, and in the wettest part of the Julian Alps, more than 3200 mm. From the Alps and the High Dinaric Plateaus, precipitation decreases towards the southwest and northeast. Along the sea it is between 900 and 1000 mm (Strunjan 947 mm; Portorož Airport 958 mm; Koper 989 mm), and in Prekmurje less than 850 mm (Kobilje 772 mm; Lendava 790 mm; Murska Sobota 812 mm; Cankova 830 mm).

Large regional differences in the wetness and humidity of the climate are therefore one of the most important factors in the climate classification of Slovenia. Spatial differences in climate humidity were determined using Lang's rain factor. According to this indicator, the Alpine-Dinaric barrier has a perhumid climate. Slovenian Istria, northeastern Slovenia, the Krško-Brežice Plain with the lower Krka Valley and some smaller areas in the east of Slovenia have a semi-humid climate, while the rest of Slovenia has a humid climate (Figure 6).

Table 3: Lang's rain factor (L) at selected meteorological stations in Slovenia in the period 1991–2020.

Meteorological station	L	Meteorological station	L
Krvavec	519	Miklavž na Gorjancih	130
Jezersko	276	Trojane-Limovce	136
Planina pod Golico	254	Gornji Grad	154
Rateče	220	Malkovec	97
Bovec-airport	236	Airport J.P. Brnik	136
Rudno polje	444	Ljubljana-Bežigrad	110
Bohinjska Češnjica	215	Vrhnika	144
Vogel	715	Kranj	125
Zgornja Sorica	258	Lesce-airport	135

Meteorological station	L	Meteorological station	L
Krn	299	Ravne na Koroškem	108
Tolmin-Volče	173	Šmartno pri Sl. Gradcu	126
Vojsko	342	Velenje	98
Vedrijan	104	Celje-Medlog	103
Bilje	106	Slovenske Konjice	89
Podnanos	115	Črnomelj-Dobliče	109
Godnje	111	Metlika	92
Ilirska Bistrica	133	Novo mesto	101
Kubed	101	Cerklje-airport	97
Portorož-airport	66	Trebnje	108
Babno Polje	230	Bizeljsko	87
Kočevje	158	Rogaška Slatina	92
Nova vas-Bloke	198	Airport E.R. Maribor	84
Postojna	195	Polički vrh	97
Logatec	203	Jeruzalem	72
Litija	109	Murska Sobota-Rakičan	73
Rogla	295	Ptuj	82
Sevno	114	Maribor-Vrbanski plato	89
Lisca	140	Lendava	66

3.5 Climate types in Slovenia for the period 1991–2020

Previous climate classifications (e.g. Kozjek et al., 2017; Melik, 1935; Ogrin, 1996; 2009) highlight the fact that mountain, Mediterranean and continental climates come into contact and intermingle on the territory of Slovenia. Climatic contact and transition represent a challenge for climate classifications: the identified climate types are atypical as compared to true continental, Mediterranean or mountain climates. This is why we characterize them as "moderate" or add the prefix "sub", or "peri" to the type (e.g. moderate continental, sub-Mediterranean, submontane, peri-Pannonian). In general, as we move away from the Alpine-Dinaric barrier towards the east and northeast of the country, continental climate characteristics become stronger, while towards the southwest Mediterranean climate characteristics are more in evidence, and with increasing elevation in the Alpine, pre-Alpine and Dinaric Karst regions, the climate takes on the characteristics of a mountain climate. The boundaries between types and subtypes of climates on maps must therefore be understood as transition zones, and not in the sense of sharp dividing lines.

Figure 6: Humidity of the climate based on Lang's rain factor (1991–2020).

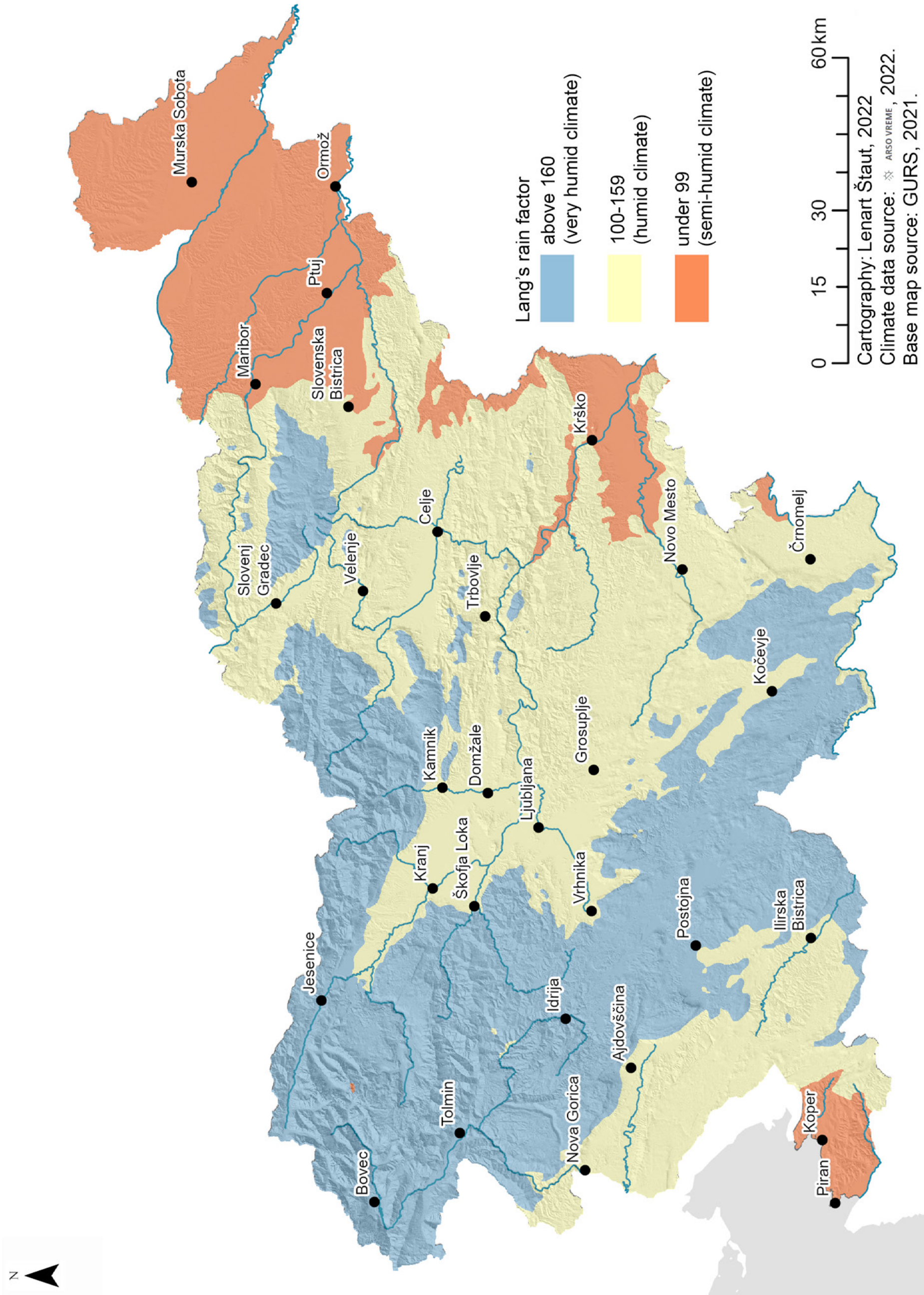
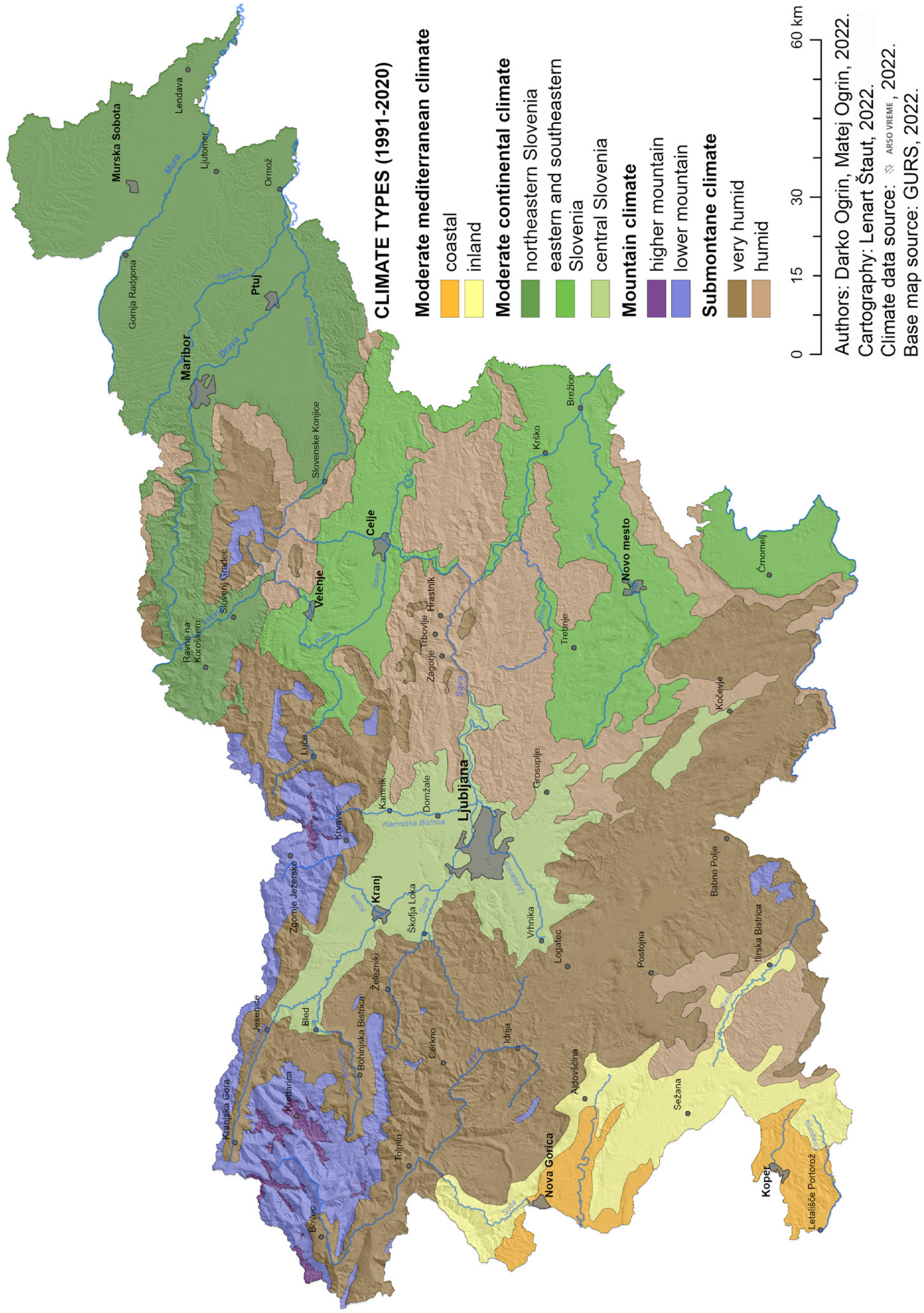


Figure 7: Climate types in Slovenia 1991–2020.



Taking into account the starting points and criteria presented in the previous sections, we distinguished four basic types of climate: moderate Mediterranean, moderate continental, mountain and submontane climate. In the second step, we divided these into nine subtypes: moderate Mediterranean into coastal and inland: moderate continental into moderate continental of northeastern, of eastern and southeastern, and of central Slovenia; mountain climate into higher mountain climate, lower mountain climate; and submontane into very humid and humid submontane climates (Figure 7).

Moderate Mediterranean climate

Due to the openness of the land towards the Adriatic Sea and the Mediterranean, a moderate Mediterranean climate occurs in the areas to the south and southwest of the Alpine-Dinaric barrier, which have the greatest number of clear days in Slovenia. Due to the influence of the sea, average temperatures are the highest in Slovenia, especially in autumn and winter. In the coldest month, on average, they do not drop below freezing, while in the warmest they are above 20 °C. The average annual temperature amplitude is less than 20 °C, as the influence of the sea mitigates the cold in winter and the heat in summer. The precipitation regime is moderate Mediterranean with peak precipitation in the autumn months. Snow cover is rare.

Bora wind is frequent in the colder half of the year and jugo wind blows before the weather deteriorates, especially in the colder half of the year. The occurrence of local thermal winds during anticyclonic weather is also noteworthy: during the day the sea breeze (maestral) and at night the land breeze (burin) which is less pronounced than the sea breeze along the Slovenian coast. From the coast towards the Alpine-Dinaric barrier, temperatures decrease and precipitation increases, which is the basis for dividing the moderate Mediterranean climate into warmer and less humid coastal and slightly cooler and more humid inland. During the transition from winter to spring and in July and August, there is usually a drought, which is more pronounced in karst areas due to surface features.

Areas of Slovenia with a moderate Mediterranean climate are dominated by a cultural landscape. The climate overlaps with the Littoral wine-growing region, and areas with a coastal climate, where January temperatures are above 3 °C and July temperatures above 22 °C, overlap with the area of olive cultivation (olive-growing climate). As a result, the natural vegetation is greatly altered. The climatic conditions suit the heat-tolerant and drought-resistant deciduous forests typical of the Mediterranean fringes. The most widespread are moderately heat-loving and deciduous associations dominated by downy oak (*Quercus pubescens*), hop-hornbeam (*Ostrya carpinifolia*) and flowering ash (*Fraxinus ornus*). The most common forest associations are the association of hop-hornbeam and downy oak (*Ostryo-Quercetum pubescentis*) and the association of hop-hornbeam and autumn moorgrass (*Sesleria autumnalis-Ostryetum*) (Repe, 2012). On warmer sites, they are joined by the oriental hornbeam

(*Carpinetum orientalis*) and Montpellier maple (*Acer monspessulanum*). On the warmest sites in Slovenia (the Karst Rim, the southern slopes of Nanos), with warm soil conditions, fragments of evergreen maquis (*Ostryo-Quercetum ilicis*) are also preserved, consisting of evergreen Mediterranean trees and shrubs, such as holm oak (*Quercus ilex*), green olive (*Phillyrea latifolia*), laurel (*Laurus nobilis*). Other heat-loving deciduous species also appear in between, e.g. Jersualem thorn (*Paliurus spina-christi*) and evergreen climbing plants, e.g. wild asparagus (*Asparagus acutifolius)* (Kaligarič, 2004). Black pine (*Pinus nigra*) is anthropogenically present in this area, as a result of afforestation in the first half of the 20th century (Repe, 2020). There are more cultivated plants than true Mediterranean natural species: in addition to the olive tree, there are also fig trees, almond trees, pomegranate trees, etc.

Figure 8: Climograms for coastal (Portorož Airport) and inland (Ilirska Bistrica) moderate Mediterranean climate.

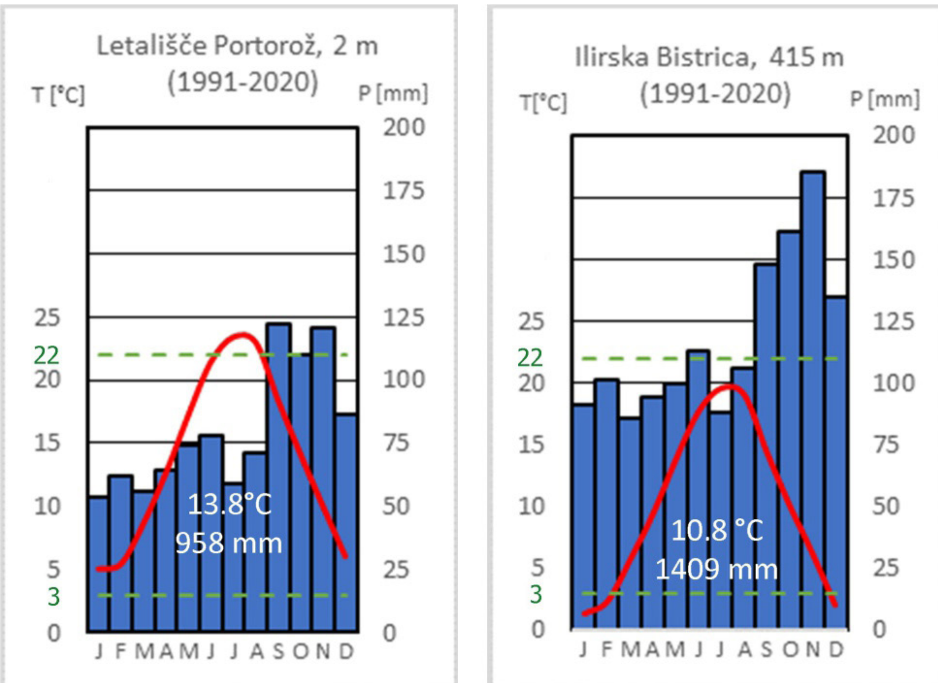


Table 4: Basic characteristics of a moderate Mediterranean climate.

<table>
<tr><td colspan="2">Moderate Mediterranean climate
- Average temperature of the coldest month above 0 °C
- Average temperature of the warmest month above 20 °C
- October warmer than April
- Average annual temperature amplitude below 20 °C
- Average annual amount of precipitation 900 to 1400 mm
- moderate Mediterranean precipitation regime (MI >10)</td></tr>
<tr><td>Coastal moderate Mediterranean climate (Cfaw‘ according to Köppen)
- Avg. temp. of the coldest month above 3 °C
- Avg. temp. of the warmest month above 22 °C
- Percentage of precipitation in the colder half of the year 45 to 50%
- semi-humid climate (L < 99)</td><td>Inland moderate Mediterranean climate (Cfbw‘ according to Köppen)
- Avg. temp. of the coldest month between 0 and 3 °C
- Avg. temp. of the warmest month between 20 and 22 °C
- Percentage of precipitation in the colder half of the year generally above 50%
- Humid climate (L = 100 do 159)</td></tr>
</table>

Moderate continental climate

A moderate continental climate is found in lower-lying areas in northeastern, eastern, southeastern, and central Slovenia. It is the second warmest climate in Slovenia after the moderate Mediterranean climate, and is characterized by the greatest average annual temperature amplitude (more than 20 °C) and high summer maximum temperatures. It receives below-average annual precipitation (below 1400 mm), most of which falls in the warmer half of the year. Northeastern Slovenia has the most pronounced continental climate features, where April is warmer than October (inland areas warm up faster in spring than areas influenced by the sea), receives the least precipitation (even under 1000 mm) and has a moderate continental precipitation regime. Lower-lying areas in the east and southeast of Slovenia, which are also open towards the Pannonian Plain, have similar temperature characteristics, except that they receive more precipitation and have a moderate Mediterranean precipitation regime. The latter is also characteristic of the moderate continental climate of central Slovenia, which is even more humid due to its location near the Alpine-Dinaric barrier, and the greater influence of sea air masses is also evident as October is warmer than April.

Figure 9: A maquis patch in the wall above the Osp Valley (photo: D. Ogrin).

Figure 10: Climograms for the moderate continental climate of northeastern (Murska Sobota), eastern and southeastern (Črnomelj-Dobliče), and central Slovenia (Kranj).

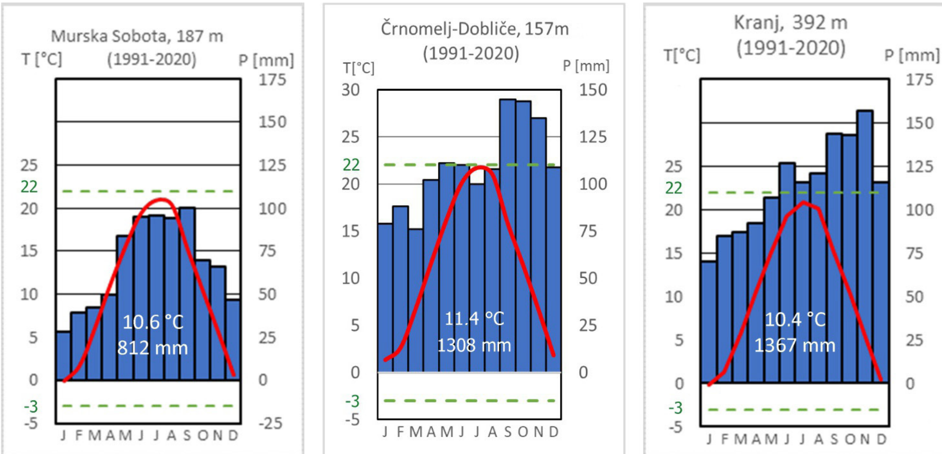


Table 5: Basic characteristics of a moderate continental climate.

<table>
<tr><td colspan="2">Moderate continental climate
- Average annual temperature above 20 °C
- Average July temperature 20 to 22 °C
- Average annual temperature 9 to 12 °C
- Average annual amount of precipitation below 1400 mm
- Over 50% of the annual amount of precipitation occurs in the warmer half of the year</td></tr>
<tr><td>Northeastern Slovenia
(Cfbx' according to Köppen)
- April warmer than October
- Annual amount of precipitation between 750 and 1200 mm
- Over 60% of precipitation occurs in the warmer half of the year
- Moderate continental precipitation regime (MI = 0 to –10)
- Semi-humid to humid climate</td><td>Eastern and southeastern Slovenia
(Cfbw' according to Köppen)
- April warmer than October
- Annual amount of precipitation 1000 to 1400 mm
- 50 to 60% of the annual amount of precipitation occurs in the warmer half of the year
- Moderate Mediterranean precipitation regime (MI = 0 do 5)
- Semi-humid to humid climate</td></tr>
<tr><td colspan="2">Moderate continental climate of central Slovenia (Cfbw' according to Köppen)
- October warmer than April
- Annual amount of precipitation 1200 to 1400 mm
- 50 to 60% of the annual amount of precipitation occurs in the warmer half of the year
- Moderate Mediterranean precipitation regime (MI = 0 to 10)
- Humid climate (L = 100 do 159)</td></tr>
</table>

Despite the higher proportion of precipitation in the warmer half of the year, summers in northeastern, eastern and southeastern Slovenia, and partly also in central Slovenia on gravel and sand deposits, are susceptible to drought due to the relatively low amount of precipitation and high temperatures (average July temperatures are above 20 °C). Freezes are common in winter, and cold days also occur (daily temperatures stay below freezing). Snow cover occurs in all areas of this climate type, about four weeks out of the year, but snowfall is much less compared to previous decades, and periods with snow cover are getting shorter. Spring frosts are relatively common, with lowlands, basins and valleys especially susceptible. Periods of summer heat are often punctuated by storms (including hail and high winds) that cause major damage to agriculture and buildings. Lowland areas in the eastern half of Slovenia are more exposed to storms. In particular, the lowlands of eastern and southeastern Slovenia, due to their low elevation, the openness to the Pannonian Basin, and their leeward location with respect to southwesterly winds (Bela Krajina, Krško-Brežiško polje), are often the areas of greatest heat in summer, where the highest daily temperatures can even exceed those in the Vipava Valley and along the coast.

Due to the favourable natural conditions, areas with a moderate continental climate have a predominantly cultural landscape; this is where the largest areas of arable land in Slovenia are located, which are often exposed to drought in summer. The moderate continental climate of northeastern, eastern and southeastern Slovenia (it could also be called a Pannonian climate) roughly overlaps with the Drava Valley and Lower Sava Valley wine-growing regions. Due to the more favourable local climatic conditions, vineyards and orchards are mostly located in sun-exposed areas of the thermal belt. In the plains and valleys, where there are frequent temperature inversions, there are mainly crop fields and meadows. Larger basins such as Ljubljana and Celje and the lowlands (Mura Plain, Drava – Ptuj Plain) often have morning fog, which is most persistent in autumn and in the first half of winter. The lowlands are poorly ventilated and without wind energy potential and have lower air self-cleaning capacities, which increases air pollution especially in the colder half of the year (Ogrin, Vintar Mally, 2013; Strle et al., 2020). There are no constant strong winds in the lowlands; only in some places in the Savinja Valley and in the lowlands of the eastern half of the country is there a stronger southwesterly wind before the weather deteriorates, while an even less frequent Foehn wind can blow from the southern slopes of the Karawanks, the Kamnik Savinja Alps and the Pohorje Massif, which can also cause damage.

Figure 11: The sun-exposed hills of the peri-Pannonian regions in the thermal belt are less susceptible to spring frosts, having more sun and lower air and soil humidity, which is why they offer favourable conditions for the growth of grapevines. The photo shows the vineyard landscape of Trška Gora near Novo Mesto (photo: D. Ogrin).

With respect to vegetation, the area with a moderate continental climate can be divided into three parts:

a) excessively humid flat areas directly next to water bodies (wet meadows) and areas with high levels of groundwater (riparian forest);
b) well-drained flat areas;
c) hills and foothills.

Humid lowland areas are characterized by moisture-loving forest vegetation with oak (*Quercus robur*), black and grey alder (*Alnus glutinosa* and *A. incana*), European ash (*Fraxinus excelsior*), willows (e.g. white willow, *Salix alba*) and poplars (black and white, *Populus nigra* and *P. alba*). Common associations are black alder (*Alnetum glutinosae*) and white willow (*Salicetum albae*). Where water does not accumulate, the plains were once covered with oak (*Quercus petraea*) and European hornbeam (*Carpinus betulus*) forests. Since it is one of the best growing areas in Slovenia, today these forests have been almost completely cleared. The elevated parts are overgrown with deciduous trees. Above the plain, oak and hornbeam are quickly replaced by beech (*Fagus sylvatica*), which becomes the dominant species particularly on the shaded slopes. On silicate rocks, beech most often grows together with chestnut (*Castanea sativa*, the acid-loving *Castaneo sativae-Fagetum* association), where silver birch (*Betula pendula*) and Scots pine (*Pinus sylvestris*) are also mixed in, and blueberry (*Vaccinium* *myrtilus*) in the understorey. Beech associations thrive on carbonate rocks, e.g. with haquetia (*Hacquetio-Fagetum*) or dead nettle (*Lamio orvalae-Fagetum*), characteristic of the milder form of the continental climate. A heat-loving and drought-tolerant association of beech and hop-hornbeam (*Ostryo-Fagetum*) thrives on particularly sunny and above-average warm and dry slopes of limestone and dolomite (Marinček, Čarni, 2002; Repe, 2020). With climate change, it can be expected that the latter will be among those that will spread the most in the future (Kutnar, Kobler, 2014; Gregorčič et al., 2022).

Mountain climate

With altitude, the air temperature usually decreases, the amount of precipitation increases, the duration and depth of the snow cover increases, there is more wind, the growing season shortens, etc. Therefore, one of the main characteristics of a mountain climate are the altitude climatic-vegetation zones, in Slovenia mainly the mountain, sub-alpine and alpine zones (there is no real nival zone). The mountain climate of the Alps, Pohorje and the highest areas of the Western Pre-Alpine Hills and the High Dinaric Plateaus is the coldest and wettest in Slovenia (and among the wettest in Europe), with long-lasting and deep snow cover that in average winters exceeds 150 cm. The average temperature of the coldest month is lower than –3 °C, and the annual precipitation mostly above 1600 mm. Western areas with a mountain climate are wetter (over 2500 mm of precipitation annually) and have peak precipitation in late autumn, while eastern areas receive less precipitation, and the wettest part of the year shifts to summer. The least precipitation occurs in winter. The highly dissected relief of mountain areas also engenders very diverse topoclimatic conditions with a great variety of microclimates. Temperature conditions can be extreme in mid-mountain and high-mountain frost hollows, as temperatures there can be around 30 °C lower than in areas outside frost hollows at the same altitude (Dovečar et al.,. 2009; Ogrin, Ogrin, 2005; Ogrin, 2007; Ogrin et al., 2012; Ortar, 2011; Svetlin, 2020; Trošt, 2008). In mountain areas, in addition to the greatest amount of precipitation, we also observe the greatest precipitation gradients. This is especially true of some Alpine valleys (Ogrin, Kozamernik 2018, 2020a, 2020b). Higher areas, especially ridges and peaks, are the areas most exposed to the wind in Slovenia, and towards the valleys the ventilation quickly weakens. The valley floors are, however, better ventilated than the plains and basins, because with anticylonic weather, daily thermal winds occur regularly, which increases the self-cleaning capacity of the atmosphere. In recent decades, the extent of the mountain climate in Slovenia has been decreasing due to the warming of the atmosphere.

Figure 12: Climogram for the climate of higher (Kredarica) and lower (Krvavec) mountain areas.

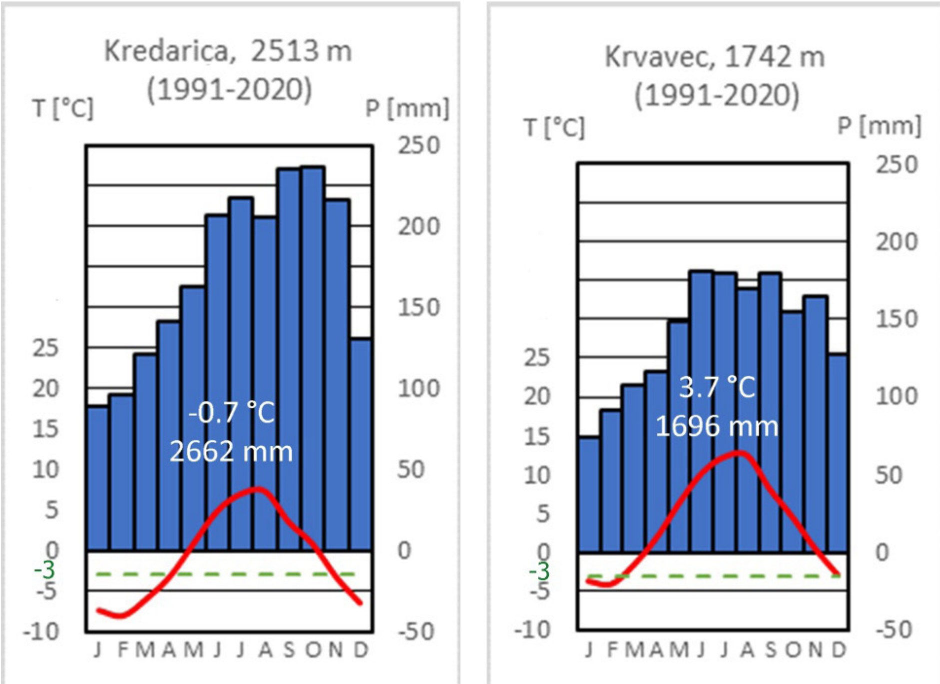


Table 6: Basic characteristics of a mountain climate.

Mountain climate - Average temperature of the coldest month below –3 °C (January isotherm –3 °C at about 1530 m) - October warmer than April - Average annual temperature below 6 °C - Average annual temperature amplitude less than18 °C - Annual amount of precipitation more than1600 mm (Pohorje 1400 to 1600 mm) - Perhumid climate (L >160)	
Higher mountain climate (ET according to Köppen) - Avg. temp. of the warmest month below 10 °C (July isotherm 10 °C at around 2200 m) - Avg. annual temperature below 3 °C - Annual amount of precipitation more than 2000 mm - Moderate Mediterranean precipitation regime (MI over 10)	**Lower mountain climate** (Dfcw‘ (x‘), Dfbw‘ (x‘) and Cfcw‘ (x‘) according to Köppen) - 1 to 4 months with an average monthly temperature above10 °C - Avg. annual temp. 3 to 6 °C - Average annual amount of precipitation 1400 to 2000 mm - moderate Mediterranean precipitation regime (MI >10); Pohorje moderate continental precipitation regime

A higher mountain climate is found along the highest ridges of the Julian and Kamnik-Savinja Alps, where the average temperature of the warmest month does not exceed 10 °C. Thus, in the highest and coldest areas (above 2400 m, sub-snow zone), where the mean annual temperatures are around or slightly below 0 °C, the vegetation is sparse and includes typical representatives of alpine flowers such as pink cinquefoil (*Potentilla nitida*), alpine forget-me-not (*Eritrichium nanum*) and similar. Between about 2000 and 2400 m, mean annual temperatures are a degree or two higher than in the sub-snow zone, which is enough for the alpine zone to appear. Grasses and perennial cushion plants such a various sedges (e.g. evergreen, rusty, hardy), mountain aven (*Dryas octopetala*), etc. thrive here. Lower down, a zone of cool-loving shrubs begins to appear. The most common is the dwarf mountain pine (*Pinus mugo*), while underneath it grows the hairy alpenrose (*Rhododendron hirsutum*), rhododendron *(Rhodothamnus chamaecistus*) and heather (*Erica carnea*) (Blatnik and Repe, 2012). Between the alpine zone and the tree line is the subalpine zone, which includes areas mostly between 1500 and 2000 m. Average annual temperatures are approximately between 4 and 2 °C. In this zone, it is still too cold for stands of forest to appear. Scattered larches (*Larix decidua*) and spruces (*Picea abies*) as well as mountain ash (*Sorbus aucuparia*) begin to appear mixed in with the mountain pine. The number of tree species increases with decreasing altitude, until they transition into forest stands with lush undergrowth. In addition to the mountain pine, the alpine honeysuckle (*Lonicera alpigena*), alpine clematis (*Clematis alpina*), spurge laurel (*Daphne mezereum*), etc. thrive in the shrub layer (Repe, 2017).

Lower down, below the tree line, where one to four months have an average temperature above 10 °C, up to an altitude of about 1200 m, is a lower mountain climate. This also extends to some mountain valleys and higher-lying karst depressions, where temperatures are similar to mountain ones mainly due to strong temperature inversions. With respect to natural vegetation, this area could be classified as a lower montane zone; spruce (*Picea abies*) is the predominant tree species, while beech (*Fagus sylvatic*a) is also common, while in lower parts of this area silver fir (*Abies alba*) and maples (e.g. the sycamore maple, *Acer pseudoplatanus*) grow, and higher up larch (*Larix decidua*). Beech associations (with the three-leaved anemone (*Anemono trifoliae-F.*), large white buttercup (*Ranunculo platanifoliae-F.*), *Homogyne sylvestris-F.* etc.) and natural spruce forest associations (with buckthorn *(Rhamno fallici*), alpine plantain (*Adenostylo glabrae-Piceetum*)) etc. are common. On sun-exposed slopes beech along with hop-hornbeam grows (Repe, 2019). In the past, in many places in the mountains a cultural landscape of mountain pastures could be seen up to the tree line, as the wet summers enable the lush growth of grass. In many places, this process anthropogenically lowered the natural tree line, which has been gradually rising in recent decades due to the abandonment of grazing as well as climate change.

Figure 13: Upper tree line on the southern slope of Golica (photo: D. Ogrin).

Submontane climate

The foothills of the Alps and most of the pre-Alpine hills and the Dinaric karst plateaus and hills have a submontane climate. This is a transitional climate between mountain and moderate continental on the eastern side, and mountain and moderate Mediterranean on the southwestern side of the Alpine-Dinaric barrier. Average January temperatures are mostly between 0 and –3 °C and July temperatures between 16 and 20 °C. Due to the location in the area of the Alpine-Dinaric barrier, the climate is wetter than average, with the least precipitation in winter. Snow cover is less reliable than in mountain climates due to lower elevations and higher temperatures. Precipitation and temperature conditions are the basis for dividing the submontane climate into very humid, found in the central, highest, coldest and wettest part of the barrier, and humid, found in the lower and slightly warmer areas on the continental and coastal sides of the barrier at the edge.

Due to the less favourable climatic, relief and soil conditions, areas of Slovenia with a submontane or lower mountain climate have a lot of forest. The entire area is noticeably dominated by beech forests, which on carbonate rocks typically form distinctive climate- and altitude-dependent belts. At the lowest altitudes, the already mentioned beech associations with haquetia and dead nettle occur. As the altitude increases, the proportion of conifers begins to increase, primarily fir (*Abies alba*), and higher still spruce (*Picea abies*). Thus, the high Dinaric karst plateaus are completely dominated by fir-beech forests (an association of beech and blue-eyed-Mary, *Omphalodo-Fagetum*), which gives way to an association with three-leaved anemone (*Anemono trifoliae-Fagetum*) in the direction of the Alps. In frost hollows of the Dinaric Karst, beech is first replaced by spruce and then dwarf mountain pine. Beech forests with hop-hornbeam (*Ostryo-Fagetum*) grow on sun-exposed slopes. On silicate rocks, acid-loving beech forests with chestnut and deer fern (*Blechno-Fagetum*) thrive where spruce, fir and red pine are abundantly mixed in (Gregorčič et al., 2022; Marinček, Čarni, 2002; Repe, 2020).

In areas with a submontane climate with favourable relief, soil and local climatic conditions, the natural landscape has been transformed by agriculture. In the lower elevated parts, there is a warm belt, which is conducive to growing fruit trees due to the lower risk of frost and less humid nights. Higher up, forests of the species already mentioned predominate, interspersed with meadows, which the relatively humid summers suit. The high moisture of the Western Pre-Alpine Hills, especially in autumn, is often reflected in extreme precipitation events, which can cause abundant torrential floods, and less destructive karst flooding in karst poljes. In Dinaric Karst areas in this type of climate, pronounced temperature inversions occur on the karst poljes, depressions. and other depressed landforms. For example, on clear mornings, the karst poljes often become true frost hollows, and the settlements in these places are the coldest populated areas in Slovenia (e.g. Babno Polje, Rakitna, Retje, Travnik) (Ogrin et al., 2006).

The occurrence of temperature inversions in populated karst poljes and depressions is also associated with the low self-cleaning capabilities of the air and increased pollution as a result of local emissions from households and traffic, especially in the colder half of the year (Glojek et al., 2018; 2020; 2022). Higher areas with this type of climate are moderately ventilated, but the lowlands lack any pronounced winds, with the exception of valleys in Alpine and pre-Alpine areas, where daily thermals occur with anticyclonal weather (katabatic and anabatic wind).

Figure 14: Climogram for very humid (Babno Polje) and humid (Lisca) submontane climate.

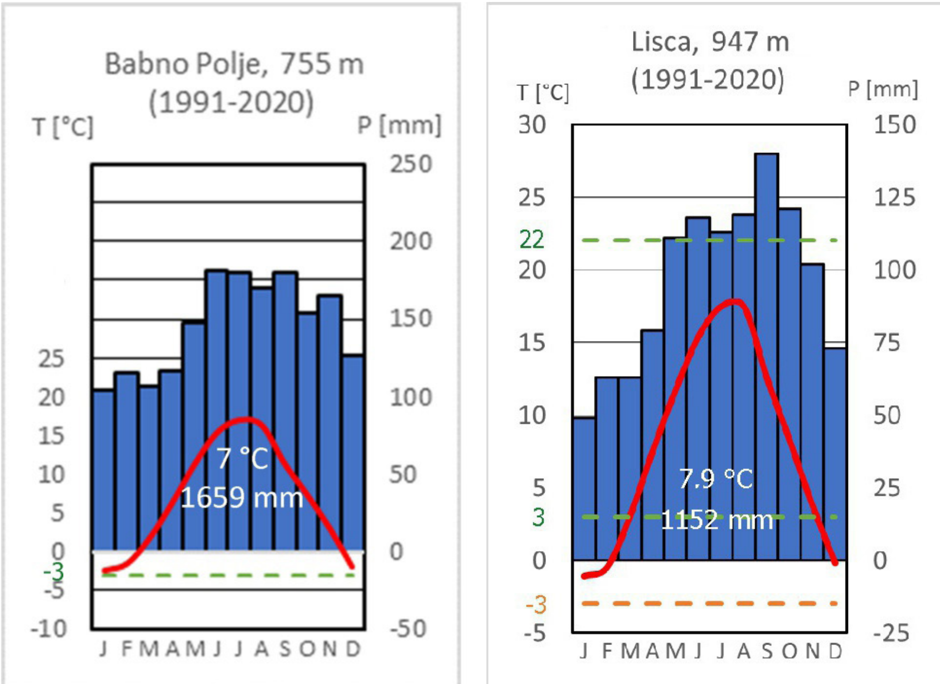


Table 7: Basic characteristics of a submontane climate.

Submontane climate (Cfbw' and Cfbx' according to Köppen) - Average January temperature 0 to –3 °C, average July temperature 16 to 20 °C, average annual temperature 6 to 9 °C - Average annual temperature amplitude 18 to 20 °C - October warmer than April - Annual amount of precipitation more than 1400 mm - Moderate Mediterranean precipitation regime (except for Pohorje and Kozjak with Košenjak)	
Very humid submontane climate - Perhumid climate (L >160)	**Humid submontaneclimate** - Humid climate (L = 100 to 159)

Figure 15: A high amount of precipitation falls in mountain areas, including in Bohinj. The umbrella is therefore one of the symbols of these places (photo: D. Ogrin).

4 DISCUSSION

The climate classification of Slovenia for the period 1991–2020 is partly based on different criteria than all the previous ones, so a direct comparison with previous classifications is not possible. Although it partially preserves the naming of certain climate types, e.g. moderate continental climate, climate of lower and higher mountains, coastal and inland moderate Mediterranean climate, the criteria differ from past studies, which is a consequence of the general warming of the atmosphere and climate change. At the same time, it also eliminates certain climate types (e.g. the moderate continental climate of western and southern Slovenia and the climate of the lower mountains and intervening basins and valleys of northern Slovenia) and introduces new ones. The method on which the classification is based is also not comparable to climate classifications in neighbouring countries, as its purpose is to identify the climatic types of Slovenia by describing their characteristics and finding differences and similarities between Slovenian regions. Four large geographical units come together on the territory of Slovenia (Ogrin, Plut, 2009), which in turn leads to the great geographical diversity of Slovenian landscapes; this is also reflected in high abiotic diversity (geodiversity), in which climate types can also be included. Climate types are the result of established weather processes and their properties, which are the result of the action of other abiotic and biotic factors (geological composition, relief, water bodies, vegetation) and at the same time also influence and shape them.

The largest share of Slovenian territory is in the submontane climate type (46.4%), followed by moderate continental (40%), moderate Mediterranean (7.1%) and mountain climate (6.5%). The dominance of the submontane climate overlaps in large degree with the Pre-Alpine and Dinaric Karst regions, with the exception of the Ljubljana Basin and the lower parts of the Dinaric Karst regions. At the same time, it indicates the transition of climatic characteristics between mountain, moderate Mediterranean and moderate continental areas. The second most dominant climate type, the moderate continental climate, also indicates a transition between the mountain and submontane areas of Slovenia and the distinctly continental areas east of it. This climate type is also present in Croatia (Zaninović et al., 2008), in Bosnia and Herzegovina (Bosnia and..., 2023) and in Serbia (Republički hidrometeorološki..., 2023). The moderate Mediterranean climate is the result of a transition between the Mediterranean regions south of Slovenia and the regions in its interior. An understandable consequence of the marked transitional nature of Slovenia's climate is also seen in the fact that the mountain climate, which is not a transitional type, covers the smallest area of the climate types.

With regard to subtypes, the largest share of Slovenia (30%) has a very humid submontane climate. It is the only subtype that covers more than 20% of the area. It is followed by the moderate continental climate of northeastern Slovenia (19%) and the humid submontane climate (17%). More than 10% of the territory of Slovenia has the moderate continental climate of eastern and southeastern Slovenia (14%). Less than 10% has the moderate continental climate of central Slovenia (7%), either mountain (6.5 and 0.5%) or moderate Mediterranean (4.7 and 2.7%) subtypes of climate, respectively (Table 8). The smallest share has a higher mountain climate, which occupies only 0.5% of the surface of Slovenia, coinciding roughly with the territory above an elevation of about 2200 m.

With respect to population density by climate subtypes and types, the moderate continental type greatly stands out: almost three-quarters of the population of Slovenia (74.6%) live in areas with this climate type. Within this type, the moderate continental climate of central Slovenia is most prominent, where 31% of the population live (a density of 421 inhabitants/km2). A little over one-sixth (16.1%) of the population lives in areas with a submontane climate, and a little over a tenth (9.5%) in areas with a moderate Mediterranean climate, of which only a little under 3% live in the areas with the inland subtype. The contact of sea and land and the attractive climate of the coastal zone are the reason for the second highest population density among the climatic subtypes in Slovenia, which amounts to 277 inhabitants/km2. The area with a mountain climate area is practically devoid of population, as only 1‰ of Slovenia's population live here, and there are no inhabitants in areas with a higher mountain climate.

Table 8: Spatial and demographic representation of climate types in Slovenia.

Climate type	Average el. (m)	Area (km^2)	Share of area (%)	No. of inhabitants	Share of pop.	Pop. density (inh./ km^2)
Moderate continental	327	8111	40.0	1,516,291	74.4	187
Moderate continental of northeastern Slovenia	311	3824	18.9	511,722	25.1	134
Moderate continental of eastern and southeastern Slovenia	285	2786	13.7	372,479	18.3	134
Moderate continental of central Slovenia	384	1501	7.4	632,090	31	421
Moderate Mediterranean	245	1441	7.1	193,194	9.4	134
Coastal moderate Mediterranean	123	488	2.4	134,973	6.6	277
Inland moderate Mediterranean	367	953	4.7	58,221	2.9	61
Mountain climate	1734	1314	6.5	2516	0.1	1.9
Higher mountain	2096	102	0.5	0	0	0
Lower mountain	1372	1212	6.0	2516	0.1	2
Submontane climate	635	9404	46.4	327,114	16.1	35
Very humid submontane	788	6015	29.7	168,537	8.3	28
Humid submontane	517	3389	16.7	158,577	7.8	47

Demographic data are from 2016 (SURS, 2016).

5 CONCLUSION

From the 1930s to the end of the century, geographers prepared six climate classifications for the area of Slovenia. These have been methodologically improved and updated and also covered other time periods, but the trend of global warming was not taken into account. In 2009, Ogrin's classification was updated based on data for the period 1971–2000 (Ogrin, 2009), which preserved the criteria of the previous classification (D. Ogrin, 1996). Global warming is already reflected in this classification, as for example the spread of the moderate Mediterranean climate towards the interior of Slovenia, the shift of the climate of lower mountains to higher altitudes, the mitigation of the continental temperature regime due to the rise in winter temperatures, and in the case of precipitation, the shift of a moderate Mediterranean precipitation regime towards the east of the country. In 2017, a climate classification for the period 1981–2010 was prepared by meteorologists (Kozjek et al., 2017) using factor analysis and cluster analysis, and it was updated by calculating the measures of variability of the most important climatic elements for the period 1961–2011. In our research, we prepared a revised climate classification based on Ogrin's earlier classification that includes the last completed 30-year reference period (1991–2020), and methodologically improved it. The improved methodology, compared to Ogrin's previous classification, takes into account Lang's precipitation factor in describing humidity conditions, we have adapted Köppen's criteria of the precipitation regime and the Mediterranean index of precipitation, and we have also included differences in humidity between the warmer and colder halves of the year. The classification is also based on a higher density of point data, on data in a kilometre grid and more objective spatial interpolation.

More recent data reflect the current climate conditions resulting from climate change, which is manifested in positive temperature deviations in certain areas from the values that we have been used to. Changes are also evident in some other criteria, e.g. in terms of annual temperature amplitudes and the Mediterranean index. It turns out that the new classification cannot be based only on the expansion or contraction of existing climate types, but it is also necessary to introduce a new climate type, and some established climate types have disappeared. Greater spatial density of input data and more objective spatial interpolation also enable more precise demarcation of climate types, which, even after a basic generalization, still appear in less regular or more complex spatial forms (polygons). The main modifiers of climate and climate types in Slovenia remain altitude, relief and distance from the Adriatic Sea; geographical location in relation to the most frequent winds must also be considered.

Our research also confirmed the strongly transitional character of Slovenia's climate, as well as the high climatic variety, which is the result of the variability of the main climate modifiers. With the exception of the mountain climate, all climate types in Slovenia are transitional climate types; the area of the mountain climate covers only 6.5% of Slovenia's territory and is inhabited by only 1‰ of the population. The most spatially extensive climate type is the submontane climate, which covers 46% of Slovenia, and the most populated area is the moderate continental climate (75% of the population, 421 inhabitants/km2), which prevails in the largest and thus most densely populated lowlands of inner Slovenia. In terms of population density, the area covered by the coastal moderate Mediterranean climate stands out (277 preb./km2), more a result of the proximity of the sea than the favourable climate.

In our research we analysed the climate conditions for the last 30-year reference period, which provides the basis for a new interpretation of climate conditions in Slovenia, for which we must be aware that the dynamics of climate change dictate the adaptation of climate classifications faster than was necessary throughout most of the 20th century. Although the purpose of our research was not to compare the climate types of older classifications with the current ones, by analysing and processing the data of the last reference period, we obtained a good basis for the preparation of such studies.

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