Climate and Climate Change in the Larger Carpathian Region in the 20th and 21st centuries based on Feddema

THESES OF THE PHD DISSERTATION

Written by:

Amanda Imola Szabó

Supervisors:

dr. habil. Ferenc Ács
associate professor
PhD

dr. Hajnalka Breuer
associate professor
PhD

Eötvös Loránd University
Institute of Geography and Earth Sciences
Department of Meteorology

Eötvös Loránd University
Doctoral School of Environmental Sciences
Head of School: Dr. habil. Tamás Turányi, professor

Environmental Geosciences Program
Head of Program: dr. habil. Zoltán Szalai, associate professor

Budapest, 2023

DOI: 10.15476/ELTE.2023.117

1. Introduction and the aims of this study

The climate of a region may affect the daily lives of its inhabitants, from the availability of food to the clothing they need, or the leisurely activities they undertake. It is therefore important that information on climate characteristics and their expected changes is available to all, but this is a major science communication challenge for the climate science field. Climate classifications, such as Feddema's method (FEDDEMA, 2005), can be used to describe the complex interactions of the climate system in a simplified way. Parameters summarising these interactions can be used either for educational purposes or as input data for further research. The advantage of using climate classifications is that the climate and the processes of climate change can easily be described with a relatively low data and computational requirements.

The Feddema method is a descriptive climate classification method. These methods can be used to visualise and quantify the current climate (BELDA ET AL., 2015; RUBEL ET AL., 2017) and they can be also useful in other disciplines. For example, accurate knowledge of the Earth's climatic heterogeneity is necessary to study the distribution of vegetation (KARTIKA ET AL., 2022) and can be used to validate climate model results (LÜ ET AL., 2020). In my dissertation, I aimed

- to demonstrate that the Feddema method can provide more information about the climate than other widely used descriptive classifications by assigning more clearly interpretable seasonal characteristics to the climate of an area;
- to show that Feddema's method is more suitable for the analysis of the climate in the Carpathian region than other descriptive methods used for comparison according to the criteria of ESSENWANGER (2001);
- to show the types of climate change expected in the Larger Carpathian Region and the expected future distribution of climate and seasonality types using the Feddema method,
- to show that, in addition to the discrete category changes, the Feddema method is suitable for determining the direction and magnitude of the expected continuous shifts in climate and seasonality indices;
- to show that the so-called Feddema-continuous approach can provide additional information on climate change in a region compared to the Feddema-discrete approach.

2. Data and method

In my dissertation, I studied climate and climate change processes in terms of heat and water availability and seasonality using the Feddema method. I have chosen the Larger Carpathian Region as the region of interest. As a reference database, I used CarpatClim with a spatial resolution of 0.1° × 0.1° (SZALAI ET AL., 2013). To study climate change I used EURO-CORDEX climate simulations (JACOB ET AL., 2020) for 19 climate model pairs matched from 10-10 global and regional climate models. The climate simulations used are at EUR-44 and EUR-11 resolution and follow the RCP4.5 and RCP8.5 scenarios. I interpolated the data to a grid with the same spatial resolution and the simulations were corrected using the delta method (DÉQUÉ, 2007). I calculated the Feddema indices to apply the Feddema method, which are: heat and water availability; seasonality of temperature (T) and precipitation (P); and the magnitude of seasonal variability. Feddema expresses heat availability in terms of potential evapotranspiration (PET). Feddema defines PET using the Thornthwaite and Mather method, which is also used in the classification of THORNTHWAITE (1948). The heat availability categories shown in Table 1 occur during the period under study in the Larger Carpathian Region.

Table 1. FEDDEMA (2005) thermal regime categories found in the Larger Carpathian Region

Thermal regime categories	PET [mm year^{-1}]
Warm	900 < PET ≤ 1200
Cool	600 < PET ≤ 900
Cold	300 < PET ≤ 600

Table 2. FEDDEMA (2005) moisture regime categories found in the Larger Carpathian Region

Moisture regime categories	Annual I_m
Saturated	$0.66 < I_m \leq 1.00$
Wet	$0.33 < I_m \leq 0.66$
Moists	$0.00 < I_m \leq 0.33$
Dry	$- 0.33 < I_m \leq 0.00$
Semiarid	$- 0.66 < I_m \leq (-0.33)$

Water availability is determined according to the Willmott and Feddema moisture index I_m (FEDDEMA, 2005). If I_m is positive, the atmospheric water balance is also positive, indicating a water surplus (more precipitation falling than would evaporate based on the amount of radiation reaching the area). If I_m is negative then the water balance is also negative, indicating a water deficit, while I_m values around zero indicate a balance between water demand and available water supply. In the Larger Carpathians Region, the water availability categories shown in Table 2 occur during the period under study.

With the Feddema method, the seasonality of an area can be characterised on the basis of two indices. The A_s (seasonality attribution) index attributes seasonality to either intra-annual variation of T or P or a combination of both (Table 3). The value of A_s depends on the ratio of intra-annual PET and P variation. The seasonality index I_s is defined as the range of intra-annual variation in I_m (Table 4).

Table 3. Seasonality attribution category (FEDDEMA, 2005)

Seasonality attribution categories	A_s
Temperature	$A_s < -0.5$
Temperature and precipitation	$-0.5 < A_s \leq 0.5$
Precipitation	$0.5 < A_s$

Table 4. Seasonality magnitude category (FEDDEMA, 2005)

Seasonality magnitude category	I_s (I_{mmax} - I_{mmin})
Low	$0.0 < I_s \leq 0.5$
Medium	$0.5 < I_s \leq 1.0$
High	$1.0 < I_s \leq 1.5$
Extreme	$1.5 < I_s \leq 2.0$

One can identify different climate and seasonality types by categorising Feddema indices, which together result in a climate pair. I refer to this as the Feddema-discrete approach. The climate and climate change of an area can be studied by foregoing discrete categories. This is the Feddema-continuous approach, where climate change can be estimated through the values of indices expressing annual and seasonal characteristics and their continuous changes.

3. Thesis points

New insights from applying the method

1. As a continuation of my MSc thesis, it is a novel application of Feddema's method to the CarpatClim database.
2. The main strength of the Feddema method is that it provides a clearer way of assigning seasonal characteristics to the climate of an area in contrast to the widely used KÖPPEN (1936) and the Worldwide Bioclimatic Classification System (RIVAS-MARTÍNEZ ET AL., 2011), both of which I used to develop a comparative analysis in my dissertation and the latter of which was first to be applied to the region in my dissertation.
3. Feddema's method can be applied with the original discrete approach (FEDDEMA, 2005) and continuous approach, foregoing the categories. In this dissertation, my application of the Feddema-continuous approach to seasonality indices was a novelty (this approach was previously used only by ELGUINDI ET AL., 2014 for a continuous analysis of changes in heat

and water availability) and it was the first case during which the approach was applied to the Larger Carpathian Region (SZABÓ ET AL., 2022).

New results on describing climate change

4. In this research project, I first investigated climate change in the Larger Carpathian Region using the Feddema method based on EURO-CORDEX simulations following the RCP4.5 and RCP8.5 scenarios.

5. I used the Feddema method to show the expected changes in heat and water availability and climate type distribution in the region by the end of the 21st century (2069–2098) based on EURO-CORDEX simulations in comparison with the reference period (1971–2000). Among the simulations following the RCP4.5 scenario (considering both spatial resolutions), the largest increase in heat availability is expected for the RCA4-HadGEM2-ES (regional and global) model pair (EUR-11) and the RACMO-HadGEM2-ES model pair (EUR-44). In both case, the category with the highest heat availability occurs in the period is the 'cool' in more than 90% of the region, compared to 70% during the reference period. The lowest increases in heat availability are estimated by HIRHAM5-EC-EARTH and RCA4-MPI-ESM-LRA. For RCP8.5, the largest increases in heat availability are expected by RCA4-CM5A-MR and RCA4-HadGEM2-ES (EUR-11) and RACMO-HadGEM2-ES and RCA4-CanESM2 (EUR-44). For RCP8.5, RCA4-HadGEM2-ES (EUR-11) and RCA4-CanESM2 (EUR-44) project the greatest increase in water availability.

6. I used Feddema's method to show changes in seasonality characteristics and seasonality-type expected in the region by the end of the 21st century. Models estimating the expected future distribution of seasonality types for RCP4.5 include ALADIN-CM5, RCA-4-HadGEM2-ES (EUR-11) with almost 60% area coverage and COSMO-HadGEM2-ES (EUR-44) with nearly 90% coverage; these are the largest estimated increases in spatial coverage of areas with 'extreme' seasonality. The highest area of 'extreme T' seasonality is projected by RCA4-HadGEM2-ES and COSMO-HadGEM2 (increasing from 35% in the reference period to 40% and more than 70% by the end of the 21st century). The model pair with the highest proportion of high 'T' seasonality estimated for the area is WRF-CM5A-MR following scenario RCP4.5 for both resolutions (around 40% coverage). For this model pair, the only increase in the 'medium' level of seasonality associated with 'T and P' is observed. For RCP8.5, the most significant increases in 'extreme T' seasonality are shown by the RCA4-HadGEM2-ES, RCA4-MPI-ESM-LR (EUR-11) and RCA4-CanESM2

(EUR-44) model pairs, with increases about 30%, 40% and 60%, respectively, compared to the reference period.

7. Using Feddema's method, I have shown that new climate types are expected to emerge in the region by the end of the 21st century that did not occur during the reference period. According to the RCP4.5 and RCP8.5 scenarios, the emergence of areas with ‘semiarid’ water availability and areas with warm heat availability are expected by the end of the century according to the RCP8.5 scenario. For both the ‘warm-moist’ and ‘warm-dry’ climate types, a combined median area coverage of 0.3% is expected based on the EUR-11 resolution simulations following RCP4.5. For the ‘warm-dry’ climate type, the range of uncertainty for the potential area coverage values obtained from the different model pairs following RCP8.5 is 14% (i.e. the difference between the lower and upper extremes). Estimates obtained for the RCP8.5 scenario at EUR-44 resolution show that RCA4-CanESM2 gives the highest expected areal coverage for the ‘warm-semiarid’ and RACMO-HadGEM2-ES for the ‘warm-dry’ climate types. The range of uncertainty in the expected coverage for these climate types according to the projections is 17.8% (former) and 17% (latter). For the ‘cool-semiarid’ climate type, the percentage of expected areal coverage estimated from different model pairs following RCP4.5 covers an uncertainty range of 1.4% (EUR-11) to 15% (EUR-44), while the uncertainty range for RCP8.5 has a much larger range of expected area coverage (12.6% and 15.3%) based on different model pairs. COSMO-HadGEM2-ES estimates the highest area coverage for the ‘cool-dry’ category for RCP4.5 and RCA4-EC-EARTH for RCP8.5.

8. Feddema can be used to show the expected changes in climate and seasonality types in the region and the spatial distribution of these processes. The results presented in this and the following thesis points are based on the RCA4-EC-EARTH model pair. According to the RCP4.5 scenario, the main driver of change is warming, leading to a change of category mainly in the mountain regions. In the RCP8.5 scenario, warming is expected in large parts of the mountain regions, while drying is mainly observed in lowlands, hills and low-altitude mountain regions. For seasonality, the most typical category change is from 'T and P' seasonality to 'T' seasonality, while the degree of seasonality remains unchanged or increases in both scenarios with RCP8.5 in a significant part of the mountain regions.

9. Using the Feddema method, I have shown that changes in climatic heterogeneity are expected at different altitudinal regions. For climate types, the increase in heterogeneity is expected to be strongest in the lowlands, where the number of climate types is expected to more than double by the end of the century under the RCP8.5 scenario. Increase in homogeneity is likely in hills and low-altitude mountain regions. In terms of seasonality types, the RCP4.5 scenario does not result in a change in the number of seasonality types in most altitude categories, with a decrease expected only in the mid- and high-altitude mountain regions. The RCP8.5 scenario does not result in a change in the number of seasonality types in the low-altitude mountain and mid- and high-altitude mountain regions, with a decrease expected in other categories.

10. The Feddema-continuous approach can provide more information on climate change in a region than the Feddema-discrete approach. With Feddema-continuous, it is possible to show which regions are those where even a small change leads to a category change and where a large change occurs within the same category. The largest shifts in the values of the Feddema indices for heat and water availability are observed for areas in the 'cool-dry' climate type. For the PET, which expresses heat and water availability, following the RCP8.5 scenario is expected to result in an increase of more than 100 mm, but does not lead to a change of category. For the newly emerging climate types, it can be seen that the PET values and moisture index (I_m) values for the 'warm-semiarid', 'warm-dry' and 'cool-semiarid' climate types are close to the category boundaries. Furthermore, the Feddema-continuous allows to show that climate types with positive annual average I_m values in the reference period are expected to become wetter, while those with negative I_m values are expected to dry out further.

11. The Feddema continuous can also be used to examine changes in the seasonality attribution index (A_s) and the seasonality magnitude index (I_s). My results show that there is no as major shift in the seasonality characteristics within the category boundaries as in case of heat and water availability. The shifts in the Feddema indices can also be examined for altitudinal regions. The largest difference in the shift in I_s and A_s values between the results obtained with the RCP4.5 and RCP8.5 scenarios is expected in the mid- and high-altitude mountain regions (> 1000 m above sea level). The shifts in I_s and A_s indices are largest in areas with 'high seasonality of T and P', where A_s shows decreasing values – i.e. temperature variability is increasingly dominating seasonality – with increasing I_s values, implying increasing seasonal variability.

12. The Feddema-continuous approach can also be used to show how much and in what direction an area classified as a particular climate type changes over the reference period, based on each Feddema indices. In the case of areas categorised as 'cool-dry' in the reference period, it can be shown that, despite an increase of more than 170 mm in PET, these areas are not expected to be placed in a new heat availability category. The areas categorised as 'cool-wet' in the reference period are expected to move to the warmer 'cool' and drier 'moist' type by the end of the century, based on the average water availability characteristics of the area, even with a PET increase of ≈150 mm.

13. The Feddema-continuous approach can also be used to show to what extent the rate and direction an area, classified into a given seasonality type, changes over the reference period, based on the Feddema indices. Areas characterised by 'medium seasonality of T and P' over the reference period in the RCP8.5 scenario show a larger change until mid-21st-century only in the seasonally variable element. The seasonality of 'T' will become more pronounced in the first half of the 21st century, but a change in the intensity of seasonality is expected for the second half of the 21st century. Increasing seasonality is expected to lead to a shift from 'medium' to 'high' seasonality. A similar trend can be observed in areas with 'high seasonality of T and P'.

14. The Feddema-continuous approach can be used to give the direction and magnitude of change of a given grid point, classified into a given climate and seasonality type during the reference period, over the course of the 21st century. For example, for each grid point of the 'cool-wet' climate type, which covers 0.71% of the total area, the heat availability is similar over the reference period, the main difference being the extent of water availability. The standard deviation of PET and I_m values for each grid point are expected to increase in the future compared to the reference period.

15. The Feddema-continuous approach can be used to give the direction and magnitude of change in each Feddema index for grid points expected to be in a 'new' climate category in the region by the end of the century relative to the reference period, leading to the emergence of the new category. For example, all grid points except one have similar PET and I_m values for the 'warm-dry' climate type occurring in 0.34% of the total area at the end of the 21st century, all grid points except one have similar PET and I_m values, whereas in the reference period these grid points cover a wider range of water availability in the 'dry' category compared to the reference period although with almost identical heat availability.

4. Conclusion

Feddema's method provides more information on the climate of the Larger Carpathian Region than other descriptive methods used in my research. Moreover, the Feddema-continuous approach provides additional information to the Feddema-discrete approach. My results suggest the emergence of new, drier and warmer climate types in the Larger Carpathian Region, which did not occur in the reference period. The main processes are expected to be an increase in heat availability in mid- and high- and low-altitude mountain regions and an increase in heat availability and a decrease in water availability in hills and lowlands. Seasonality is projected to be increasingly attributed to intra-annual temperature variability and the greatest increase in the magnitude of seasonality is expected in the mid- and high mountain regions.

5. References

Belda, M., Holtanová, E., Halenka, T., Kalvová, J., Hlávka, Z. (2015): Evaluation of CMIP5 present climate simulations using the Köppen-Trewartha climate classification. *Climate Research 64*, 201–212. https://doi.org/10.3354/cr01316

Déqué, M. (2007): Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: Model results and statistical correction according to observed values. *Global and Planetary Change*, 57(1–2), 16–26. https://doi.org/10.1016/j.gloplacha.2006.11.030

Elguindi, N., Grundstein, A., Bernarder, S., Turuncoglu, U., Feddema, J. (2014): Assessment of CMIP5 global model simulations and climate change projections for the 21stcentury usinga modified Thornthwaite climate classification. *Climatic Change*, 122, 523–538. https://doi.org/10.1007/s10584-013-1020-0.

Essenwanger, O. M. (2001): Classification of climates, world survey of climatology 1C. General climatology. *Elsevier*, Amsterdam, 126.

Feddema, J.J. (2005): A revised Thorntwaite-type global climate classification. *Physical Geography*, 26, 442–466. https://doi.org/10.2747/0272-3646.26.6.442

Jacob, D., co-authors. (2020): Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community. *Regional Environmental Change 20*, 51. https://doi.org/10.1007/s10113-020-01606-9

Kartika, T. Kushardono, D., Setiawan, Y., Ibrahim, A., Kustiyo, Sutanto, A. Noviar, H., Khomarudin, M. R., Carolita, I., Tosiani, A., Ubay, M. S. N., Taufik, M., Al-Khudri, A. (2022): Identification method of vegetation cover changes derived from mosaic Landsat-8 Data: Case Study Sumatera, Kalimantan, and Java Island. *IOP Conference Series: Earth and Environmental Science*, 1109 010260. https://doi.org/10.1088/1755-1315/1109/1/012060

Köppen, W. (1936): Das geographische system der klimata. In: W. Köppen, R. Geiger and C. Teil (Eds.) Handbuch der Klimatologie. Berlin: Gebrüder Borntraeger. 44 p.

Lü, Y., Jiang, T., Wang, Y., Su, B., Huang, J., Tao, H. (2020): Simulation and projection of climate change using CMIP6 Muti-models in the Belt and Road region. *Sciences in Cold and Arid Regions*, 12, 389–403. https://doi.org/10.3724/SP.J.1226. 2020.00389

Rivas-Martínez, S., Rivas-Saenz, S., Penas, A. (2011): Worldwide Bioclimatic Classification System. *Global Geobotany,1*, 1–634. http://www.globalbioclimatics.org/book/bioc/global_bioclimatics_0.htm

Rubel, F., Brugger, K., Haslinger, K., Auer, I. (2017): The climate of the European Alps: shift of very high Köppen-Geiger climate zones 1800–2100. *Meteorologische Zeitschrift,* 26(2), 115– 125. https://doi.org/10.1127/metz/2016/0816

Szabó, A. I., Breuer, H., Ács, F., Belda M., Feddema, J. (2022): Projected changes in Feddema climate characteristics in the Larger Carpathian Region by the end of the 21st century. *International Journal of Climatology,* 42, 11, p. 5732–5747. https://doi.org/10.1002/joc.7558

Szalai, S., Auer, I., Hiebl, J., Milkovich, J., Radim, T. Stepanek, P., Zahradnicek, P., Bihari, Z., Lakatos, M., Szentimrey, T., Limanowka, D., Kilar, P., Cheval, S., Deak, Gy., Mihic, D., Antolovic, I., Mihajlovic, V., Nejedlik, P., Stastny, P., Mikulova, K., Nabyvanets, I., Skyryk, O., Krakovskaya, S., Vogt, J., Antofie, T., Spinoni, J. (2013): Climate of the Greater Carpathian Region. Final Technical Report. http://www.carpatclim-eu.org/pages/download/

Thornthwaite, C.W. (1948): An approach toward a rational classification of climate. *Geographical Review,* 38, 5–94. https://doi.org/10.2307/210739

6. Publications on the subject of the dissertation

Papers published in peer-reviewed scientific journals

Szabó, A. I., Ács, F., Breuer, H., 2021: Larger Carpathian Region climate according to Köppen, Feddema and the Worldwide Bioclimatic Classification System methods, International Journal of Climatology, 41(S1), E2482–E2496. https://doi.org/10.1002/joc.6859

Szabó, A. I., Ács, F., Breuer, H., Belda, M., Feddema, J. 2022: Projected changes in Feddema climate characteristics in the Larger Carpathian Region by the end of the 21st century, International Journal of Climatology, 42, 11, p. 5732–5747. https://doi.org/10.1002/joc.7558

Full papers in conference proceedings

Szabó, A. I., Ács, F., Breuer, H., 2018: Éghajlat-osztályozási módszerek összehasonlító elemzése a Kárpát-medence térségében CarpatClim adatok alapján. XIV. Kárpát-medencei Környezettudományi Konferencia, Gödöllő, Hungary, 5 –7 April, 2018.

Presentations and poster showcased at scientific conferences

Szabó, A. I., Ács, F., Breuer, H., 2017: Climate Analysis of the Carpathian Basin on the Basis of Using Climate Classification Schemes. 7. Österreichischer MeteorologInnentag, Graz, Austria, 9–10 November 2017. https://wegcwww.uni-graz.at/meteotag2017/

Szabó, A. I., Belda, M., Breuer, H., Ács, F., 2019: On the role of model output statistical postprocessing methods in inverstigating projected changes of climate zones, European Geosciences Union General Assembly 2019, Vienn a,Austria, 7–12 April 2019. https://meetingorganizer.copernicus.org/EGU2019/EGU2019-954.pdf

Szabó, A. I., Breuer, H., Ács, F., 2021: Ács, F., Első Országos Interdiszciplináris Éghajlatváltozási Tudományos Konferencia, Budapest, Hungary, 12– 15 April 2021. https://hupcc.hu/konferencia/program/

Szabó, A. I., Breuer, H., Belda, M., Ács, F., 2021: Az évi és szezonális hő- és vízellátottság várható változásai a Kárpát-régióban a 21. század végére Feddema alapján. In: A Magyar Tudomány Ünnepe MTA programsorozat keretében megvalósult III. Interdiszciplináris konferencia a kárpát-medencei magyarság társadalmi és gazdasági helyzetéről. Organiser: Nemzetstratégiai Kutatóintézet. Budapest, 25–26 November 2021. https://tti.abtk.hu/images/Maps/III_Interdiszciplinris_Konferencia_Programfzet_NSKI.pdf

Szabó, A. I., Breuer, H., Belda, M., Ács, F., 2023: Studying the process of climate change using the continuous form of the Feddema climate classification, European Geosciences Union General Assembly 2023, Bécs, Ausztria, 23–28 April 2023.