


Climate and climate change in the Austrian–Swiss region of the European Alps during the twentieth century according to Feddema

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Abstract Feddema’s generic climate classification method is applied to study climate and climate change in the Austrian–Swiss region of the European Alps during the course of the twentieth century. A fine-tuned version of it is also tested in addition to the original scheme. Monthly precipitation and air temperature data at a spatial resolution of $10' \times 10'$ are taken from the Climatic Research Unit TS 1.2 database to construct 30- and 50-year period averages. It is shown that the alpine climate is sufficiently heterogeneous to make it unnecessary to perform fine-tuning of the original scheme for its characterization on the meso- β scale (20–200 km). It is also demonstrated that data organizational effects are much less intense than the effects caused by the fine-tuning. The area heterogeneity of climate and climate change types is the highest in the vicinity of lakes (Austria: Lake Constance; Switzerland: Lakes Geneva, Neuchâtel, Biel, Zurich, and Constance) and along river valleys (Austria: the Danube, Drava, and Mur; Switzerland: the Aare and Ticino). The dominant climate change process was drying in Austria and warming in Switzerland. Large areas characterized by cold and saturated climate in the Central Eastern Alps did not experience climate change during the twentieth century.

1 Introduction

Generic climate classification methods serve the best characterization of climate in the given region (e.g., Rholi et al. 2015). Among other climate classification methods, for instance, genetic methods or mostly mathematically established methods, these generic methods use as little data as possible and are the simplest, which enables their classroom applications while also being biophysically based. According to Essenwanger’s (2001) criteria, generic methods based on these features should be preferred to other methods.

Among generic methods, the two most commonly used methods in the scientific community are the Köppen-Geiger (Geiger 1961) scheme and the Thornthwaite-based methods (Thornthwaite 1948; Feddema 2005). The main difference between them is in estimating the available heat. Köppen (1900, 1923, 1936) solved this problem as simply as possible using temperature data only. Thornthwaite (1948) recognized that potential evapotranspiration (PET) is a better indicator for this, so his method is PET based in estimating not only thermal but also moisture characteristics. This PET-based method increases both the complexity and the applicability. Its applicability is increased since PET is a more suitable quantity for fine-tuning than temperature. Both methods are constructed for global-scale analysis. There is an abundance of studies where the Köppen-Geiger (Geiger 1961) scheme was used for climate (Kottek et al. 2006; Peel et al. 2007) or climate change (Rubel and Kottek 2010) analyses. Thornthwaite’s original method (Thornthwaite 1948) was never applied on the global scale, only its very simplified version constructed by Feddema (2005). There are also regional-scale analyses in which Köppen’s (1936) scheme was also in the majority (e.g., Alvarez et al. 2014; Engelbrecht and Engelbrecht 2016; Baker et al. 2010; Stern et al. 2000). Note that such analyses refer to countries or regions where the climate is fairly heterogeneous.

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Applications at even smaller scales are not common, but recently, there have been such attempts (e.g., Ács et al. 2015; Breuer et al. 2017). These studies refer to a continental climate where the relief is quite uniform. To the best of our knowledge, similar treatments referring to upland regions are very rare (e.g., Rubel et al. 2016) though the climate of upland regions is strongly heterogeneous even at local scales.

In this work, Feddema’s (2005) method is used to characterize an upland climate, specifically, the climate of the European Alps, in its Austrian–Swiss region during the course of the twentieth century. We chose this region since it is located at about the same geographical latitude as Hungary. So, the climate differences between the lowland and the upland can be attributed mainly to differences in relief. The data needed are monthly precipitation (*P*) and temperature (*T*). They are taken from the Climatic Research Unit (CRU) TS 1.2 database (Mitchell et al. 2004). The analysis is performed using data of three 30-year periods (1901–1931; 1936–1965; 1971–2000) and two 50-year periods (1901–1950; 1951–2000).

We wish to answer the following questions: (1) Is it necessary to fine-tune Feddema’s (2005) original scheme to be able to characterize the structure of climate on the mezo-β scale (20–200 km)? (2) What are the main features of the alpine climate in the Austrian–Swiss region according to Feddema? (3) What are the main features of climate change in this region during the twentieth century? Finally, (4) to what extent are the results sensitive to data organizational effects?

2 Method and data

2.1 Feddema’s original scheme

The original scheme is well presented in Feddema (2005). This method is based on determining the heat and water availability of an area. Since it is a Thornthwaite-based method (Thornthwaite 1948), heat availability is expressed via PET. PET is calculated after McKenney and Rosenberg (1993) since we were unable to find a special PET formula for alpine climate regions. The parameterization uses *T* and monthly mean value of day length as input. The same parameterization works well on the Pannonian Plain (Ács et al. 2015), where the climate is continental. Heat availability of the area is estimated via calculating annual PET values. Thermal type categorization is given in Table 1.

Water availability is estimated via moisture index *I_m*, which is defined as follows:

$$I_m = \begin{cases} 1 - \frac{PET}{P}, & \text{if } P > PET, \\ 0, & \text{if } P = PET, \\ \frac{P}{PET} - 1, & \text{if } P < PET. \end{cases}$$

Table 1 Thermal types used in Feddema’s original scheme

Thermal type	Annual PET (mm year ⁻¹)
Torrid	>1500
Hot	1200–1500
Warm	900–1200
Cool	600–900
Cold	300–600
Frost	0–300

Water availability of the area is estimated via calculating the annual *I_m* value. Moisture type categorization can be seen in Table 2.

Seasonality is considered through two features: the climatic variable that possesses seasonality and the magnitude of seasonal variability. The ratio between the annual *P* range and the annual PET range has to be estimated in order to determine which climatic variable possesses seasonality. The criteria used are presented in Table 3.

The magnitude of variability is estimated by calculating the annual range of *I_m*. The criteria used for both *P* and *T* can be seen in Table 4.

2.2 Feddema’s fine-tuned scheme

To fine-tune Feddema’s (2005) original scheme, we determined the distribution of the relative frequencies of PET and *I_m* among the categories used. By changing the scale, we always intended to obtain a distribution that is as homogeneous as possible. On the basis of this principle, we slightly modified the thermal and moisture type categorizations as well as the categorization referring to the magnitude of seasonal variability. These new sub-categorizations and criteria referring to the European Alps and the features mentioned are presented in Tables 5, 6, and 7.

Concerning thermal types (Table 5), we introduced the “moderately cold” type in addition to the “cool” and “cold” categories. Concerning moisture types (Table 6), the procedure was similar: the “moderately wet” category is introduced beside the categories “dry,” “moist,” “wet,” and “saturated.” In Table 7, the new category is the “very high” type, which is introduced in addition to the categories “low,” “medium,”

Table 2 Moisture types used in Feddema’s original scheme

Moisture type	Moisture index (<i>I_m</i>)
Saturated	0.66 to 1.00
Wet	0.33 to 0.66
Moist	0.00 to 0.33
Dry	−0.33 to 0.00
Semiarid	−0.66 to −0.33
Arid	−1.00 to −0.66

Table 3 Criteria for determining the climatic variable that possesses seasonality according to Feddema's original scheme

Climatic variable	(Annual <i>P</i> range)/(annual PET range)
Temperature	<0.5
Temperature and precipitation	0.5–2.0
Precipitation	>2.0

“high,” and “extreme.” The criteria for deciding which climatic variable possesses seasonality remained unchanged.

2.3 The treatment of climate change

Feddema's (2005) method enables us to determine unequivocally the climate change process type. This is possible by comparing climate types referring to 30- and/or 50-year periods. For reasons of simplicity, the treatment is briefly illustrated in Table 8 for annual characteristics of the original scheme on the basis of climate maps referring to the beginning (Fig. 2) and to the end of the century (Fig. 4).

The annual climate characteristics registered are as follows: “cool, dry”; “cool, moist”; “cool, wet”; “cold, moist”; “cold, wet”; and “cold, saturated.” In principle, the “cool, dry” climate type can transform into “cool, moist”; “cool, wet”; “cold, moist”; “cold, wet”; and “cold, saturated” climate types. A “cool, dry” → “cool, moist” transformation means that there is no thermal regime change, at the same time the moisture regime changes: the climate becomes wetter. The same type of change can happen via “cool, dry” → “cool, wet”; “cool, moist” → “cool, wet”; “cold, dry” → “cold, moist”; or “cold, moist” → “cold, wet” climate type transformations. In the analysis, we made no distinction between transformations of this type. Of course, there can be also such changes when the thermal regime changes and the moisture regime remains unaltered. Such transformations are, for instance, “cold, wet” → “cool, wet” or “cold, moist” → “cool, moist” changes, when the climate becomes warmer. Lastly, there can also be changes when both the thermal and the moisture types change. These possible change types are located in Table 8 towards the bottom–left and top–right corners. Of course, the number of climate change

Table 4 The magnitude of seasonal variability according to Feddema's original scheme

Magnitude of seasonal variability	Annual range of I_m
Low	0.0–0.5
Medium	0.5–1.0
High	1.0–1.5
Extreme	1.5–2.0

Table 5 Thermal types used in Feddema's fine-tuned scheme version

Thermal type	Annual PET (mm year ⁻¹)
Cool	600–800
Moderately cold	545–600
Cold	300–545

types that occur in reality is much less than the number of possible climate change types. Note that we are only discussing annual characteristics here. The situation is much more complex when both the annual and seasonal characteristics are considered. An example of such a treatment referring to Hungary can be seen in the work of Breuer et al. (2017). The procedure is applied only to the original scheme. We did not apply it to the fine-tuned scheme since the number of the possible climate change types is too large.

2.4 Data

Monthly temperature and precipitation data are taken from the Climatic Research Unit (CRU) data center of the University of East Anglia. The data are part of the CRU TS 1.2 database (Mitchell et al. 2004), refer to the period 1901–2000, and possess a spatial resolution of 10' × 10' (approximately 18 × 18 km²). The studied region is presented in Fig. 1 together with the most important geographical designations used in the study. The area contains 1536 pixels located between the 5.83–17.33°/45.67–49.17° longitude/latitude lines. In the analysis, we focused only on the Austrian–Swiss region using 30-year (in total 71 fields) and 50-year (51 fields in total) means of temperature and precipitation.

3 Results

The climate and the change of the climate in the Austrian–Swiss region of the European Alps during the course of the twentieth century will be discussed separately for 30- and 50-year datasets. In the analysis, we mainly used Feddema's (2005) original scheme. Feddema's fine-tuned scheme is not used for investigating climate change.

Table 6 Moisture types used in Feddema's fine-tuned scheme version

Moisture type	Moisture index (I_m)
Saturated	0.66 to 1.00
Wet	0.47 to 0.66
Moderately wet	0.33 to 0.47
Moist	0.00 to 0.33
Dry	–0.33 to 0.00

Table 7 The magnitude of seasonal variability according to Feddema’s fine-tuned scheme version

Magnitude of seasonal variability	Annual range of I_m
Low	0.00–0.50
Medium	0.50–1.00
High	1.00–1.25
Very high	1.25–1.50
Extreme	1.50–2.00

3.1 The climate of the Austrian–Swiss alpine region—original scheme

3.1.1 30-year periods

Climate maps obtained from the original scheme at the beginning, in the middle, and at the end of the twentieth century based on 30-year datasets are presented in Figs. 2, 3, and 4, respectively.

The climate is the most heterogeneous in the northeastern part of Austria. At the end of the century (Fig. 4), a total of nine climate types are located along the Danube valley. The greatest climate gradient is on the line that connects the eastern parts of Lower Austria and the Central Eastern Alps. This agrees well with the results obtained by Auer et al. (2000). The warmest and driest parts of the region during the twentieth century (Figs. 2, 3, and 4) are located on the Pannonian Plain (Lower Austria) and in the river and lake valleys. In these areas, (1) “cool, dry”; (2) “cool, moist”; and (3) “cool, wet” climate types can be found with different seasonal characteristics. Extreme and high seasonality of T is a mainly Lower Austrian characteristic, but it can also be found on the shores of Lake Geneva and Lake Biel and along the Danube valley. Through the whole twentieth century (Figs. 2, 3, and 4), Switzerland is cooler and wetter than Austria. In Switzerland, the climate type “cool, dry” does not exist. The climate type “cool, wet” covers larger areas than the climate type “cool, moist” (Figs. 2, 3, and 4). Areas with the climate

type “cool, moist” are rare and can only be found at Lake Geneva and Lake Biel and in the very small area of the Upper Rhine Plain (Fig. 4). Note that in the whole region the representation of the climate type “cool, wet” increases during the twentieth century (Figs. 2 and 4). At the end of the century (Fig. 4), they can be found in the valleys of the Mur, Drava, Danube, and Inn; on the shores of Lake Geneva and Lake Constance; in the region of the Swiss Plateau; and in the Canton of Ticino, which is the most southern part of Switzerland. In these areas, seasonality is characterized by medium or high seasonality of both P and T . Note that this seasonal change characteristic is typical of alpine areas.

In the Central Eastern Alps, the “cold, wet” and “cold, saturated” climate types prevail with low or medium seasonality of both P and T . All these characteristics, especially the annual characteristics, clearly reflect the pronounced effect of relief. Lastly, in total, 15 different climate types (different annual and seasonal characteristics) are registered by Feddema’s (2005) original scheme in the Austrian–Swiss region of the European Alps during the twentieth century.

3.1.2 50-year periods

The climate maps obtained using the original scheme referring to the first and second parts of the twentieth century based on 50-year datasets are presented in Figs. 5 and 6, respectively.

Inspecting Fig. 5, we see that it is very similar to Fig. 2. There are only minor differences, that is, the spatial distribution of climate types is almost unaltered. Inspecting Fig. 6, we easily detect that it is really very similar to Fig. 4. The climate types “cool, moist” and “cool, wet” are also located in river valleys; on the shores of Lakes Geneva, Neuchâtel, Biel, and Zurich; and in the Canton of Ticino. Their seasonal type characteristics are also unchanged. For instance, the extreme and high seasonality of T for the climate type “cool, dry” in lowland areas of the northeastern part of Austria can equally be found in Figs. 2 and 5 as well as in Figs. 4 and 6. Note that seasonality type “extreme or high seasonality of T ” is

Table 8 The annual characteristics of the climate and the possible climate change types in the Austrian–Swiss region of the European Alps during the twentieth century according to Feddema’s original scheme

Period	1971–2000						
	Type	Cool, dry	Cool, moist	Cool, wet	Cold, moist	Cold, wet	Cold, saturated
1901–1930	Cool, dry	No change	Wetting	Wetting	Cooling, wetting	Cooling, wetting	Cooling, wetting
	Cool, moist	Drying	No change	Wetting	Cooling	Cooling, wetting	Cooling, wetting
	Cool, wet	Drying	Drying	No change	Cooling, drying	Cooling	Cooling, wetting
	Cold, moist	Warming, drying	Warming	Warming, wetting	No change	Wetting	Wetting
	Cold, wet	Warming, drying	Warming, drying	Warming	Drying	No change	Wetting
	Cold, saturated	Warming, drying	Warming, drying	Warming, drying	Drying	Drying	No change

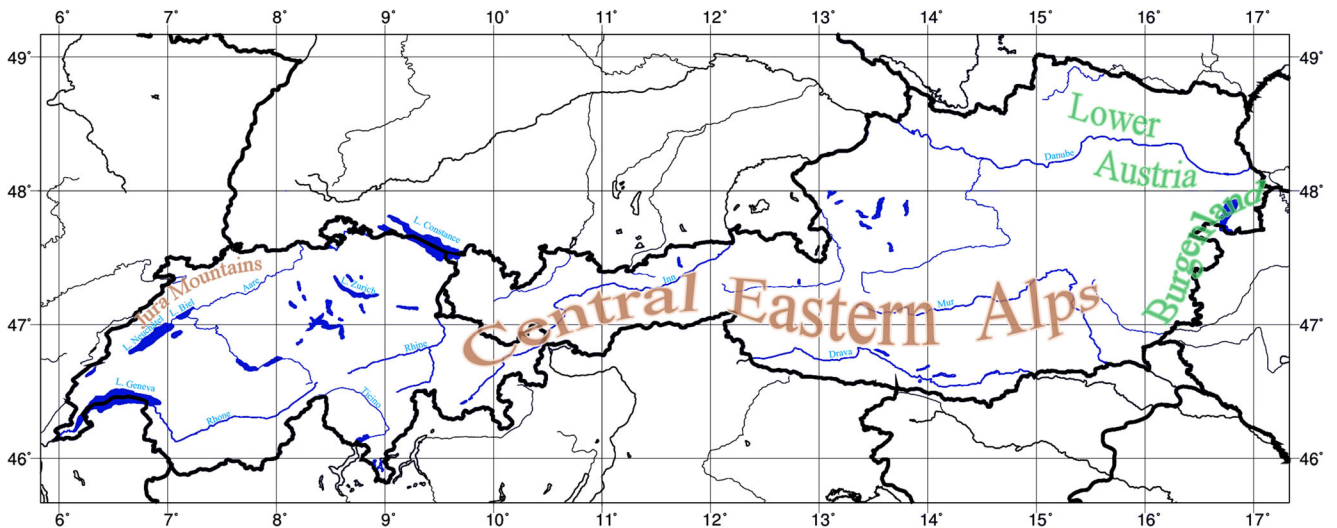


Fig. 1 Austria and Switzerland in the studied region together with the major geographical designations used in the study

characteristic for lowland continental areas. Similarly, the medium or high seasonality of both *P* and *T* for the climate types “cool, moist,” “cool, wet” or “cold, moist,” “cold, wet” in river valleys or on the shores of the lakes can also be found in Figs. 2 and 5 as well as in Figs. 4 and 6. Note that in these cases the seasonality type “high seasonality of *T*” can also be observed. The climate types “cold, wet” and “cold, saturated” are also typical only of alpine areas. As for 30-year periods, there are 15 climate types in total.

3.2 The climate of the Austrian–Swiss alpine region—fine-tuned scheme

3.2.1 30-year periods

The climate maps obtained from the fine-tuned scheme at the beginning, in the middle, and at the end of the twentieth century based on 30-year datasets are presented in Figs. 7, 8, and 9, respectively.

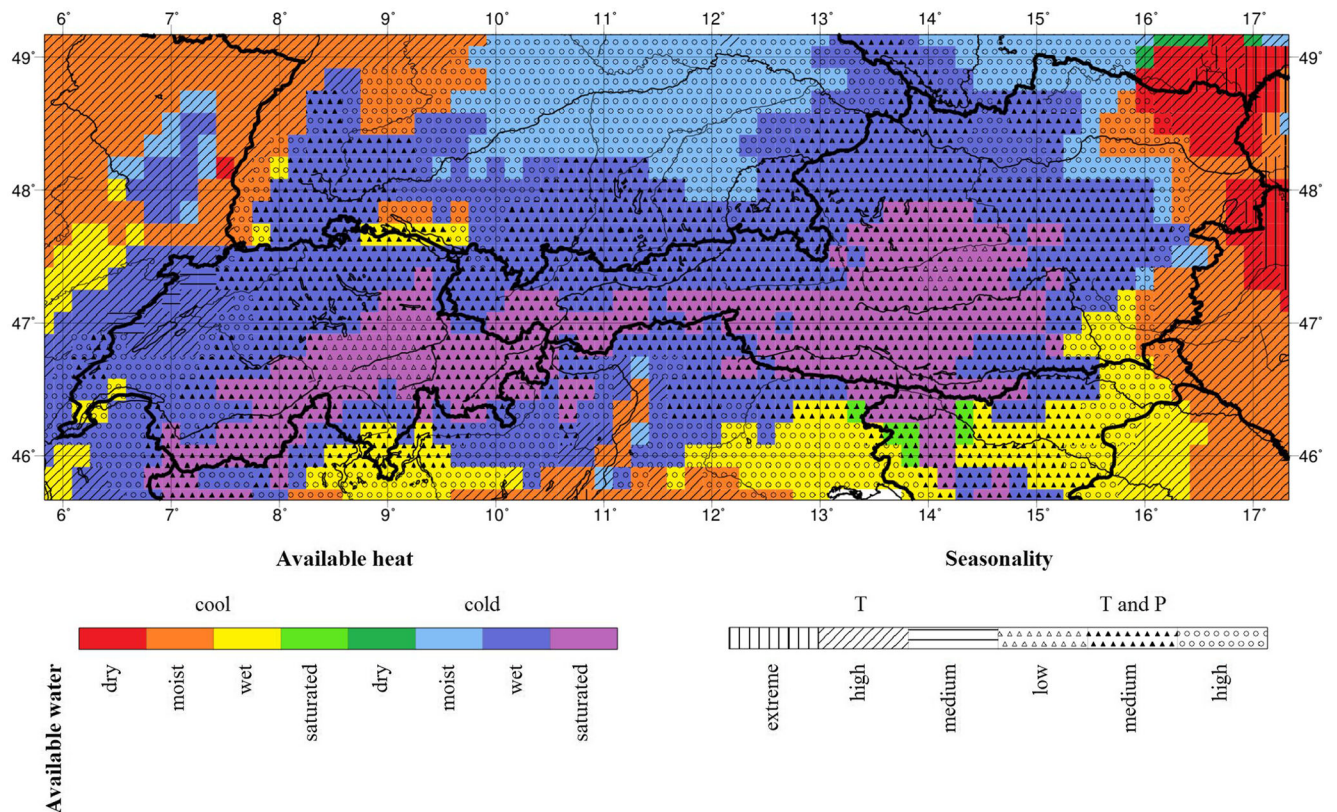


Fig. 2 The climate of the Austrian–Swiss alpine region in the period 1901–1930 according to Feddema’s (2005) original scheme

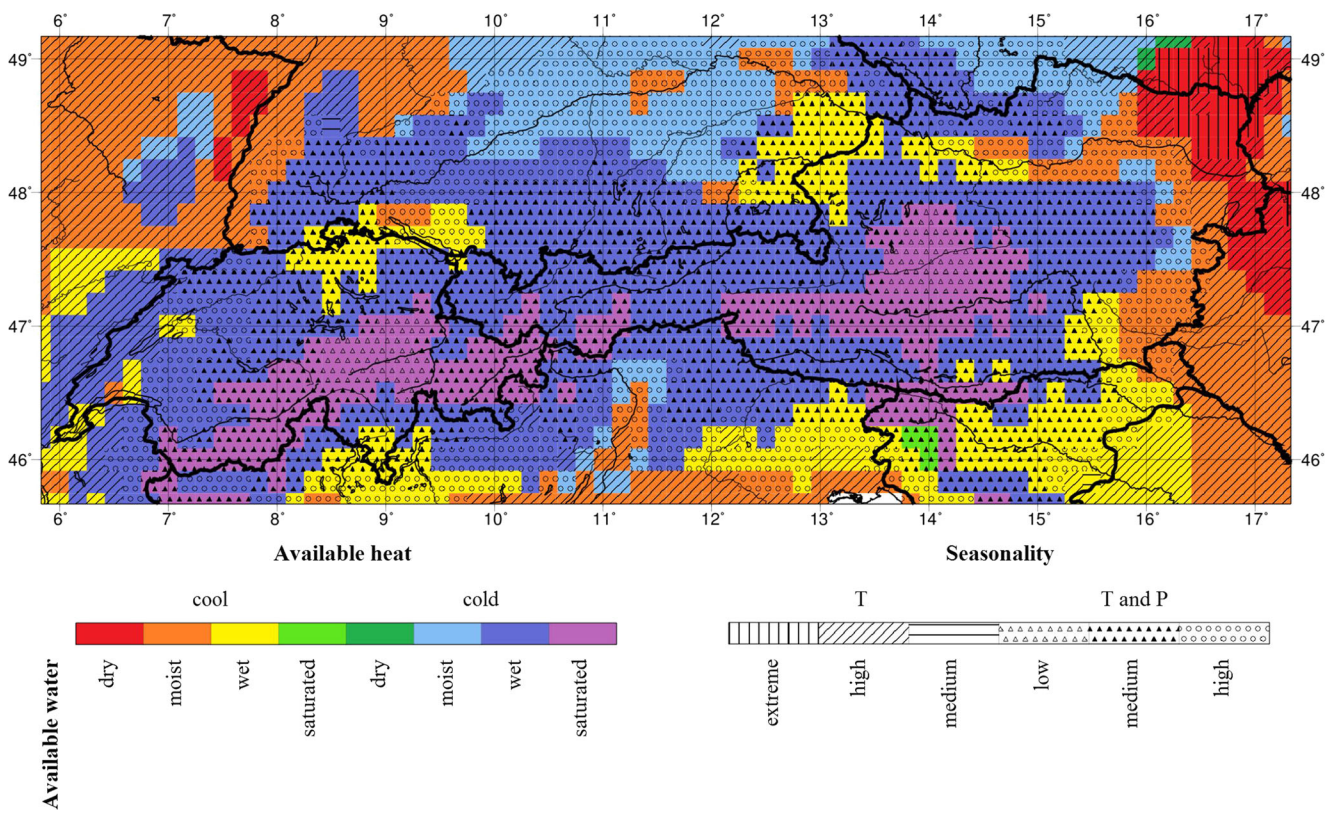


Fig. 3 The climate of the Austrian–Swiss alpine region in the period 1936–1965 according to Feddema’s original scheme

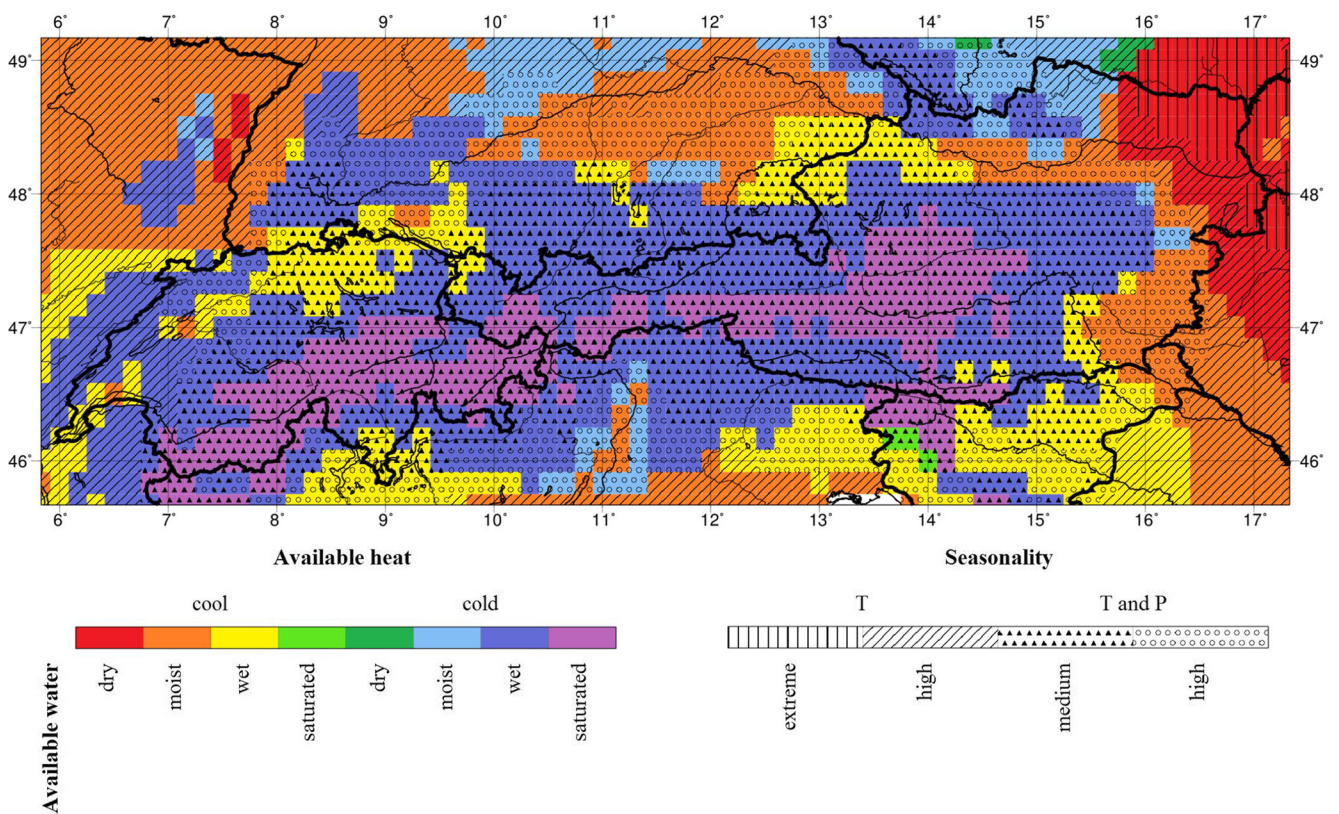


Fig. 4 The climate of the Austrian–Swiss alpine region in the period 1971–2000 according to Feddema’s original scheme

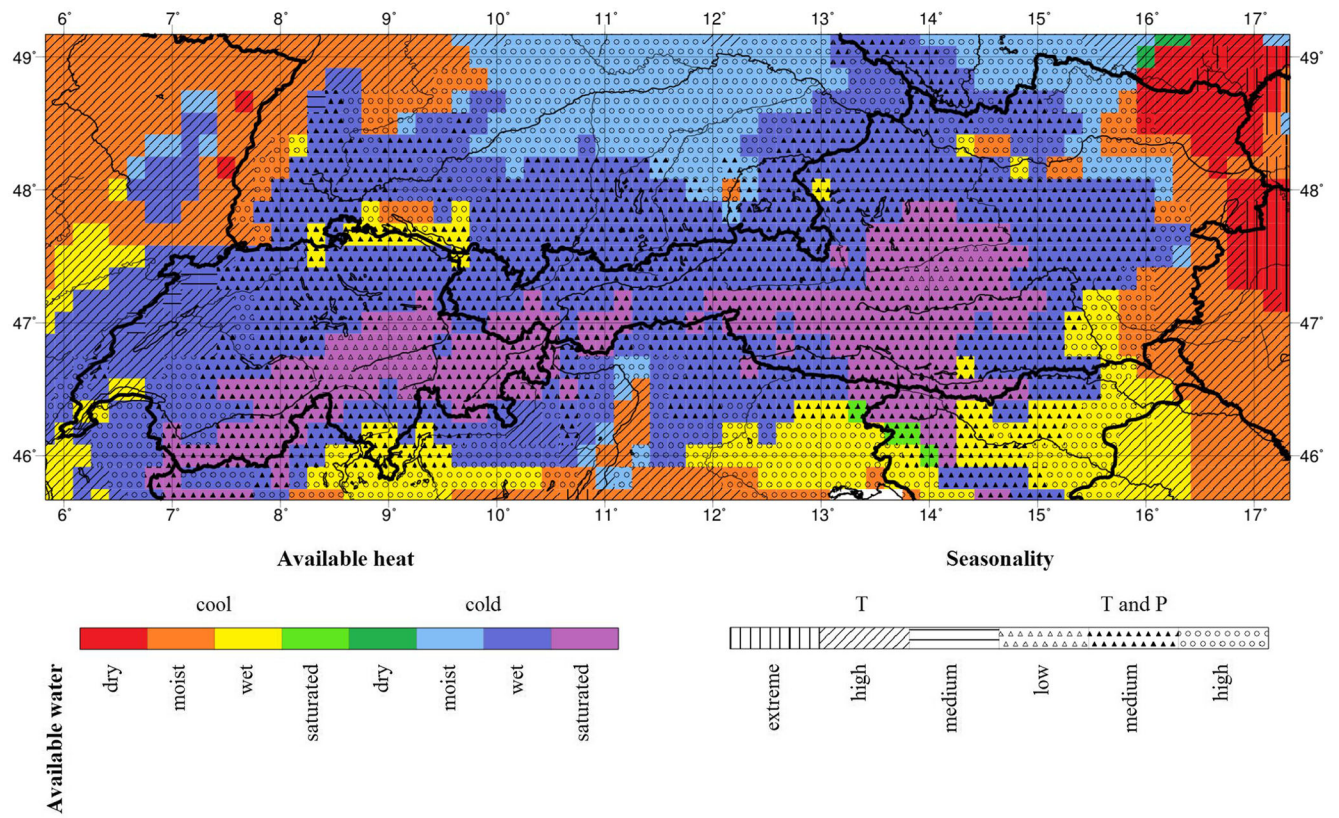


Fig. 5 The climate of the Austrian–Swiss alpine region in the period 1901–1950 according to Feddema’s original scheme

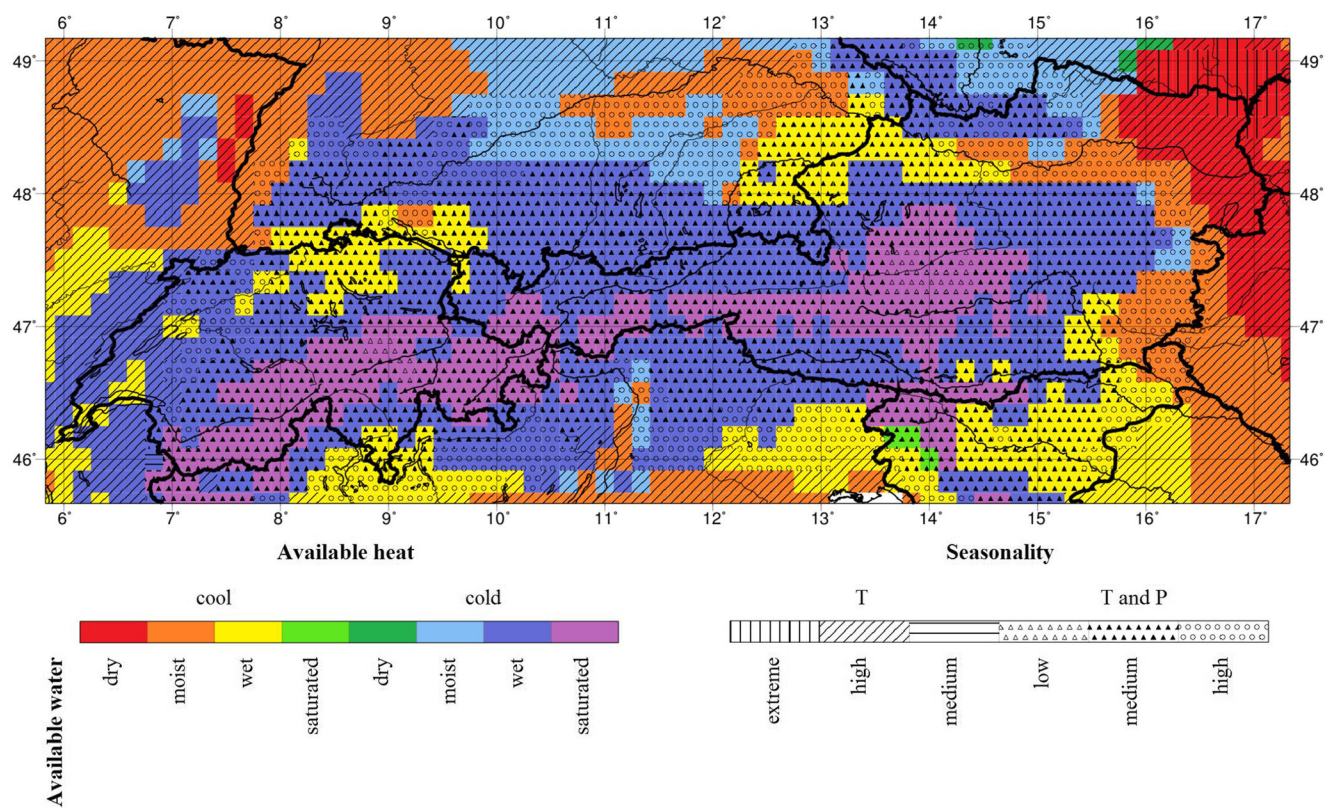


Fig. 6 The climate of the Austrian–Swiss alpine region in the period 1951–2000 according to Feddema’s original scheme

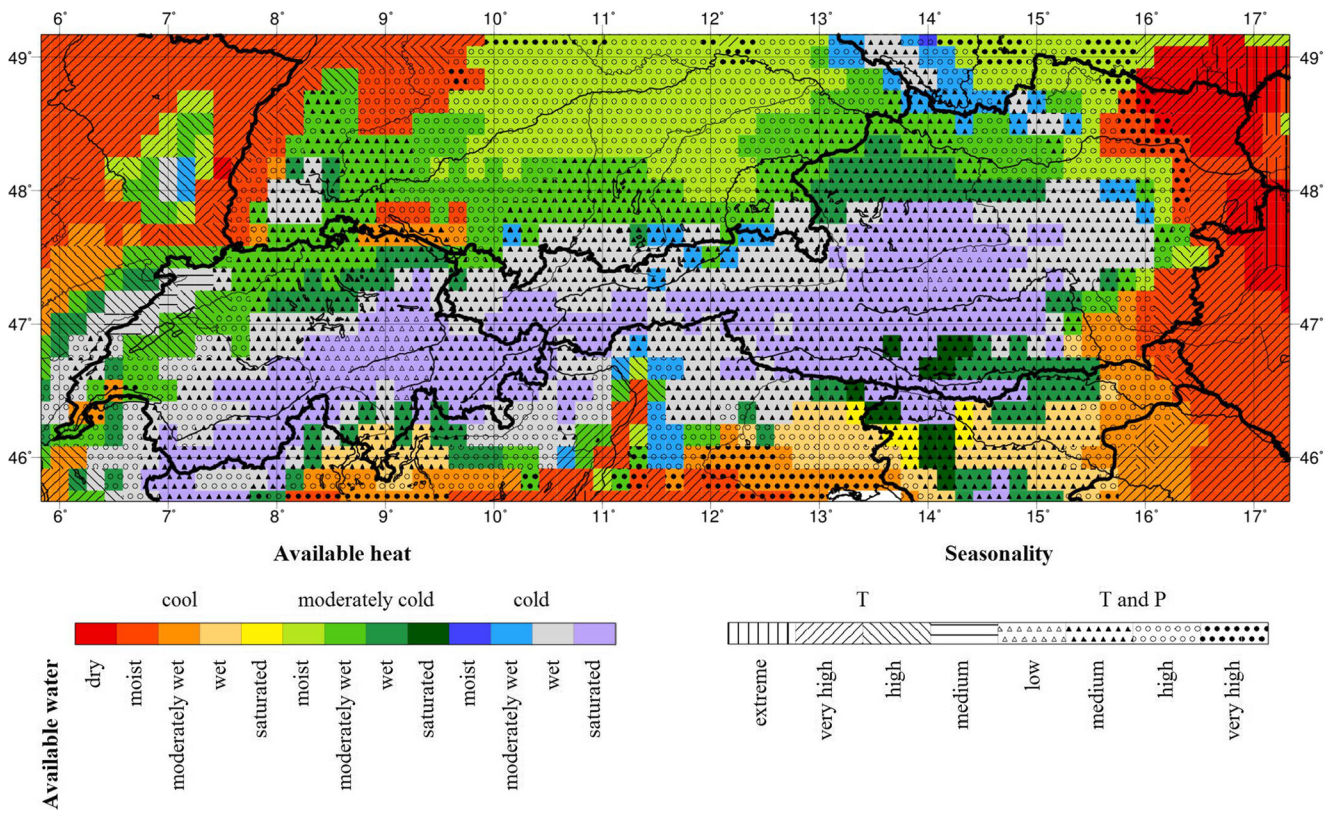


Fig. 7 The climate of the Austrian–Swiss alpine region in the period 1901–1930 according to Feddema’s fine-tuned scheme

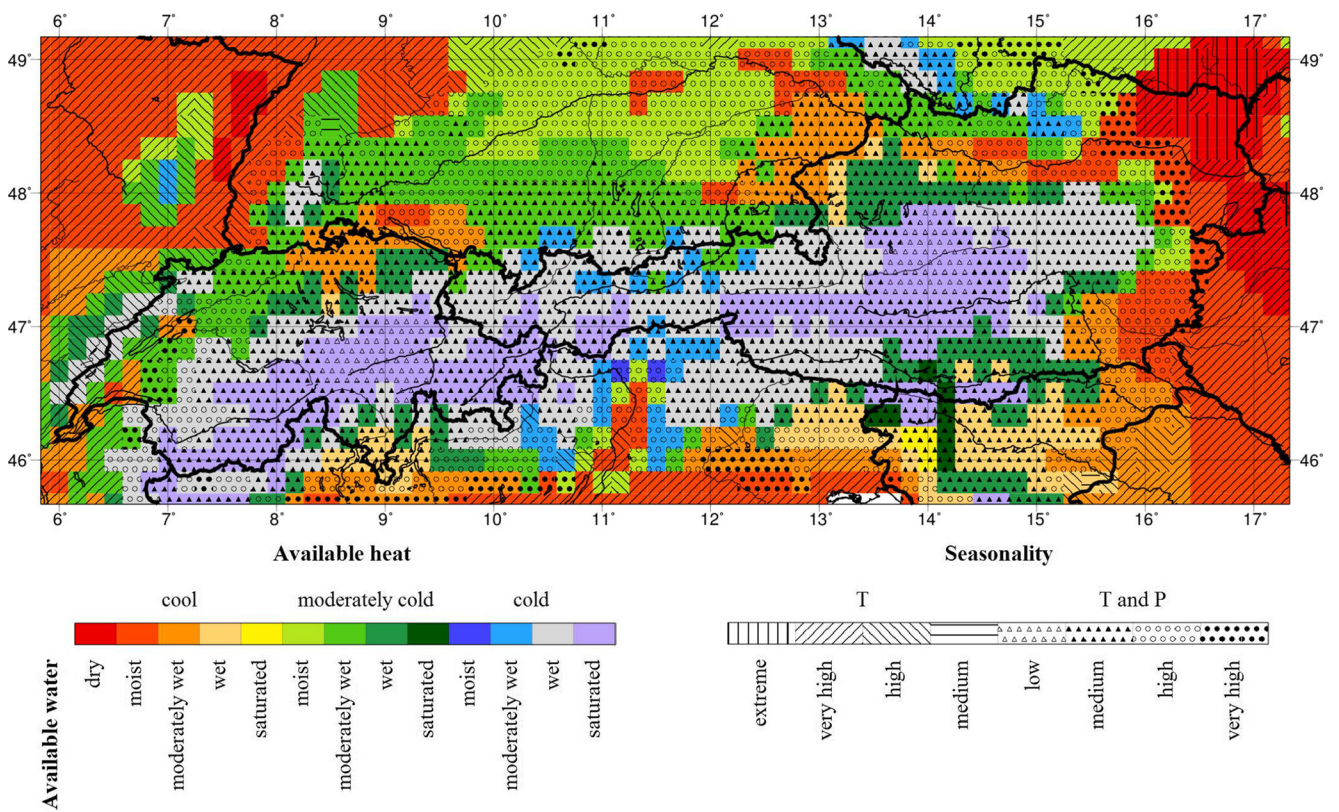


Fig. 8 The climate of the Austrian–Swiss alpine region in the period 1936–1965 according to Feddema’s fine-tuned scheme

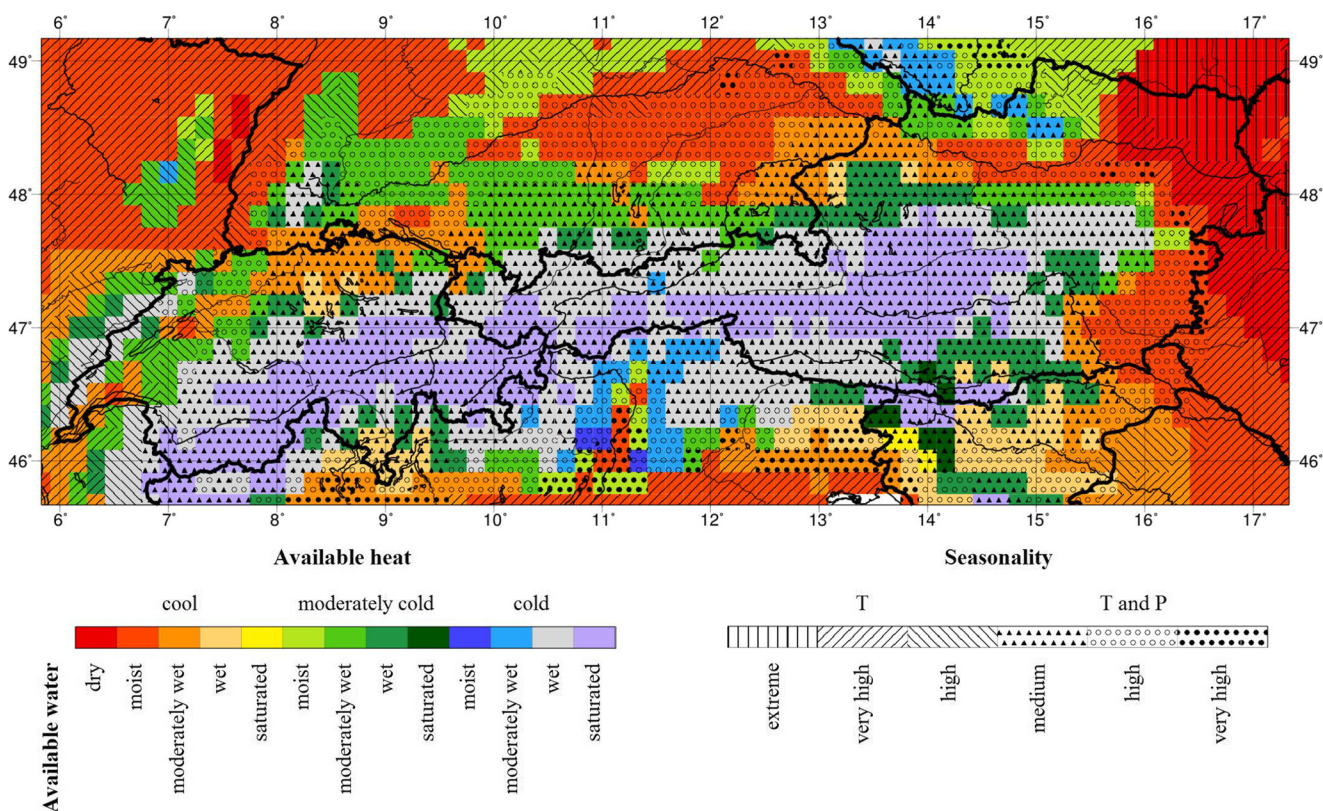


Fig. 9 The climate of the Austrian–Swiss alpine region in the period 1971–2000 according to Feddema's fine-tuned scheme

It is obvious that the number of climate types is much higher than in the cases (Figs. 2, 3, and 4) when the original scheme was applied. Fine-tuning does not influence the area heterogeneity of climates in high mountainous regions, rather in river valleys and in the vicinity of large lakes. This is especially valid for the Mur and Danube in Austria, for Lake Geneva, the river Aare, and the river Ticino in the most southern part of Switzerland. The change in climate types along the Mur valley is really pronounced (see Fig. 7). At the beginning of the twentieth century, there were six climate types within a distance of about 100 km:

- 1. Cool and moderately wet with high variability of T and P
- 2. Moderately cold and moderately wet with high variability of T and P
- 3. Moderately cold and moderately wet with medium variability of T and P
- 4. Moderately cold and wet with medium variability of T and P
- 5. Cold and wet with medium variability of T and P
- 6. Cold and saturated with medium variability of T and P

In the Danube valley, the situation is similar. There were ten climate types within the distance of about 200 km at the end of the twentieth century (Fig. 9). In the Pannonian Plain

region, the climate is “cool and moist with very high variability of T ,” while in the German–Austrian border region, the climate type is “moderately cold, moderately wet with medium variability of T and P .” In the vicinity of Lake Geneva, the area heterogeneity of climate is also high. There are in total six climate types at the beginning of the twentieth century (Fig. 7). In the western parts of the lake, the climate is “cool and moderately wet with high variability of T and P ,” while in its eastern parts, the climate is cooler and wetter. The greatest area heterogeneity of climates (high number of climate types in a small area) in Switzerland is in the Ticino valley. Four climate types can be found in this small region (Figs. 7, 8, and 9): “cool, wet”; “moderately cold, wet”; “cold, wet”; and “cold, saturated,” while the magnitude of T and P variability is medium. Lastly, at the beginning of the twentieth century (Fig. 7), there were 18 climate types in Austria and 16 climate types in Switzerland. The total number of climate types in the Austrian–Swiss region is 29. Similarly, large area heterogeneity is obtained by Auer et al. (2000) using a completely different method and data with a much larger spatiotemporal resolution than in our case.

3.3 Climate change in the region

The climate change process is investigated only by using Feddema's (2005) original scheme using both 30- and 50-

year datasets. In the first case, we compared climate maps referring to the beginning (Fig. 2) and to the end of the century (Fig. 4), while in the second case, Figs. 5 and 6 were compared. These comparisons were made as exactly as possible according to the procedure discussed briefly in Section 2.3. The fine-tuned scheme is not applied to climate change analysis as it gave 29 climate types. It can be seen that the maps presented in Figs. 7, 8, and/or 9 are very variegated. Consequently, there would also be an abundance of possible climate change types that would enormously increase the complexity of analysis and its transparency. Note that according to Essenwanger's (2001) criteria clear-cut mapping is also an important element of climate analysis.

3.3.1 Original scheme: 30-year periods

The spatial distribution of climate change types in the Austrian–Swiss alpine region during the twentieth century obtained by Feddema's (2005) original scheme and 30-year datasets is presented in Fig. 10.

The climate change process was most pronounced along river valleys and around large lakes. In Austria, the dominant process was drying. The most sensitive areas in Austria were the valleys of the Danube, Drava, and Mur and the shores of Lake Constance with the process of drying even being observable in the Drava valley. The climate change process is more complex along the Danube valley. Besides “single” changes

of warming or drying, the “double” change of warming and drying (in brief warming/drying) has also occurred. Only “single” changes of warming or drying can be found in the Mur valley. Warming was registered around Lake Constance. Changes in seasonal characteristics can be observed in Burgenland and in northern parts of Lower Austria. In some areas, seasonal type changes occurred: seasonality of T and P transformed into seasonality of T (T and $P \rightarrow T$) and, vice versa, seasonality of T transformed into seasonality of T and P ($T \rightarrow T$ and P). There are also areas (for instance, in the vicinity of Vienna) where the magnitude of variability increased.

The dominant climate change process in Switzerland is warming. The “single” change process of warming can be observed on the shores of Lake Geneva, in the river Aare valley, and in the region between the river Aare and Lake Zurich. The “double” change process of warming and drying is not typical for Switzerland; only one such pixel can be found around Lake Biel. The “single” change process of drying can also be observed, for instance, at Lake Geneva, or in the Rhine valley. Interestingly, there is also one pixel where the process of wetting occurred. This can be found in the Rhône valley. Changes in seasonality can also be observed. Such changes are typical of Lake Geneva and the Jura Mountains, but some such areas are also located in the Central Eastern Alps. Note that there is no climate change in the area of the Canton of Ticino.

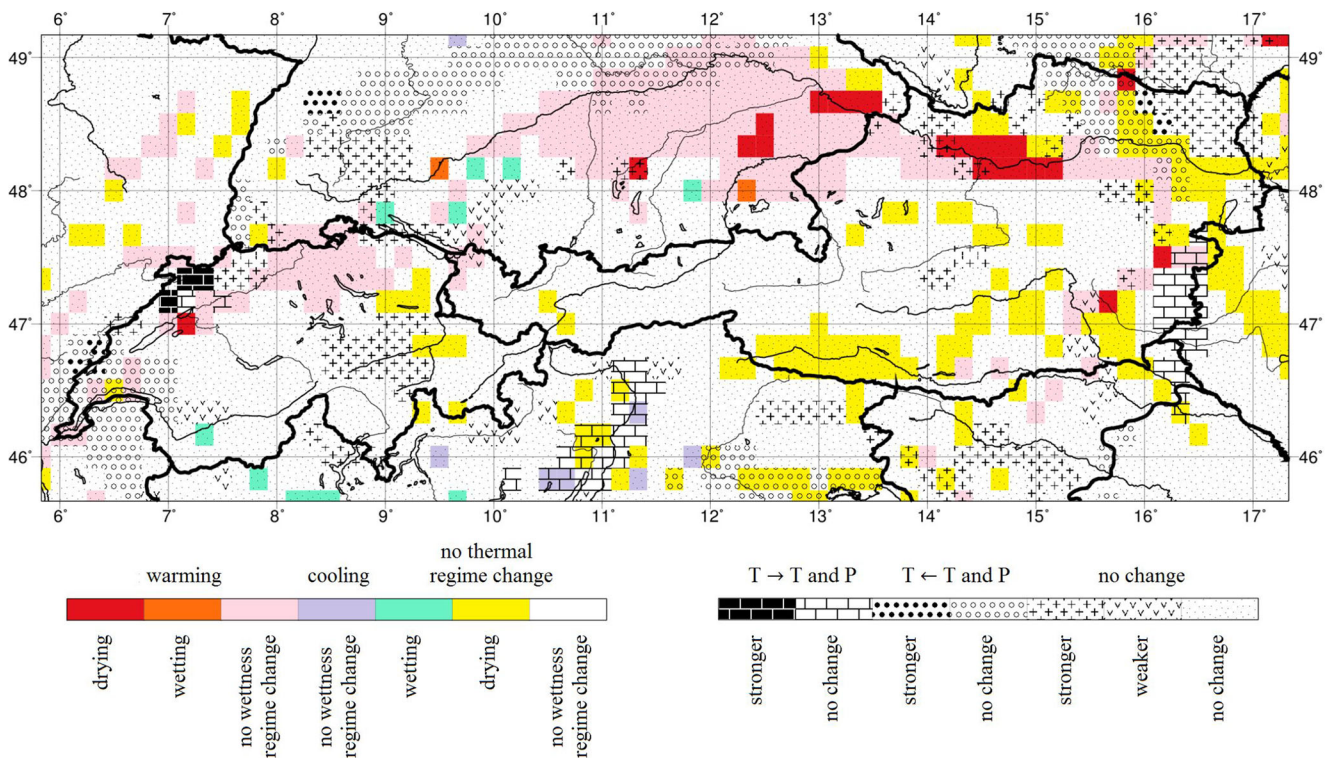


Fig. 10 The climate change types in the Austrian–Swiss alpine region during the twentieth century based on 30-year datasets according to Feddema's original scheme

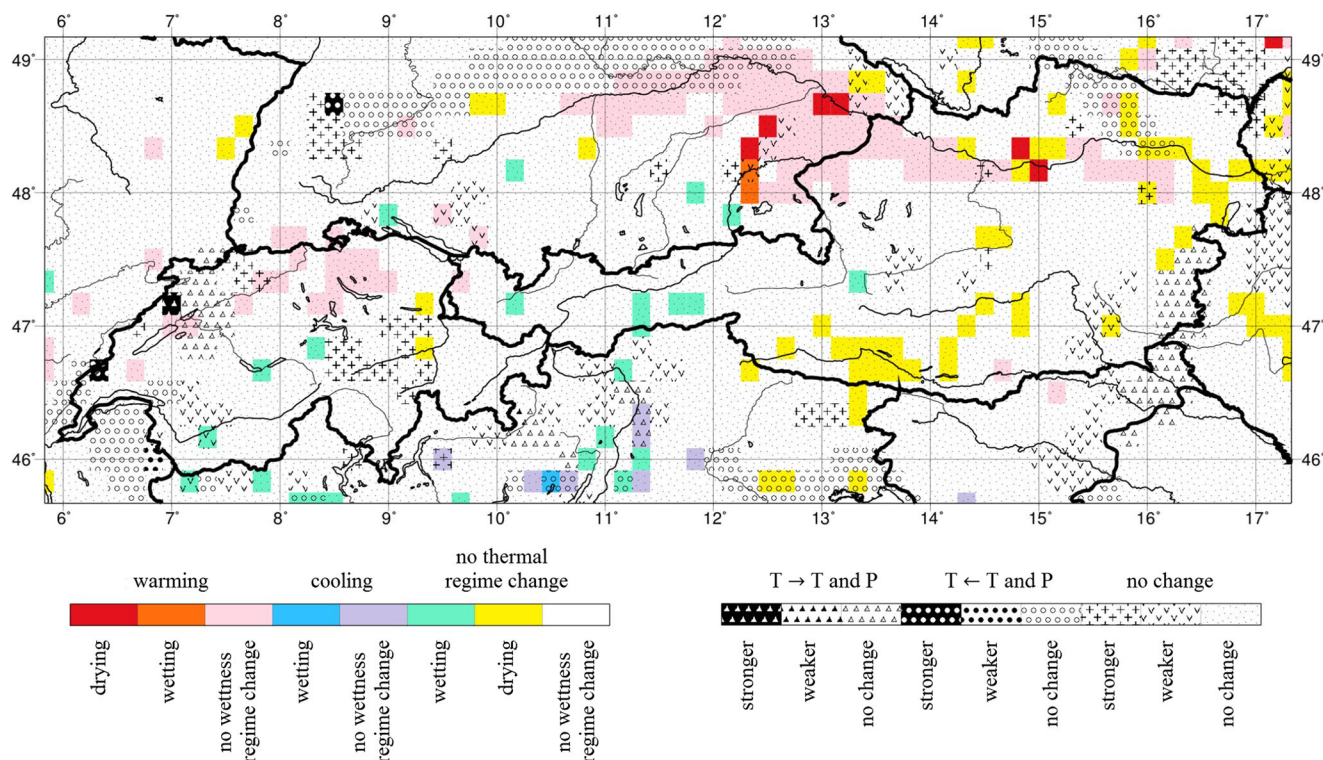


Fig. 11 The climate change types in the Austrian–Swiss alpine region during the twentieth century based on 50-year datasets according to Feddema’s original scheme

3.3.2 Original scheme: 50-year periods

The spatial distribution of climate change types in the Austrian–Swiss alpine region during the twentieth century obtained by Feddema’s (2005) original scheme and 50-year datasets is presented in Fig. 11.

This climate change map is similar to the map presented in Fig. 10, but there are also significant differences. Besides the “single” climate change processes of warming or drying, the process of wetting is also represented not only in Switzerland but also in Austria. In Austria, the processes of warming and drying are approximately equally represented and the areas where the “double” climate change process of warming and drying is represented are considerably reduced. There are only two such pixels in the Danube valley. Otherwise, the Danube valley is the area where climate change is the most pronounced. In the Drava valley, the process of drying is typical as in the former case. There is also a drying process in the Mur valley but not so pronounced. There, changes in seasonality could also be observed.

In Switzerland, warming is the dominant “single” climate change process. Areas characterized by warming can be found around lakes Zurich, Neuchâtel, and Biel and in the river Aare valley. Changes in seasonality can be observed approximately equally around Lake Geneva, in the Jura Mountains, and in the Central Eastern Alps. These changes are various; not only the type but also the magnitude of variability changed.

Concerning the magnitude of variability, both the increase (around the Rhine) and decrease (around the Rhône) can be observed. As in the former case, no climate change was registered in the area of Canton of Ticino.

4 Conclusion

The concluding remarks are organized according to the questions given in the last paragraph of Section 1. (1) The fine-tuning of Feddema’s (2005) scheme has a larger effect on the appearance of climate maps than the organization of data. Fine-tuning increased the number of climate types from 15 to 29, but with this, crowding of the map increased and transparency decreased for the Austrian–Swiss region under investigation. Based on this, we suggest the use of the fine-tuned version of Feddema’s (2005) scheme for sub-region analysis, for instance, the Canton of Ticino or around Lakes Geneva and Constance. With this, we would avoid the crowding of the maps; of course, data should have larger spatial distribution than in our case for doing such meso- β or meso- γ scale (2–20 km) analyses. As we see, Feddema’s (2005) original scheme is suitable for characterizing the structure of the climate on the meso- β scale. (2) The area heterogeneity of climate and climate change types is higher around lakes, along river valleys, and lower in upland regions. These high-heterogeneity regions are located in the valleys of the

Danube, Mur, and Drava in Austria and in the valleys of the Aare and Ticino as well as around Lakes Geneva, Neuchâtel, Biel, Zurich, and Constance in Switzerland. In Austria, the dominant climate change process was drying, while in Switzerland, it was warming. The highest climate type heterogeneity area can be found in the Canton of Ticino; at the same time, there was no climate change registered here during the course of the twentieth century. It is to be noted that there are extended areas of cold and saturated climate in the Central Eastern Alps. In these areas, no climate change occurred during the twentieth century.

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