The climate of the European region during the twentieth and twenty-first centuries according to Feddema

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Abstract

The climate of the European region during twentieth and twenty-first centuries in terms of Feddema's (2005) annual and seasonal climate characteristics is analysed. Observed data for the twentieth century are taken from the CRU TS 1.2 dataset. The projected data for the twenty-first century are obtained using simulation results of nine Regional Climate Models run in the scope of the ENSEMBLES project. In the analysis, the European region is arbitrarily divided into three subregions: the northern (72°N–55°N), middle (55°N–42°N) and southern (42°N–35°N) zones. We focused on the analysis of the relationships between Feddema's climatic characteristics and the main geographical constraints (latitude, longitude, relief and land-locked waterbodies). It is shown that Feddema's climatic maps agree well with the expected effects of the main geographical controls. Climate type/geographical control dependence is very strong in the upland coastal regions of the Atlantic Ocean, that is, in the Norwegian Alps, the Scottish Highlands and in the Galician Massif Mountains. A characteristic seasonal type change can be observed in these regions: the seasonality of P changes through the seasonality of both P and T into the seasonality of T. This behaviour is registered by all model simulations in both the twentieth and twenty-first centuries. The Atlantic Ocean-relief-longitude interplay effect on Feddema's climate types can be observed in all three zones. The uplands in Europe determine climate on the local scale. This upland effect is stronger when it is combined with the effect of extensive land-locked water bodies. This relationship is obtained by all model simulations in both the twentieth and twenty-first centuries. Lastly, the area heterogeneity of the European region's climate is well reproduced. The observations and the modelling tools show that the climate became and will become warmer and dryer during the course of the twentieth and twenty-first centuries.

keywords: climate, Europe, Feddema's method, 20th and 21st century

1 Introduction

Today, the methods of Köppen (1900, 1936) and Thornthwaite (1948) are the most popular climate classification methods. Köppen's method is a common method used worldwide in almost all branches of science (Rubel and Kottek, 2011) because of its extreme simplicity. It may be used on both the global (Kottek *et al.*, 2006; Peel *et al.*, 2007) and the regional (Engelbrecht and Engelbrecht, 2016; Alvarez *et al.*, 2014) scales, and its application in the classroom can be easily implemented. Its applications have increased with the development of visualisation tools (Jylhä *et al.*, 2010). At the same time in some cases its local scale applications can be less successful as, for instance, in Hungary (Ács and Breuer, 2013). It cannot be fine-tuned, therefore it has a number of modified versions (Trewartha, 1980, 1981; Réthly, 1933). With respect to Köppen's method, Thornthwaite's method is more complex. It is able to represent more climate types than Köppen, so, it seems to be more appropriate for local (Drucza and Ács, 2006) or regional (Richard, 1962) scale applications. Its global scale application has not been carried out (Feddema, 2005). The method was considerably remodelled by Feddema (2005) introducing significant simplifications. The new Thornthwaite-based Feddema's method became more competitive with Köppen than Thornthwaite's method. It may be easily fine-tuned and became more appropriate for classroom applications especially at the local scale (Ács *et al.*, 2015; Breuer *et al.*, 2017). Nevertheless, its regional scale applications are rare, and to the best of our knowledge it has not been applied to Europe as a separately chosen region. Note that Feddema (2005) estimated the European climate, but in scope of a global-scale treatment without discussing it.

The aim of this study is to characterise the European region's climate during the twentieth and twenty-first centuries according to Feddema. In the analysis, we will pay more attention to the relationship between Feddema's climate types and the main geographical controls on climate, namely, latitude, longitude, relief and extensive land-locked water bodies. This view will be applied in order to better understand both the climate and the method. Understanding will be more complete if both the twentieth and the twenty-first centuries are considered. Observed data referring to the period 1901–2000 are taken from the Climatic Research Unit (CRU) data centre as part of the CRU TS 1.2 database (Mitchell *et al.*, 2004). Projected data for the twenty-first century are obtained by using outputs of regional climate models (RCM) in the scope of the ENSEMBLES climate change project. These data are widely used since the project is well known. The results of different climate models are available in this project thus we are able to get a wider picture about our future. The projected data were bias-corrected on the basis of measured E-OBS data (Ehret *et al.*, 2012). The analysis is performed using data of four 30-year periods (1901–1930, 1971–2000, 2021–2050, 2071–2100).

2 Methods

2.1 Feddema's method

Feddema's (2005) method is a revised Thornthwaite-type (Thornthwaite, 1948) climate classification method, as such, its basic quantity is potential evapotranspiration (PET). PET is introduced by Thornthwaite (1948) for describing evapotranspiration, but he realized that PET is a useful quantity for characterizing both an area's heat and water availability. Feddema (2005) drastically simplified Thornthwaite's treatment of seasonality, so, this method has the opportunity to be as competitive as Köppen's.

PET is a better quantity for characterizing an area's heat availability than temperature, but its calculation is more complex. There are many PET parameterisations (e.g. Jianbiao et al., 2005), we used Thornthwaite's formula as it is presented in McKenney and Rosenberg's (1993) work, which uses monthly air temperature (T) and daylight length data. All details related to the formula and its use can also be found in the work of Ács and Breuer (2013). Water availability, that is, moisture type is estimated by calculating the moisture index I_m, which depends on precipitation P and PET as follows:

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

Annual values can be calculated from monthly values of P, PET and I_m. Annual and monthly values serve for calculating annual and seasonal thermal and moisture characteristics, respectively. The climate’s annual thermal and moisture characteristics are categorized as it is given in Table 1 and 2, respectively.

Regions with negative I_m, are dry regions with different intensities, in these regions PET is greater than P. Of course, regions, where P is greater than PET, are wet regions with different intensities.

The climate’s seasonal thermal and moisture characteristics are estimated by calculating the annual ranges of P [maximum monthly P value (P^{max}) minus minimum monthly P value (P^{min}), that is $P^{max} – P^{min}$], PET ($PET^{max} – PET^{min}$) and I_m ($I_m^{max} – I_m^{min}$). The ratio of the annual ranges of P ($P^{max} – P^{min}$) and PET ($PET^{max} – PET^{min}$) is actually an indicator for deciding which climatic variable (P or T) possesses seasonality (Table 3). In defining the criteria, it was relevant whether P is two times greater than PET or, vice versa, whether PET is two times greater than P. Details related to the thresholds used can be found in Feddema’s (2005) work. The magnitude of seasonal variability is estimated by calculating the annual range of I_m ($I_m^{max} – I_m^{min}$) (Table 4). The criteria used for temperature, precipitation and temperature together and precipitation are given in Table 4. The motivations why precisely these criteria are chosen can be found in Feddema’s (2005) work.

2.2 Bias correction

The bias correction of daily precipitation and temperature data obtained by RCM is performed by Ehret *et al.*’s (2012) method separately for each month and grid point. The probability distribution functions of the RCM outputs and of the E-OBS data for the period 1961–1990 were compared to determine correction factors for the RCM distribution functions for each percentile in one percent steps. The correction factors for temperature and precipitation are calculated using differences and ratios of percentiles, respectively.

3 Data

3.1 CRU TS 1.2 dataset

For the twentieth century, the so called CRU TS 1.2 database (Mitchell *et al.*, 2004) is used as a source for calculating monthly air temperature and precipitation data. The database is a product of the Climatic Research Unit (CRU) of the University of East Anglia. The data possess spatial resolution of 10’x10’ (~18 km x 18 km) and are located in the region between the -11°–32°/34°–72° longitude/latitude lines. The chosen European region contains a total of

31143 grid points. Thirty-year means are constructed from the data, so a total of 71 temperature and precipitation fields are available.

3.2 E-OBS dataset

The E-OBS database contains daily air temperature (minimum, maximum and mean), precipitation and pressure data (van der Besselaar *et al.*, 2011) in a spatial resolution of 25 km x 25 km referring to the period 1950–2010. Elevation data for each grid box are also given. The measured, quality controlled data in Europe obtained from observation stations reach their final form after interpolation, which is performed in three steps: first, the so called thin-plate spline method is applied on monthly means, then, daily anomaly values were determined by using kriging and lastly daily anomalies were combined with monthly means to get final data. The elevation data for the elevation intervals -200 m – 0 m, 0 – 200 m, 200 – 1000 m, 1000 – 3200 m are plotted in Fig. 1.

3.3 ENSEMBLES project simulations

RCM simulation results obtained in scope of the ENSEMBLES project (van der Linden and Mitchell, 2009) are used as the data source for the twenty-first century. The data possess a spatial resolution of 25 km x 25 km in the region located between the -11°–40.75°/36.5°–74° longitude/latitude lines. The RCM we used are as follows: HadRM3Q, CLM, RCA, RegCM, RACMO2, REMO, HIRHAM5, HIRHAM and ALADIN. The models were run assuming the A1B emission scenario, which hypothesises a rather convergent world with a reasonably rapid population and economic growth using all energy sources in a balanced way.

All the RCM results were used. Among these we have chosen those results that were the most extreme. The choice was simply done by setting up precipitation and temperature differences between the periods 2071–2100 and 1971–2000. The ensemble mean of the P and T fields has also been generated. The model results showing the most extreme features for all grid points are presented in Figure 2.

Concerning precipitation, HIRHAM5 produced the largest increase, while HIRHAM the largest decrease. HIRHAM5's precipitation increase is especially obvious on the Scandinavian Peninsula in its southwestern parts. The decrease is moderate to the south from 45°N. In spite of this, the precipitation decrease produced by HIRHAM is much larger and it can be observed up to 60°N. Note that HIRHAM's temperature increase is the smallest. This increase is larger than 4 °C only in the northern parts of the Scandinavian Peninsula. The strongest increase is produced by HadRM3Q. Here, the increases reaching 4 °C are typical not only in the northern but also in the southern regions of Europe.

4 Results

As mentioned, climate maps will be analysed for four 30-year periods: at the beginning and at the end of the twentieth century (1901–1930, 1971–2000) and at the end of the first (2021–2050) and second part (2071–2100) of the twenty-first century. Before analyzing the results a brief PET comparison will be presented for validation purposes. For the reason of completeness, the results obtained for the period 1901–1930 will be also briefly compared by Feddema's (2005) global scale analysis results. As mentioned, Feddema's (2005) climate types will be considered from the point of view of their relationship to the main geographical controls on climate, namely to latitude, longitude, relief and extensive land-locked water bodies such as the eastward directed Mediterranean Sea or the northward directed Baltic Sea.

4.1 Checking the PET

The validation of area-averaged PET is a complex task. There are many limitations in this process. Firstly, PET is a very complex quantity (Lhomme, 1997), it depends not only on atmospheric but also on surface characteristics, so, its precise determination needs a great deal of information. Secondly, PET's surface dependence cannot be neglected, it can significantly differ above different land-surface types [e.g. water, vegetation (forests, crops), bare soil]. Thirdly, it is difficult to find exact methods for its direct determination. Because of the reasons mentioned above, we did not directly validate the estimated PET values, instead, we performed a simple comparison between the PET results obtained in this study (PET_T) and the PET results obtained in Choudhury's (1997) study (PET_{PM}).

In his global scale analysis Choudhury (1997) used Penman-Monteith's equation for calculating PET (PET_{PM}) assuming a well-watered grass-covered land-surface with an albedo and surface resistance of 0.23 and 70 sm^{-1}, respectively. Solar radiation, fractional cloud cover, air temperature and vapour pressure data are taken from satellite observations, while wind velocity data for estimating aerodynamic resistance are obtained from a four-dimensional data assimilation procedure. The PET values are calculated for 2.5° x 2.5° grid cells. These values were also compared with in-situ lysimeter measurements from well-watered grass surfaces (Choudhury, 1997; Table 1) for different climate types at thirty-five locations in total. According to Choudhury (1997), the average error of calculated PET_{PM} values is somewhere between 15–20% for any month or location. The PET_{PM} values used in this study (Choudhury, 1997; Fig 13) refer to the Earth between latitudinal zones 35°N–70°N for the period 1987–1988. Note that the PET_T values refer to the same latitudinal zones and period but only to the European region, where the grid cells are 10'x10' (~18 km x 18 km). A comparison of zonally-averaged PET_{PM} and PET_T values for the period 1987–1988 is presented in Fig. 3.

Despite the enormous differences in methodology and data, the agreement between PET_{PM} and PET_T values seems to be good (the coefficient of determination R^2 is 0.87). The largest differences are obtained in high latitudinal zones, where PET_T overestimates PET_{PM}. It is hard to explain this deviation, one possible cause may be that the data sources are different. Evapotranspiration is a more temperature than radiation-limited process in high latitudes, so, some differences between PET_T, which is obtained by a temperature-based method and PET_{PM}, which is obtained by a radiation-based method, are not surprising. The area distribution of PET_T for the periods 1987–1988 and 1971–2000 is presented in Figs. 4 and 5, respectively.

Comparing Figs. 4 and 5, we see that heat availability in the period chosen for comparison was similar to the heat availability of the period 1971–2000. Larger differences can be observed only in the East European Plain, where in some areas the PET for the period 1987–1988 is lower than the PET for period 1971–2000.

4.2 Twentieth century

4.2.1 The period 1901–1930

The annual and seasonal characteristics of Feddema's (2005) climate types referring to the period 1901–1930 are presented in Figure 6. To the north, on the Norwegian coast and to the northwest (Scottish Highlands), the climate is “cold, saturated”, which is caused by the effects of latitude and relief. The relief strongly determines moisture type, this is clearly observable, for instance, in Scotland, where the climate on the lee side of the Scottish Highlands on the North Sea coast is “cold, moist”. The Norwegian Alps have the same effect. This is clearly observable on the Scandinavian Peninsula, especially to the north of the Arctic Circle. There, the moisture type changes from “saturated” to “dry”, while the thermal type remains “cold”. The latitudinal effect in combination with the effect of the Baltic Sea can also be observed in the eastern parts of the Scandinavian Peninsula and in the Baltic States. This is manifested by the “dry” → “wet” moisture type transition moving southwards. Note how both the latitudinal and longitudinal effects strongly affect the climate in Denmark, which is not a large country. Moving eastwards the annual characteristics change from “cool, moist” through “cold, wet”, “cold, dry” to “cool, wet”. Denmark is such a country where the oceanicity gradient is large (Metzger et al., 2005). Concerning seasonal characteristics, the main features are as follows: where the moisture type is “saturated” or “wet”, the seasonality is mostly characterised by medium or high variability of both T and P. Of course, there are exceptions. In some regions of the Scottish Highlands or in southwestern parts of the Norwegian Alps only P possesses seasonality with high or extreme variability. Where the moisture type is “moist” or “dry”, the seasonality is characterised by medium, high or extreme variability of T except some areas in south central Sweden and Norway, Latvia and Lithuania.

To the south, roughly in the zone between latitudes 55°N–42°N, the climate is very variable, which is caused by the joint effects of latitude, longitude and relief. The thermal type is either “cold” or “cool”. The latitudinal effect shows up in Great Britain and on the interior of the Eastern European Plain, between latitudes 55°N–45°N. The thermal type “cold” transforms into thermal type “cool”. The variability of moisture type is much greater, it changes from “dry” to “saturated”. This is visible in the case of Great Britain. On the territory of Wales, in the Cambrian Mountains, the climate is “cold, saturated”, going eastwards the climate changes from “cold, wet”, through “cool, moist” to “cool, dry”. In the coastal zone of North Sea in continental Europe, the climate is “cool, moist”, which transfers into “cold, moist” because of the effect of relief (Harz Mountains). Going eastwards, the climate becomes drier; it is either “cool, dry” or “cold, dry”. Note that Poland’s extensive territories bordered by Belarus and Ukraine are “dry”. The combined effect of longitude and relief is also visible in the southern regions of the middle zone. The climate in the mountainous regions (Cantabrian Mountains, Pyrenees Mountains, Massif Central in France, Swiss, Austrian and Dinaric Alps, Carpathian Mountains) is “cold, saturated” or “cold, wet”; in the lowlands to the west it is “cool, moist” or “cool, wet”, and to the east “cool, dry”. Note the heterogeneity of climate in northern Italy caused by the combined effects of longitude, relief and of the Mediterranean Sea. Mediterranean Sea obviously acts as a moisture source. Concerning seasonal characteristics, two effects can be seen, the longitudinal effect and the effect of relief. In the mountainous regions, both T and P possess seasonal variations with medium, high or extreme magnitude of variability. The same seasonality can be observed in the far western parts of Great Britain, France and the Iberian Peninsula as well as in the coastal zone of the Mediterranean Sea. In Galicia (the Atlantic coastal zone of north Spain), only P possesses seasonality with high or extreme variability. In lowland areas, the seasonality of T with high or extreme variability is typical. Of course, exceptions can also be found.

To the south from 42°N, the climate is mostly “cool, dry” or “cool, semiarid”, exceptions are north Portugal and the mountainous regions of Albania. In the case of Portugal, the effect of relief is clearly visible. The moisture type is “wet” or “moist” in the highlands and “dry” in the lowlands. Moisture contrasts caused by the combined effects of relief and the Mediterranean Sea can be found in the mountainous regions of Albania and Macedonia (Dinaric Alps and Pindus Mountains). The driest areas in Europe, which are located in Spain around the city of Almeria, are also well reproduced. The heterogeneity of climates in central Italy caused by combined effects of relief and Mediterranean Sea (moisture source) is also clearly visible. In lowland areas around the Ebro, Douro and Tagus rivers on the Iberian Peninsula, in the Po Valley and in the lee of Dinaric Alps in Albania and the Pindus Mountains in Greece, seasonality of T is characteristic, with a high or extreme magnitude of variability.

As mentioned, Feddema (2005) also estimated the European climate for the twentieth century, but in the scope of a global scale analysis without focusing on it. The relevant results are given in Figs. 10, 11 and 12, but the estimation period is not mentioned. Of course, the main characteristics are reproduced, including the “cold, wet or moist” climate in the Scandinavian Peninsula, the “cool, dry” climate in the East European Plain, the “wet” climates along the coastal regions of the Atlantic and in the uplands and the “cool, dry or semiarid” climates in the southern parts of Europe. As it was expected, much sub-regional information on the Scandinavian Peninsula, the Scottish Highlands, Denmark, Great Britain, Central Europe, northern Italy, the Iberian Peninsula, Portugal, Albania, and Greece, etc. is not mentioned or discussed at all. This is understandable since the aim of Feddema’s (2005) work was different.

4.2.2 The period 1971–2000

The climate map of the period 1971–2000 is presented in Figure 7. The similarity of Figure 7 to Figure 6 is obvious, but there are also some main differences. They are as follows.

1) The climate type “warm, semiarid” appeared in southwestern parts of Spain, in the Guadalquivir river valley.
2) The extent of areas with an alpine climate characterised as “cold, saturated” or “cold, wet” irrespective of their north-south oriented position is much less than in the period 1901–1930.
3) There is an obvious increase of the area of the climate type “cool, dry” with respect to the previous period especially in Eastern Europe.
4) In Northern Europe, the climate became somewhat wetter. At many places the moisture type “dry” transformed into the moisture type “moist”.
5) The size of the areas characterised by seasonal type “high or extreme seasonality of T” increased unequivocally with respect to the period 1901–1930.

4.3 Twenty-first century

4.3.1 The period 2021–2050

As for the twentieth century, the main direction of the analyses will be finding the main relationships between the geographical constraints and Feddema’s (2005) annual and seasonal climate characteristics. Feddema’s (2005) annual climate characteristics using simulation results obtained by using HIRHAM, ensemble averaging, HIRHAM5 and HadRM3Q referring to the period 2021–2050 are presented in Figure 8. In the analysis, we will focus on the results obtained by ensemble averaging. Results obtained by HIRHAM, HIRHAM5 and HadRM3Q will be treated with respect to the results of ensemble averaging. In the Northern European zone, here between the latitudes 72°N–55°N, the dominant thermal type is “cold” except the east coast of the Scotland, Denmark, large parts of the Southern Sweden, Baltics and East Europe.

Note that HadRM3Q produced much warmer climate extending to the north up to 67°N, much further north than the Gulf of Bothnia and to the east deep into Eastern Europe. Going from west to east, the moisture type changes from “saturated” through “wet” to “moist” or “dry”. This is caused by both the longitudinal effect and the effect of relief. These effects are also visible on the maps obtained by HIRHAM, HIRHAM5 and HadRM3Q. It can also be seen that HadRM3Q produced a much drier Baltic region than the other models. In the region of Baltic States, the climate is very heterogeneous. This heterogeneity is not reproduced by HIRHAM, HIRHAM5 and HadRM3Q.

The main seasonal characteristics in this region can be seen in Figure 9. The longitudinal effect on seasonal variations is unequivocally visible in Scotland, in the Scandinavian Peninsula and Denmark. This is reproduced in all four cases, but the weakest effect is obtained using HIRHAM5. For instance, the seasonality of T with high or extreme variability is not reproduced in the Baltic States nor in extensive areas of Eastern Europe. This is not surprising seeing that HIRHAM5 gave the largest increase in precipitation.

In the zone between latitudes 55°N–42°N, the dominant thermal type is “cool”, while the moisture types vary from “saturated” through “wet” or “moist” to “dry” or “semiarid”. The effects of relief and longitude are visible in both Great Britain and mainland Europe, just as they were in the twentieth century. This is reproduced not only by ensemble averaging but also by all the models. Drying is unequivocally visible: alpine areas characterised by the moisture type “saturated” are much less extensive (Figure 8) than in the twentieth century. This is especially valid for the Dinaric Alps (Figure 1). The moisture type “semiarid” appeared in Eastern Europe. These changes are reproduced in all cases. Concerning seasonal characteristics, HIRHAM5 gave a somewhat different picture than ensemble averaging, HIRHAM and HadRM3Q (Figure 9). As HIRHAM5 produced the largest increase in precipitation, the areas characterised by seasonality of P in Galicia and north Portugal are rather extensive. Note that the extent of the areas characterised by seasonality of T with high or extreme variability is also much less than for ensemble averaging or HadRM3Q.

In the zone between latitudes 42°N–35°N, the climate is mostly “cool, dry” or “cool, semiarid”, but there are also “warm, dry” or “warm, semiarid” climates, for instance in the valleys of the Guadalquivir and Guadiana rivers in southwestern Spain, on the Salento peninsula in South Italy, on the coastal areas in Albania and in the Epirus region of Greece. These warm regions are registered not only by ensemble averaging but also by all the models (Figure 8). The largest warm areas are produced by HadRM3Q. Note that in “warm” climates both seasonal types, namely, the seasonality of T (see Salento Peninsula) and the joint seasonality of P and T (Guadalquivir River) can be found (Figure 9). The effect of relief (Figure 1) in Portugal can be seen through drying (Figure 8), similarly to the twentieth century.

4.3.2 The period 2071–2100

The annual climate characteristics using the simulation results obtained using HIRHAM, ensemble averaging, HIRHAM5 and HadRM3Q for the period 2071–2100 are presented in Figure 10.

Comparing the results of ensemble averaging in Figures 10 and 8, we can say the following: 1) In the northern European zone, the dominant climate type is “cool, wet” or “cool, moist” instead of “cold, wet or moist” and “cold, dry”. Note that HIRHAM and HIRHAM5 produced extensive areas of climate types “cold, wet” or “cold, dry” in Finland and Russia. Going from west to east, continuous drying, that is, moisture type changes from “saturated” or “wet” to “moist” or “dry” can be observed. This is caused by both the longitudinal effect and the effect of relief. 2) In the middle zone (latitudes 55°N–42°N), the climate type “warm, semiarid” exists also in addition to the dominant climate types “cool, moist” and “cool, dry”. These areas can be found around the Iron Gates, on the Danubian Plain, in the Po Valley and on the French Riviera. Alpine areas with the climate types “cold, saturated or wet” are much smaller (Figure 10) as compared to the first part of century (Figure 8). This is especially valid for the Dinaric Alps. Note that HadRM3Q produced an alpine climate only in the European Alps. 3). In the southern zone (42°N–35°N), the climate type “torrid, dry” can also be found (Guadalquivir Valley) in addition to the dominant climate types “cool, dry” or “cool, semiarid”. HIRHAM did not yield the climate type “torrid, dry”. Of course, areas characterized by the climate types “warm, dry” or “warm, semiarid” are larger than those in the first part of century. The main seasonal characteristics are depicted in Figure 11.

Comparing the results of ensemble averaging in Figures 11 and 9, we can see the following: 1) The main characteristics are similar. For instance, in the northern zone, the longitudinal effect on seasonal variations is also observable in Scotland, the Scandinavian Peninsula and in Denmark. 2) It can be seen that areas characterized by seasonality of T increased somewhat to the edge of the areas characterized by seasonality of both T and P. This is also reproduced by HIRHAM and HadRM3Q. HIRHAM5 did not confirm this possible tendency. Note that HIRHAM5 simulated much larger areas characterized by seasonality of both T and P than obtained by other models and ensemble averaging.

4.4 Comparison of the twentieth and twenty-first centuries

It is also possible to compare the climate at the beginning of the twentieth century and at the end of the twenty-first century. This can be easily performed by comparing Figures 6 and 10 for annual and 6 and 11 for seasonal characteristics, respectively. We will focus on the results obtained by ensemble averaging. The main characteristics are as follows:

1) In the northern zone, the warming of the climate is unequivocal. The thermal type “cold” is replaced by the thermal type “cool” excluding the Norwegian Alps and some small areas of Scotland. The warming obtained by HIRHAM and HIRHAM5 is somewhat less with respect to the warming obtained by ensemble averaging. These results are also confirmed by Rubel and Kottek (2010). On their maps, this warming is realized by ET → Dfc, Dfc → Dfb and Dfc → Cfb climate type transformations. The main seasonal characteristics did not change. The greatest changes can be observed in the Baltics. Extensive areas characterized by seasonality of both P and T transformed into areas characterized by seasonality of T. This tendency is only not confirmed by HIRHAM5.

2) In the middle zone, both the warming and drying of the climate can be observed. The thermal type “cold” transformed into thermal type “cool” over extensive areas in uplands and the North European Plain. Note that the thermal type transformation “cool” → “warm” can also be observed on the Danubian Plain. To the south, for instance, in the Pannonian Basin, the Danubian Plain, and south Ukraine the moisture type “dry” transformed into the moisture type “semiarid”. The same transformations, but in terms of the Köppen-Geiger climate classification system (Dfb → Cfb, Cfb → Csa and Cfb → BSk transformations), are also shown by Rubel and Kottek (2010). Concerning seasonal characteristics, it can be observed that extensive areas, on the North European Plain for instance, characterized by seasonality of T with high variability transformed into areas characterized by seasonality of T with extreme variability. As in the former case, HIRHAM5 did not confirm this change.

3) In the southern zone, the tendency of warming and drying of the climate seems to be more expressed than in the middle zone. The climate types “warm, dry” or “warm, semiarid” exist over extensive areas, for instance, in south Spain, Sicily in addition to the climate types “cool, dry” and “cool, semiarid”. This is also visible in terms of the Köppen-Geiger climate classification (Rubel and Kottek, 2010) via Csb → Csa or Csb → BSk and Csa → BSk climate type transformations. The greatest seasonal type changes can be found in Spain and Sicily. The seasonality of both P and T transformed into the seasonality of T. In most of the cases, the magnitude of the variability did not change. The specific results of HIRHAM5 can, once again, be observed.

4.5 Climates and their geographical controls

4.5.1 General remarks

Already Köppen (1936) showed that the main geographical controls on climate are latitude, the land/sea surface contrast and altitude. The land/sea surface contrast depends upon both longitude and the existence of land-locked water bodies. The land/sea surface contrast can be expressed either by the notion of oceanicity (e.g. Metzger et al., 2005) or by the notion of continentality (e.g. Beniston, 2005). High oceanicity means higher (P^{max} – P^{min}) and lower (PET^{max} – PET^{min}) values and, vice versa, high continentality means lower (P^{max} – P^{min}) or higher (PET^{max} – PET^{min}) values. In the great majority of studies, the measure of oceanicity or continentality is expressed simply via (T^{max} – T^{min}) values (e.g. Pesaresi et al., 2014). According to Köppen (1936) the most important factor is latitude. This is surely so on the global scale. At smaller scales the relevance of other factors increases. Showing the governing effect of one or more geographical controls on climate is not an easy task since the factors act together and the climate types are not directly sensitive to many generated phenomena as, for instance, wind, air pressure, cyclone activity, etc. In spite of these difficulties, we will briefly summarize the main findings concerning the main relationships between Feddema’s climate types and the main geographical controls in the European region.

4.5.2 Feddema’s climate types and geographical controls

The effects of the main geographical controls (latitude, longitude, relief and extensive land-locked water bodies) on the climate in Europe can be equally observed in the twentieth and twenty-first centuries. A short summary referring to the twentieth century will be presented separately for the northern (72°N–55°N), middle (55°N–42°N) and southern (42°N–35°N) zones.

Northern zone: The four constraints mentioned act jointly influencing both the annual and seasonal characteristics. The joint effects are clearly visible in the Scandinavian Peninsula but also in smaller areas such as Scotland, Denmark and the Baltic States. Nevertheless, some differencies between the effects induced by different constraints can be noticed. The joint impact of latitude and the Baltic Sea on the Scandinavian Peninsula’s climate is clearly visible via the “dry” → ”wet” moisture type transformation and via “extreme variability of T” → “high variability of T” → “high variability of P and T” seasonal types transformations moving southwards. It is noticeable that the most frequent cyclone formation location in the Baltic Sea region roughly agrees with the location of the seasonal type “high variability of P and T” (Sepp, 2009; Fig. 5). This territory is located in Sweden close to the Norwegian border around latitude

60°N. The joint impact of the Atlantic Ocean, longitude and relief seems to be somewhat stronger than the joint impact of latitude and the Baltic Sea. It is manifested via “saturated” → “wet” → “moist”→ “dry” moisture type transformations and via “high variability of P” → “high or extreme variability of P and T” → “high variability of T” → “extreme variability of T” seasonal types transformations moving eastwards. Note that Feddema’s (2005) method is highly sensitive to the seasonal changes of heat and water availability. This is clearly visible in smaller areas such as Scotland and Denmark. In upland areas the “cold” thermal type and the “medium or high variability of P and T” seasonal type prevails. This is in accordance with Beniston’s (2005) considerations.

Middle zone: In this zone the governing constraints are longitude, latitude and relief. The land/sea contrast effect (e.g. Metzger at al., 2005) is indirectly included in the longitudinal effect. The latitudinal effect can be observed via “cold” → “cool” thermal type as well as via “wet” → “moist” → “dry” → “semiarid” moisture type transformation moving soutwards from the Baltic Sea to the Black Sea. The longitudinal effect in combination with the effect of the Atlantic Ocean and relief can be observed in Wales and England, in the East European Plain, in France and in the northern part of the Iberian Peninsula. The effect is manifested via “wet” → “moist” → “dry” → “semiarid” moisture type and via “high variability of P” → “medium or high variability of P and T” → “high variability of T” → “extreme variability of T” seasonal type transformations moving eastwards. Note how this effect is pronounced in both the annual and seasonal characteristics in the Iberian Peninsula. As it is mentioned, in upland areas the “cold, wet” climate with medium, high or extreme variability of P and T is the prevailing climate type. In these sub-regions the latitudinal and longitudinal effects are subsidary.

Southern zone: All constraints are active, but the effect of longitude compared to the effect of latitude, of course, in combination with the effects of relief and the Mediterranean Sea, is unequivocally more visible. This is understandable because of the smaller latitudinal zone (42°N–35°N) width and because of the position of the Mediterranean Sea. The latitudinal impact is visible via “moist” → “dry” → “semiarid” moisture type, and via “cool” → “warm” thermal type transformations around longitudinal line 15°E in areas of Southern Italy, Sicily and Malta. “Wet” → “moist” → “dry” → “semiarid” moisture type transformations can also be found in Portugal, but this is produced by the interplay between the Atlantic Ocean, relief and the latitudinal changes. The longitudinal effect in combination with the effect of the Atlantic Ocean and relief is recognizable in Iberian Peninsula, with less contribution of the Atlantic Ocean in central Italy, via “moist” → “dry” → “semiarid” moisture type transformations moving eastwards. The effect of uplands in combination with the Atlantic Ocean’s or Mediterranean Sea’s impact is pronounced. It is clearly visible in the Iberian Peninsula, in Corsica, central Italy as well as in the southwestern part of the Balkan Peninsula. In these areas, the climate is alpine: “cold, wet” climate with medium or high variability of P and T together. The “medium or high variability of P and T” seasonal type is produced by the combined effects of the Atlantic Ocean or the Mediterranean Sea and the uplands. Such a seasonal type is characteristic in Portugal, Southern Spain, Corsica, Sardinia, Sicily, along the Mediterranean coast of Italy, in Albania, western Greece and Crete.

Lastly, the relationships in the twenty-first century differ somewhat from the relationships in the twentieth century. The effects mentioned can be more easily observed in the twenty-first century than in the twentieth (Figure 8b, 8d, or Figure 10b, 10d). These relationships can be seen for all four types of simulation results. Concerning seasonal characteristics, it is striking that the results obtained by HIRHAM5 differ significantly to the results obtained by ensemble averaging, HIRHAM and HadRM3Q.

5 Concluding remarks

The European region’s climate in the twentieth and twenty-first centuries is analysed according to the Feddema method (2005). Observed data for the twentieth century are taken from the CRU TS 1.2 dataset. The projected data for the twenty-first century are obtained using simulation results of nine RCM runs in the scope of the ENSEMBLE project. The precipitation and temperature data required were bias-corrected on the basis of the E-OBS data referring to the period 1961–1990. The climate is analysed in terms of annual and seasonal characteristics focusing on the analysis of relationships between climatic features and main the geographical controls.

The results unequivocally show that Feddema’s (2005) method effectively reproduces the expected effects of the main geographical controls on the formation of the climatic characteristics of the European region. The four constraints (latitude, longitude, relief and extensive land-locked water bodies) act jointly but with different strengths, which joint action highly depends on geographical features. The effect of their interplay on the formation of Feddema’s climate types (annual and seasonal characteristics together) can be registered in all three subjectively introduced European zones: the northern zone (72°N–55°N), the middle zone (55°N–42°N) and the southern zone (42°N–35°N). In the northern zone, the effect of the interplay between the Atlantic Ocean, relief and longitude seems to be larger than the effect of the interplay between latitude and the Baltic Sea on the changes of Feddema’s (2005) climate types. In the middle zone, the latitudinal effect is unequivocally less than the Atlantic Ocean-relief-longitude interplay effect on the changes of Feddema’s climate types. In the southern zone, two regions can be set out: the Iberian Peninsula and the southwestern part of the Balkan Peninsula. In the Iberian Peninsula, the climate type changes can be unequivocally related to the Atlantic Ocean-Mediterranean Sea-relief-longitude interplay effects. The climate in the southwestern Balkans (Pindus mountain range) is determined mainly by the Mediterranean Sea-relief interplay effect. The strongest effects are in the upland coastal regions of the Atlantic Ocean, that is, in the Norwegian Alps, the Scottish Highlands, the Cambrian Mountains, and in the Galician Massif Mountains. In these regions, except the Cambrian Mountains, the seasonality of P changes through the seasonality of both P and T into the seasonality of T. This behaviour is registered by all model simulations in the twenty-first century. The uplands in Europe determine climate on the local scale. Of course, the relief’s impact is stronger when the upland is in interplay with an extensive land-locked water body. The local scale impact can be remarkably observed for both the annual and seasonal characteristics going, for instance, from Burgundy (east-central France) through the European Alps, the Pannonian Basin and the Carpathian Mountains to Moldova and Ukraine’s lowland in the latitude zone 45°N–50°N. This is so for both centuries and all model simulations. The effect of land-locked water bodies (the Baltic Sea and the Mediterranean Sea) on the European climate is unequivocally recognisable via the generation of the “medium, high or extreme variability of P and T” seasonal type. This seasonal type is common not only on the coast of Atlantic Ocean but also on the coasts of the Mediterranean Sea and the Baltic Sea. During the twentieth century, the climate changed mostly in terms of its seasonal characteristics. In the twenty-first century, climate warming is foreseen to be the most typical climate change process.

Feddema’s method is strictly physically based and does not possess any biogeographic basis as, for instance, Köppen’s (1900, 1936) method, which intends to reproduce the area distribution of the major types of world vegetation. The main difference between them is in estimating the available heat. Feddema’s (2005) method, like Thornthwaite’s (1948), is PET-based. In Köppen’s (1900) method, vegetation’s heat availability is characterised via critical air temperature values. Köppen’s biogeographically-based approach is simpler, but cruder with respect to Feddema’s (2005) strictly physically-based method, which remarkably reproduces the heterogeneity of the European climate.

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