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Observed and projected climate change in the European region during the twentieth and twenty-first centuries according to Feddema

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Abstract

Climate change in the European region during the twentieth and twenty-first centuries is analyzed according to Feddema's method. Precipitation and air temperature data from the twentieth century are taken from the Climatic Research Unit, while data for the twenty-first century are taken from the ENSEMBLES climate change project. The latter were bias-corrected to ensure homogeneity across the twentieth and twenty-first centuries. Climate classes based on monthly and annual values of potential evapotranspiration, precipitation and their ratio, are defined for 30-year averages, from which trend and spatial agreement analysis are calculated. There are separate classes for annual values and for intra-annual variation. The results indicate that the change of annual climate characteristics will be much more intense in the twenty-first than it was in the twentieth century. The dominant process in the projections is warming, mostly via cold to cool (about 45% of grid points) in north Europe and cool to warm (about 8% of grid points) transformations. The second most important process is the drying of moderately moist classes affecting about 10% of the grid points in south Europe. Changes in intra-annual variability classes are more common than changes in the annual ones during the twentieth century. The chance of increase in intra-annual temperature variation from high to extreme is about 5% during the course of the twentieth century, and about 10% in the following century.

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1 Introduction

The climate change process can be treated either strictly physically using, for instance, the time series analysis of selected climatic elements (e.g., Diaz and Bradley 1997; Beniston and Jungo 2002) or biogeographically by using generic climate classification methods (e.g., Lohmann et al. 1993). In this study, the latter method will be used, since it is able to represent climate (e.g., Holdridge 1947; Köppen 1936; Feddema 2005) and climate change (e.g., Emanuel et al. 1985; Fraedrich et al. 2001; Beck et al. 2005; Elguindi et al. 2014) as comprehensively as possible (Rohli et al. 2015). Among generic classification methods, Köppen's method (e.g., Geiger 1954) is the most popular. Köppen's method is widespread because of its extreme simplicity and since it can be successfully applied on both the global (e.g., Rubel and Kottek 2010; Chen and Chen 2013) and regional (e.g., Wang and Overland 2004; Engelbrecht and Engelbrecht 2016; Jylhä et al. 2010; Ying et al. 2012; Rubel et al. 2017) scales. In all of these studies, the focus was on the annual characteristics of climate; seasonal characteristics are usually not considered. At local scales, its application could be less efficient (e.g., Fábián and Matyasovszky 2010), since the categorization is constructed for global scale analysis. Because of this limitation, Feddema's (2005) method was constructed and promoted as a rival method for Köppen's (Thornthwaite 1948; Thornthwaite and Mather 1955; Willmott and Feddema 1992). This classification system is more successful on local scales (e.g., Breuer et al. 2017), its regional (e.g., Grundstein 2008; Skarbit et al. 2018) and/or global (e.g., Elguindi et al. 2014) scale applications are rarer. In these studies, both the annual and seasonality climate characteristics are considered, but more attention is paid to the annual characteristics. The Holdridge (1947) life zone system is also popular; it is applied to study the potential effects of climate change on vegetation. Its application ranges from global (e.g., Emanuel et al. 1985) to regional (e.g., Szelepcsényi et al. 2018) analysis.

It should be mentioned that Köppen's method was more frequently applied for assessing future climatic conditions (e.g., Lohmann et al. 1993) than Feddema's (e.g., Elguindi et al. 2014). More and more frequently ensemble model simulation results (e.g., Castro et al. 2007; Hewitt and Griggs 2004) are used for analyses using different SRES (Special Report on Emissions Scenarios) scenarios (Nakićenović et al. 2000). Castro et al. (2007) showed that, depending on the chosen regional climate model (RCM), the agreement of Köppen classes range from 72 to 83% when comparing the 1961–1990 climate to the 2071–2100. EURO-CORDEX (Jacob et al. 2014) ensemble runs provide the newest such dataset but it is generally used for local analysis, e.g., Rubel et al. (2017). These model results translated to Köppen climates can be used for validation purposes (Gallardo et al. 2013). To date Feddema's (2005) method has not been applied to Europe for climate change analysis purposes.

The aim of this study is to apply Feddema's (2005) method for analyzing the European region's climate change during the twentieth and twenty-first centuries, focusing equally on both annual and seasonality climate characteristics. Using Feddema's (2005) method, the climate change process can be objectively defined instead of qualitative descriptions of the shifts of the climate types (e.g., Rubel and Kottek 2010) furthermore the complex process of climate change can be comprehensively described in terms of annual and seasonality climate characteristics. The observed, twentieth-century data are taken from the Climatic Research Unit (CRU) data center (CRU TS 1.2 database, Mitchell et al. 2004). For the twenty-first century projections, RCM outputs made in the scope of the ENSEMBLES climate change project (van der Linden and Mitchell 2009) are taken. For the observed data, the periods between 1901–1930 and 1971–2000, and for the projected data, the periods between 1971–2000 and 2071–2100, are used.

2 Data

2.1 CRU TS 1.2 dataset

For the twentieth century, the CRU TS 1.2 database (Mitchell et al. 2004) is used as the source of monthly air temperature and precipitation data. The database is a product of the Climatic Research Unit of the University of East Anglia. The data possess a spatial resolution of 0.166° × 0.166° and are located in the region between 11 °W–32 °E/34 °N–72 °N, covering the period 1901–2000. The European region contains a total of 31,143 grid points.

2.2 E-OBS dataset

The used E-OBS (v5) database (Haylock et al. 2008) contains daily air temperature (minimum, maximum, and mean), precipitation in a spatial resolution of 0.22° × 0.22° referring to the period 1950–2011. The measured, quality-controlled, and homogenized data in Europe obtained from observation stations then were interpolated to the predefined grid resolution. The interpolation is organized in three steps: first, the thin-plate spline method is applied on monthly means. Then, daily anomaly values were determined by using kriging, and lastly, daily anomalies were combined by monthly means in order to obtain the final data.

2.3 ENSEMBLES project simulations

For the twenty-first century, RCM simulation results obtained in the scope of the ENSEM-BLES project (van der Linden and Mitchell 2009) are used as the data source. The spatial resolution is 0.22° × 0.22°, covering the region located between 11 °W–40.75 °E/36.5 °N–74 °N. In the scope of the project, 11 transient (1951–2100) RCM simulations of 9 different RCMs were performed. A detailed reference for the models can be found in the supplementary materials. The models were run assuming the A1B emission scenario (Nakićenović et al. 2000), which hypothesizes that global decisions and solutions, are reached by convergence among regions. In this hypothetical world, population and economic growth is reasonably rapid, using all energy sources in a balanced way. Ensemble mean of the precipitation and temperature fields of all nine RCMs are used; separate analysis for the models that showed the most extreme behavior are not considered here.

2.4 Climate signal

When considering changes in climate, one usually refers to temperature and precipitation change as climate indicators. According to the CRU dataset, through the twentieth century, the temperature increase affected most of the continent, but mostly in France, the Iberian Penin-sula, central Scandinavia, and east Europe. The highest changes are around 1 °C. In the case of the ENSEMBLES dataset through 1971 to 2100, the temperature is expected to increase significantly in all RCMs. On average, the highest increase is assumed in north Europe (> 4.5 °C) and in the mountainous areas of central and southern Europe (> 3.5 °C).

Regarding the annual precipitation sum change, the only regularity in the twentieth century is that the coastal regions of Iberia and Scandinavia should experience an increase over 150 mm, while in the Alps the same amount of decrease was found. The RCMs present a different perspective. All models show a significant increase in precipitation north of 57 °N

and a decrease south of 45 °N (with the exception of northern Italy). The "hinge" latitude between positive and negative change is 47 °N. Between 45 °N and 57 °N at least five RCMs show a significant change in precipitation. On average, a more than 150 mm decrease in annual precipitation is predicted over 100 years in the mountains of southern Europe and in north Portugal. North of 57 °N the increase is over 100 mm, and the highest (> 200 mm) increases are found on the Atlantic coast of Scandinavia (Online Resource 1–5).

3 Methods

3.1 Bias correction

Bias correction of daily precipitation and temperature data obtained by RCMs was performed separately for each month and grid point according to the method of Formayer and Haas (2009). Ratio distribution functions of RCM outputs and E-OBS data for the period 1961–1990 were compared to determine correction factors for RCM distribution functions for each percentile in 1% steps. Additive and multiplicative correction factors were used for temperature and precipitation, respectively.

3.2 Feddema's climate classification

Feddema's (2005) classification is based on Thornthwaite's (1948) classification, but with intent to simplify the categories while maintaining the concept of annual and intra-annual heat and moisture availability. The classes are determined by the annual value and intra-annual changes of Thornthwaite's PET (potential evapotranspiration) and Willmott-Feddema's (Willmott and Feddema 1992) unit less moisture index (I_m):

$$I_m = \begin{cases} 1 - \dfrac{PET}{P}, \text{if } P > PET \\ 0, \text{if } P = PET \\ \dfrac{P}{PET} - 1, \text{if } P \leq PET \end{cases} \tag{1}$$

where P is the precipitation [mm]. The moisture index varies between −1 and 1; starting from −1 with 0.33 intervals, moisture classes are defined from the driest, in increasing moisture availability order: arid, semiarid, dry, moist, wet, and saturated. The thermal classes are defined with equal interval classes based on the annual PET amount, starting from 0 mm with 300 mm intervals, the six thermal classes in order are: frost, cold, cool, warm, hot, and torrid. To put it into perspective, in Europe, according to the E-OBS database, the spread of the Cf and Cs Köppen (1936) classes is 435–830 mm and 467–1098 mm respectively. The range of the I_m in a given year is used to measure the amplitude of seasonality. The seasonality is classified as low, medium, high, or extreme, where the step between the classes is 0.5. For deciding which climatic variable (temperature, precipitation or both of them) is the driving factor of seasonality, the ratio of the annual P and PET ranges is calculated. If this ratio is higher than 2, then the precipitation, if it is lower than 0.5, then the temperature is the cause of seasonal variability. In between 0.5 and 2, a combined temperature-precipitation seasonality exists; in this article, this will be referred to as mixed type.

One of the main differences between Feddema's and Köppen's method is the calculation of *PET*. The other is the approach of the determination of categories. For Feddema, the method is physical, the categories are determined based on the range of annual *PET*, the inter-annual variability of meteorological variables and their relationship without the consideration of biome types. While for Köppen, the method is biogeographical as each category is related to the geographical distribution of main vegetation types to which temperature and precipitation values are paired.

3.3 Kappa statistic

Cohen's (1960) kappa coefficient is used for evaluating the agreement between different climate maps. Kappa statistic is a common tool for comparing different climate maps (e.g., Monserud and Leemans 1992; Heikkinen et al. 2006; Seo et al. 2009; Wang et al. 2017). The coefficient is defined as

$$\kappa = \frac{P(A) - P(E)}{1 - P(E)} \quad (2)$$

where $P(A)$ is the probability of the agreement between different climate types or features and $P(E)$ is the hypothetical probability of the chance of agreement between different climate types or features. The empirically calculated probabilities can be organized into a so-called contingency table, as is done, for instance, by Monserud and Leemans (1992). The contents of the table provide the probabilities of correspondence between the different categories of the individual maps. In this work, the calculation of these probabilities was performed using the most frequent classes of the annual (thermal and moisture type) and the combined seasonality characteristics. The number of grid points of each category in the two examined periods was calculated and divided by the number of grid points of all examined categories. The κ coefficient can also be calculated on the basis of this table. For $\kappa = 0$, there is no agreement between climate features or types, and, for $\kappa = 1$, the agreement is full. The categorization of agreements according to their goodness is also made after Monserud and Leemans (1992).

3.4 The treatment of climate change

Climate change is investigated by analyzing the trend of annual and seasonality climate type characteristics based on 30-year averages of climatic parameters from 1901–1930 to 1971–2000 for the twentieth, and from 1971–2000 to 2071–2100 for the twenty-first century. Different time periods can be used for averaging, e.g., 15-year, 30-year, or 50-year intervals. Previous sensitivity tests showed that these data organizational effects changed the main outputs little, and only changed the insight into the dynamics of the processes (e.g., Fraedrich et al. 2001; Breuer et al. 2017). Since the classification of Feddema is built on equal size classes, the shift of classes can also be treated as continuous probability variables and a trend can be calculated. Maximum absolute class change was always one class. The climate class of the last period of each century is given as the initial period's class of that century, plus the direction of the trend, if any significant trend is found. The discussion of annual and seasonality type characteristics is performed separately because of the high abundance of climate combinations and to provide a clear as possible analysis. In treating annual characteristics, the thermal and moisture types and the corresponding changes are also discussed

separately. For instance, possible thermal type characteristics and the corresponding changes referring to the twentieth century are presented in Table 1. Cooling can happen via, e.g., warm to cool or warm to cold thermal type transformations. It should be noted that warming/cooling that occurs as part of so-called "double" changes, such as warming and drying via (cold, wet) to (cool, moist) transformation, is not treated separately.

Table 1, presented for analyzing thermal type changes, is almost identical to the contingency tables used by Monserud and Leemans (1992) for calculating the κ statistic. Consequently, the appropriate contingency tables will be used in the subsequent analysis.

4 Results

The climate change process is represented by the spatial distribution of climate type and statistically by using the kappa statistic. The analysis is presented separately for the twentieth and twenty-first centuries. The contingency tables needed for the kappa statistic are discussed only for those cases for which the changes are the greatest.

It has to be emphasized that a significant temperature or precipitation change does not necessary mean a change in the climate class. If the seasonality of precipitation will not change, a Mediterranean climate could remain the same even with a 3 °C increase in annual temperature. Conversely at climatic borders, a shift in class can occur without significant change in meteorological variables.

4.1 Twentieth century

The spatial distribution of annual thermal and moisture type changes in the European region during the twentieth century obtained by Feddema is presented in Fig. 1. Figure 1 reveals that at most places there is no thermal or moisture type change. The relative frequency of the thermal types "cool" and "cold" is 99.4% and 98.5%, respectively, in the two periods; 91% remained unchanged. The dominant thermal type transformation is warming. Warming transitions caused changes in relative frequency of ≈ 4% and ≈ 3% for cold and cool types, and less than 1% for the warm and hot types. The thermal type "warm" is rare (0.7%) in the first period, but its coverage doubled by the end of the century.

Relative frequency change for all moisture types is below 0.7%. In Fig. 1, areas without class change are marked white. These areas can be equally found in the northern (55 °N–72 °N) and middle (42 °N–55 °N) European zones and, to a lesser extent, in the southern (35 °N–42 °N) European zone, without regularity in the spatial distribution. Similar results are obtained by Jylhä et al. (2010) using Köppen's method and A1B emission scenario for the periods 1950–1978 and 1979–2006.

Table 1 Example of thermal type characteristics and the possible thermal type changes according to Feddema

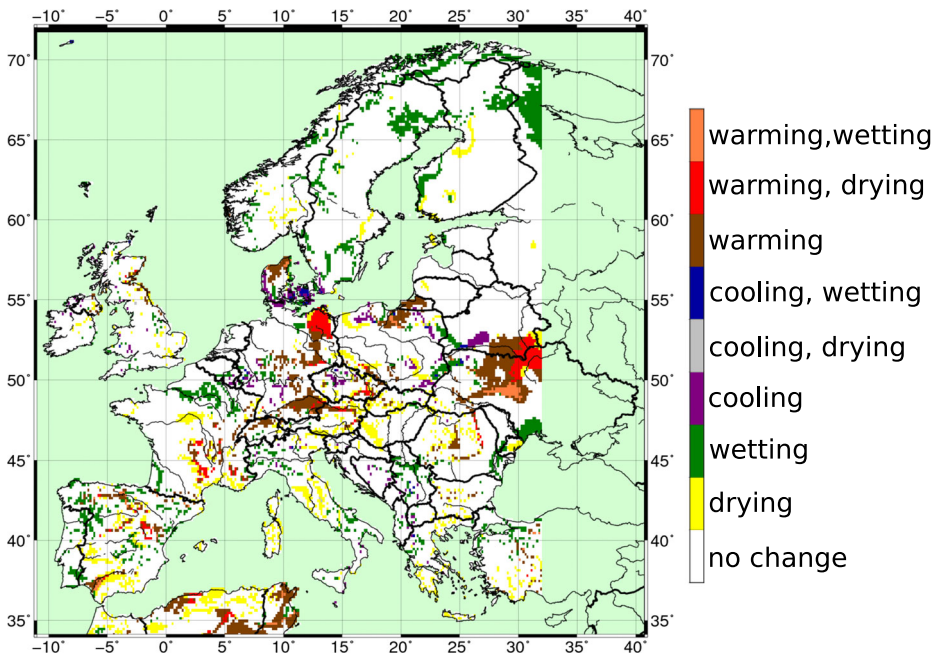| Thermal type		1971–2000		
		Warm	Cool	Cold
1901–1930	Warm	No change	Cooling	Cooling
	Cool	Warming	No change	Cooling
	Cold	Warming	Warming	No change

Fig. 1 Thermal and moisture type changes in the European region during the twentieth century (1901–1930 and 1971–2000) according to Feddema

Warming can occur either as a "single" class change (warming only) or as a "double" class change (e.g., warming and drying). Among these changes, the "double" warming transformation "warming and wetting" is the rarest, but it is present to the north of Moldavia in central Ukraine. Otherwise, warming is the dominant process in central Ukraine, happening in the frame of both "single" and "double" changes. Single warming transformations are mostly located in the middle European zone (e.g., areas in Cantabrian Mountains, Swiss Midlands, Bavaria, Harz Mountains, North European Plain, East European Plain, and Carpathian Mountains) though some areas are found around 55–57 °N in, e.g., the Jutland Peninsula, Scotland's eastern coast, and in the Iberian Peninsula (e.g., Guadalquivir river valley). Cooling also exists with a relatively low frequency (1.3%) in Europe, mostly occurring as transformation from cool to cold.

Among moisture type transformations wetting is dominant in the northern zone (regions close to the Gulf of Bothnia and in the Russian Lapland), while drying is prominent in the southern zone (southern Spain, Island of Sardinia, central Italy, Peloponnese Peninsula, central Macedonia region of Greece, and Crete). In the middle zone, areas characterized by wetting can be found in France near the English Channel and the Bay of Biscay, in some areas of the Italian Alps, and in some regions close to the Black Sea. Drying can be observed not only in plains (North European Plain and Carpathian Basin) but also in alpine regions (e.g., Austrian Alps). Wetting occurs with a relative frequency of about 8% over Europe, mostly (4.6%) via dry to moist transformation. The next two most abundant transformations are moist to wet and semiarid to dry. The relative frequency of drying is also about 7%, where the moist to dry transformation is the most typical (4.1%) followed by wet to moist and dry to semiarid. Even though the

class change probability for both thermal and moisture types reaches 5%, according to the kappa statistics, for the three most abundant classes, the agreement is very good (κ_{thermal} = 0.84, κ_{moisture} = 0.78).

The main features related to seasonal type change characteristics are presented in Fig. 2 and Table 2.

Seasonality characteristics show (Fig. 2, Table 2) the same amount of change as the annual characteristics during the twentieth century. In Table 2 about 95% of the available grid points are represented, but all together 39 combinations exist. The extreme- and high-temperature seasonality classes are the most frequent. The percentage of extreme- and high-temperature seasonality in the first period is 38% and 31%, respectively but the chance agreement is only 31% and 22%, respectively. The mixed-seasonality classes are even more prone to change. The proportion percentage of high-mixed seasonality class was 17% initially, but only 9% remained unchanged. This results in a κ coefficient of 0.59, found near the lower bound of good agreement interpretation.

The rarest seasonality type transformations are those changing between mixed and precipitation seasonality (Fig. 2). These areas are found, e.g., in Galicia, Spain, Scottish Highlands, and southwestern Norway. The dominant seasonality type transformations (Table 2) are high-mixed to high-temperature seasonality, extreme- to high-temperature seasonality and high- to extreme-temperature seasonality (6.6%, 6.1%, and 4.9% respectively). The first can be equally observed in the northern (Norwegian Alps, middle Sweden, Grampian Mountains in Scotland, and East European Plain), middle (North European Plain, Bavaria, Moravia, Lake Geneva, Dinaric Alps, Cantabrian Mountains, central Italy, and Balkan Mountains) and southern (Iberian Mountains, Baetic System, and Thrace) European zones. Some of these are related to the windward side of mountainous areas indicating a change in orographic precipitation formation. The opposite process, the high-temperature to high-mixed seasonality transformation is less probable ($\approx$ 4%), and are found in the Norwegian Alps, the western Carpathians, southern Poland, central Ukraine, the Pyrenees, and central Italy.
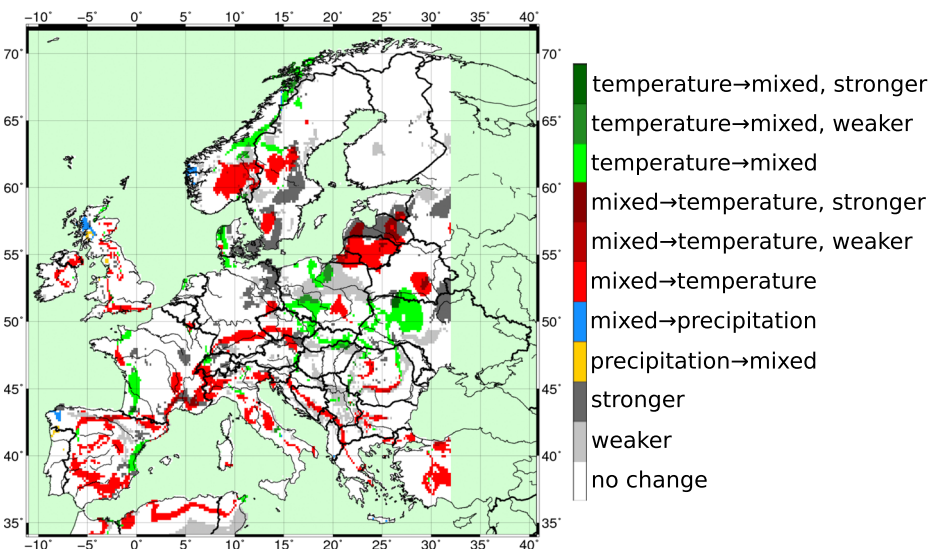

Fig. 2 Seasonality type changes in the European region during the twentieth century (the periods 1901–1930 and 1971–2000) according to Feddema

Table 2 The contingency table for calculating the κ coefficient to estimate the goodness of agreement between different seasonality classes during the twentieth century (time interval 1901–1930 and 1971–2000)

Categories of seasonality		1971–2000				
		Extreme temperature	High temperature	Extreme mixed	High mixed	Total (1901–1930)
1901–1930	Extreme temperature	30.7	6.1	0.5	0.7	38
	High temperature	4.9	22.2	0.3	3.9	31.3
	Extreme mixed	3.2	0.6	9.5	0.7	14
	High mixed	0.8	6.6	0.2	9.1	16.7
Total (1971–2000)		39.6	35.5	10.5	14.4	100

The values represent the probability (%) of category changes between the periods

4.2 Twenty-first century

As mentioned, among the ENSEMBLES project results, only the results obtained by ensemble averaging will be considered. The spatial distribution of thermal and moisture type changes in the European region during the twenty-first century obtained by Feddema is presented in Fig. 3. The contingency table for thermal types is presented in Table 3.

Both Fig. 3 and Table 3 show that warming is foreseen to be the dominant climate class change in extensive areas of the northern European zone. About 55% of the grid points have warming class change, of which the cold to cool transformation is the dominant. In the twentieth century analysis, the chance agreement was higher than the probability of change. In the first period, the marginal-frequency of the cold class is 56.4%, which is expected to
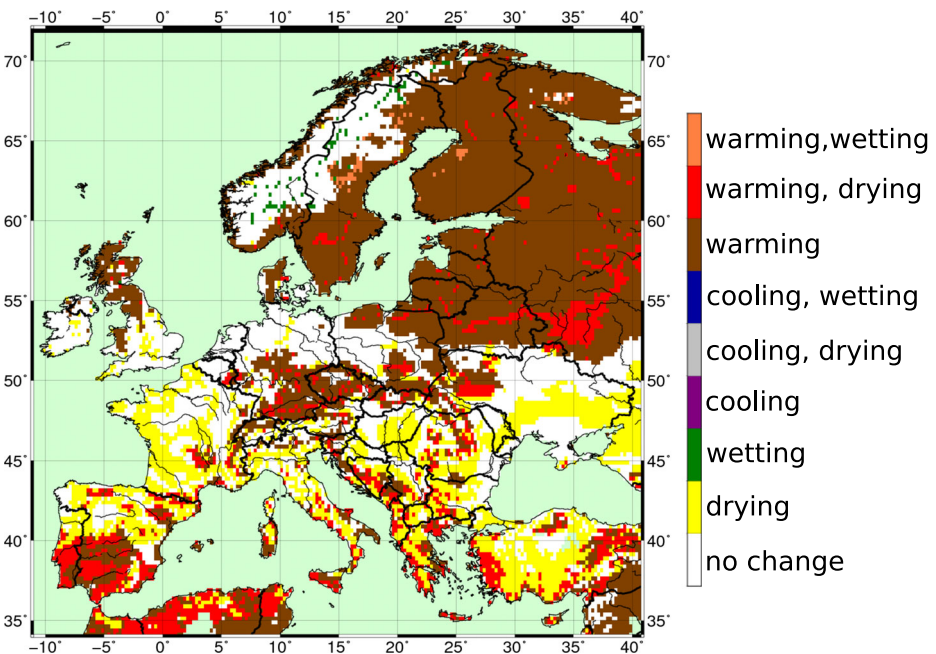

Fig. 3 Thermal and moisture type changes in the European region during the twenty-first century (periods 1971–2000 and 2071–2100) according to Feddema

Table 3 The contingency table for calculating the κ coefficient to estimate the goodness of agreement between different thermal types during the twenty-first century (1971–2000 and 2071–2100)

Thermal types		2071–2100			Total (1971–2000)
		Warm	Cool	Cold	
1971–2000	Warm	0.3	0	0	0.3
	Cool	8.4	34.8	0	43.2
	Cold	0	49	7.4	56.4
Total (2071–2100)		8.7	83.8	7.4	100

The values represent the probability (%) of category changes between the periods

decrease to 7.4% by the end of the twenty-first century because of cold to cool class transformations. The percentage of cool to warm transformation (8.4%) is also high. Warming occurs mostly (44% of grid points) as a "single" change (warming only), but there are also extensive areas with "double" changes, warming and drying (10.6%), or warming and wetting (0.4%). The "single" change process is typical not only for the Jutland Peninsula, southern Sweden, Finland, central Europe, and the East European Plain, but also for Great Britain. Warming and wetting can be found only in middle and northern Sweden, central Finland, and Lapland. Areas of "warming and drying" appear around Europe (e.g., East European Plain, central Ukraine, Carpathian Mountains, Bavaria, Dinaric Alps, Iberian Peninsula, Sicily, and Macedonia). The kappa statistic for the three most abundant classes shows a complete disassociation between the first and second period ($\kappa_{thermal} = 0.03$).

The foreseen moisture type transformations are also pronounced with respect to the twentieth century (Fig. 1). The drying climate of south Europe is the most extensive. The moist to dry and the dry to semiarid transformations are almost equally probable, 13% and 14%. The former is obviously more likely in the northern and middle zones, while the latter in the southern zone. It could happen either as a "single" (only drying) or as a "double" change process (drying and warming together). Figure 3 shows that drying alone is most pronounced in the southern zone. Note that drying is also registered in England. Even though not presented, the kappa statistics are performed for semiarid, dry, and moist classes with $\kappa_{moisture} = 0.51$ showing a fair agreement.

Even though there is about a 2.5–3.5 °C change over 100 years in central and south Europe, these areas are mostly characterized by change in the moisture but not the thermal type. For example, for the coordinates 20.125 °E/44.875 °N, the 30-year average annual temperature increased from 12.21 °C to 14.8 °C. In terms of *PET*, this means a significant change from 726 mm/year to 831 mm/year, but both *PET* values are found in the same climate class. A few degrees of variation in annual temperature are expected to be present in any climate class, so if an area is in a lower/mid-class, it is possible that the class, i.e., the type of climate, will not change. Similarly, moisture type changes are expected in regions where the climate characteristics define a class near the boundary of a class. This usually refers to regions that already have low moisture availability, where a change in either seasonality or a decrease in precipitation amount have serious consequences, e.g., in agriculture. Considering the RCM projections, in central Europe, a decrease of 40 mm in annual precipitation is enough for annual moisture class change.

The change of main seasonality climate characteristics is presented in Fig. 4. There are extensive areas (17% of grid points) where only the magnitude of seasonal variability changes. Regarding temperature seasonality, the percentage of the high- to extreme-seasonality

transformation is ≈ 10%, while for the opposite transformation it is 8.5%. Increase of seasonal variability is foreseen to be found in France, Belarus, central Ukraine, Russia, and the Dinaric Alps. In some areas (4% of grid points) temperature seasonality class transforms into the mixed seasonality class (e.g., on the Scandinavian Peninsula, British Isles, and France). Changes from the mixed to temperature seasonality class affect ≈ 8% of the grid points, out of which the extreme intra-annual variability possesses the highest (4% of grid points) coverage. Such areas can be mostly found in the middle (e.g., in Bavaria, Alps, Carpathian Mountains, Moravia, and central Ukraine) and southern (e.g., Andalusia, Sardinia, Sicily, and Calabria) zones of Europe. There are also extremely rare cases of mixed to precipitation seasonality (southwestern Norway and Scottish Highlands) and its reverse (northern Portugal) transformations. These geographical locations are characterized as: they are in the far west, where the direct influence of the Atlantic Ocean on the state of the atmosphere is high. The kappa coefficient is 0.44, showing a fair agreement.

5 Concluding remarks

The climate change process in the European region during the twentieth and twenty-first centuries is analyzed using Feddema's (2005) method. The climate change process is analyzed using a trend analysis of 30-year of periods and using Cohen's kappa statistic. Based on the CRU TS 1.2 database, the beginning and end periods of the twentieth century are defined as 1901–1930 and 1971–2000, respectively. For the analysis based on the ENSEMBLES project simulations the boundaries are 1971–2000 and 2071–2100. Only ensemble mean precipitation and temperature fields are considered here, after a bias correction of daily data.

The main outcomes are as follows:

In the twentieth century, the European climate remained mostly unchanged based on Feddema's classification, similar result was concluded based on Köppen's climate
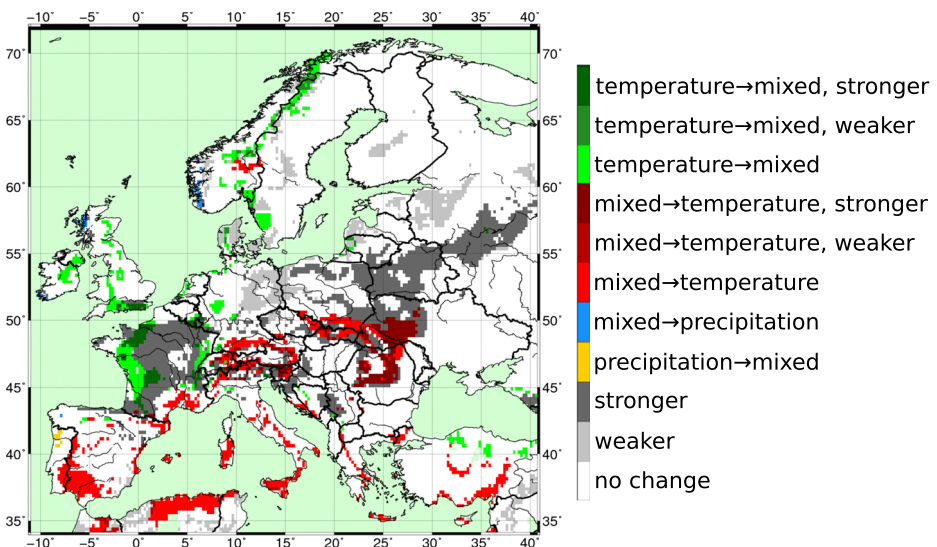

Fig. 4 Seasonality type changes in the European region during the twenty-first century (periods 1971–2000 and 2071–2100) according to Feddema

classification in Rubel and Kottek's (2010) work. Regarding changes, seasonality characteristic changes possessed the highest percentage of occurring (maximum of ≈ 7%). The two dominant seasonality class transformations are the high-mixed to high-temperature seasonality and the extreme- to high-temperature seasonality transformations. Moisture type class changes (drying and wetting) are slightly more probable than the annual thermal type changes (warming and cooling). The dominant moisture and thermal type transformations are the dry to moist, moist to dry and the cold to cool transformations, affecting 4.6%, 4.1% and 5.4% of the grid points respectively. These wetting and warming processes are not coupled, they do not appear on the same territory. Area distribution is irregular.

In the twenty-first century, the most dominant climate change process is found to be warming. This occurred mostly via cold to cool (about 46% of grid points) and cool to warm (about 8% of grid points) transformations, with a frequency of 49% and 8.4%, respectively. Warming appeared mostly as a "single" change process, especially in the northern European regions. Also, twenty-first century Europe is foreseen to be drier than twentieth century Europe. Drying is predicted to happen via dry to semiarid and moist to dry transformations, both changes have about the same frequency (14% and 13%). Especially intense drying is foreseen for southwestern parts of the Iberian Peninsula, where drying and warming are to appear together over extensive areas. Regarding seasonality characteristic changes, the increase of intra-annual variability is foreseen for vast areas. The most frequent are the changes in intra-annual variability of temperature: the increase is 10.1%, the decrease is 8.5%. The transformation of mixed to temperature seasonality is almost twice as frequent as its reverse (8.1% and 4.8% respectively).

The twenty-first century is foreseen to be a century of intense climate change, at least in comparison to the twentieth century. It is also shown that applications based on Feddema's method directly describe climate type changes instead of describing shifts between climate types (e.g., Rubel and Kottek 2010) and can provide a great deal of new information, especially regarding seasonality type changes. These features are unequivocal advantages in analyzing the climate change process with respect to other commonly used generic climate classification methods (e.g., Köppen 1936; Holdridge 1947). They also greatly contribute to the reproduction of heterogeneity of the European climate change process.

References

Beck C, Grieser J, Kottek M, Rubel F, Rudolf B (2005) Characterizing global climate change by means of Köppen climate classification. Klimastatusbericht 2005:139–149

Beniston M, Jungo P (2002) Shifts in the distributions of pressure, temperature and moisture in the Alpine region in response to the behavior of the North Atlantic oscillation. Theor Appl Climatol 71:29–42

Breuer H, Ács F, Skarbit N (2017) Climate change in Hungary during the twentieth century according to Feddema. Theor Appl Climatol 127:858–863

Castro M, Gallardo C, Jylha K, Tuomenvirta H (2007) The use of climate-type classification for assessing climate change effects in Europe from an ensemble of nine regional climate models. Clim Chang 81:329–341

Chen D, Chen HW (2013) Using the Köppen classification to quantify climate variation and change: an example for 1901–2010. Environ Dev Sustain 6:69–79

Cohen J (1960) A coefficient of agreement for nominal scales. Educ Psychol Meas 20:37–46

Diaz HF, Bradley RS (1997) Temperature variations during the last century at high elevation sites. Clim Chang 36:253–279

Elguindi N, Grundstein A, Bernardes S, Turuncoglu U, Feddema J (2014) Assesment of CMIP5 global model simulations and climate change projections for the 21st century using a modified Thornthwaite climate classification. Clim Chang 122:523–538

Emanuel WR, Shugart HH, Stevenson MP (1985) Climatic change and the broad-scale distribution of terrestrial ecosystem complexes. Clim Chang 7:29–44

Engelbrecht CJ, Engelbrecht FA (2016) Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. Theor Appl Climatol 123:247–261

Fábián AP, Matyasovszky I (2010) Analysis of climate change in Hungary according to an extended Köppen classification system, 1971–2060. Időjárás 114:251–261

Feddema JJ (2005) A revised Thorntwaite-type global climate classification. Phys Geogr 26:442–466

Formayer H, Haas P (2009) Correction of RegCM3 model output data using a rank matching approach applied on various meteorological parameters. In: Deliverable D3.2 RCM output localization methods (BOKU-contribution of the FP 6 CECILIA project), pp 5-15

Fraedrich K, Gerstengarbe F-W, Werner PC (2001) Climate shifts during the last century. Clim Chang 50:405–417

Gallardo C, Gil V, Hagel E, Tejeda C, de Castro M (2013) Assessment of climate change in Europe from an ensemble of regional climate models by the use of Köppen-Trewartha classification. Int J Climatol 33:2157–2166

Geiger R (1954) Classification of climates after W. Köppen. Landolt-Börnstein – Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, alte Serie, vol 3. Springer, Berlin, pp 603–607

Grundstein A (2008) Assessing climate change in the contiguous United States using a modified Thornthwaite climate classification scheme. Prof Geogr 60(3):398–412

Haylock MR, Hofstra N, Klein Tank AMG, Klok EJ, Jones PD, New M (2008) A European daily high-resolution gridded dataset of surface temperature and precipitation. J Geophys Res Atmos 113:D20119

Heikkinen RK, Luoto M, Araújo MB, Virkkala R, Thuiller W, Sykes MT (2006) Methods and uncertainties in bioclimatic envelope modelling under climate change. Prog Phys Geogr 30(6):751–777

Hewitt CD, Griggs DJ (2004) Ensembles-based predictions of climate changes and their impacts. EOS Trans Am Geophys Union 85:566–567

Holdridge LR (1947) Determination of world plant formations from simple climatic data. Science 105:367–368

Jacob D et al (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg Environ Chang 14:563–578

Jylhä K, Tuomenvirta H, Ruosteenoja K, Niemi-Hugaerts H, Keisu K, Karhu JA (2010) Observed and projected future shifts of climatic zones in Europe and their use to visualize climate change information. Weather Clim Soc 2:148–167

Köppen W (1936) Das geographische System der Klimate (The geographic system of climates). In: Köppen W, Geiger R (eds) Handbuch der Klimatologie, Bd. 1. Teil C – Borntraeger, Berlin

Lohmann R, Sausen R, Bengtsson L, Cubasch U, Perlwitz J, Roeckner E (1993) The Köppen climate classification as a diagnostic tool for general circulation models. Clim Res 3:177193

Mitchell TD, Carter TR, Jones PD, Hulme M, New M (2004) A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100). Tyndall Centre Working Paper 55:27

Monserud RS, Leemans R (1992) Comparing global vegetation maps with the kappa statistics. Ecol Model 62:275–293

Nakićenović N et al (2000) Special report on emissions scenarios. In: Working group III, Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge 595 p

Rohli RV, Joyner TA, Reynolds SJ, Shaw C, Vázquez JR (2015) Globally extended Köppen-Geiger climate classification and temporal shifts in terrestrial climatic types. Phys Geogr 36:142–157

Rubel F, Kottek M (2010) Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification. Meteorol Z 19:135–141

Rubel F, Brugger K, Haslinger K, Auer I (2017) The climate of the European alps: shift of very high resolution Köppen-Geiger climate zones 1800-2100. Meteorol Z 26:115–125

Seo C, Thorne JH, Hannah L, Thuiller W (2009) Scale effects in species distribution models: implications for conservation planning under climate change. Biol Lett 5:39–43

Skarbit N, Ács F, Breuer H (2018) The climate of the European region during the 20th and 21st centuries according to Feddema. Int J Climatol 38:2435–2448

Szelepcsényi Z, Breuer H, Kis A, Pongrácz R, Sümegi P (2018) Assessment of projected climate change in the Carpathian region using the Holdridge life zone system. Theor Appl Climatol 131(1–2):593–610

Thornthwaite CW (1948) An approach toward a rational classification of climate. Geogr Rev 38:5–94

Thornthwaite CW, Mather JR (1955) The water balance. Publ. In Climatology 8(l). CW Thornthwaite & Associates, Centerton

van der Linden P, Mitchell JFB (2009) ENSEMBLES: climate change and its impacts: summary of research and results from the ENSEMBLES project. Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK

Wang M, Overland JE (2004) Detecting arctic climate change using Köppen climate classification. Clim Chang 67:43–62

Wang L, Rohli RV, Yan X, Li Y (2017) A new method of multi-model ensemble to improve the simulation of the geographic distribution of the Köppen–Geiger climatic types. Int J Climatol 37:5129–5138

Willmott CJ, Feddema JJ (1992) A more rational climatic moisture index. Prof Geogr 44:84–88

Ying S, Gao XJ, Wu J (2012) Projected changes in Köppen climate types in the 21st century over China. Atmos Oceanic Sci Lett 5:495–498