On twenty-first century climate classification: Regional and continental scale analyses using Feddema's method

Ferenc Ács[1]

[1]Eötvös Loránd University, Institute of Geography and Earth Sciences, Department of Meteorology, Pázmány Péter sétány 1/A., 1117 Budapest, Hungary

Preface

In this book, I am attempting to provide a small contribution to awareness of the Earth by analyzing the European region's climate and the ongoing climate change process. The Earth's climate is changing increasingly in the twenty-first century, and this gives special topicality to the chosen theme. The subject is approached as simply as possible from the viewpoint of generic climate classification methods. Among these, I chose the revised Thornthwaite-type Feddema's (2005) method since it seems to be an effective tool not only for continental but for regional scale analyses also. However, before this, I give an extensive discussion of the method's most important features. The method is applied to both the twentieth and twenty-first centuries treating not only climate type distributions but also the processes of climate change. Regional scale analyses are performed for the Central European region focusing on the role of terrain effects.

My first contact with generic methods was in the middle of the nineteen-eighties in scope of the course "Izabrana poglavlja iz biometeorologije" (in English: Chosen chapters in biometeorolgogy) at the Faculty of Physics and Meteorology of the University of Belgrade. This contact has continued since I taught subjects in Agrometeorology and Environmental Biophysics over the years at the Faculty of Agriculture of the University of Novi Sad. In these past times, I viewed Köppen's and Thornthwaite's work merely as "interesting" things, I did not see the higher level that they were striving for: to understand the functioning of the Earth. This is especially true for Köppen, who also worked in paleoclimatology (Köppen and Wegener, 2015) with his son-in-law, Alfred Wegener, who envisioned the continental drift hypothesis (Wegener, 1929). Later on, from the second decade of this century, I became more active in the field of generic methods at the University Eötvös Loránd in Budapest. We focused more intensively on Feddema's method when we saw that the method was suitable for classifying climate on the mesoscale. The first attempts were related to the Pannonian Basin (Ács et al., 2015). Already at the beginning, I had great help from my students, who, for instance, carried out all the simulations and produced almost all the figures while writing their bachelor and post-graduate theses. I have to underline that in most cases this fruitful collaboration continued after they finished their studies. Special thanks go to Hajnalka Breuer, Nóra Skarbit, Dominika Takács, Amanda Imola Szabó and Tamás Mona. I also wish to express my thanks to those, such as Kálmán Rajkai and Michael Hantel, who saw my vision, which was realized via endless discussions in the interdisciplinary field of soil-vegetation-atmosphere interactions.

Budapest, May 25, 2017 Ferenc Ács

1 Introduction

1.1 Climate and climate classification

The climate is the ensemble of all physical, chemical and biological features of the climate system. This is a condensed term for expressing all the physical, chemical and biological characteristics of the climate system. Climate system possesses a number of various climate system components such as the atmosphere, hydrosphere, cryosphere, biosphere, pedosphere, and lithosphere. The climate system comprises the Earth or its larger subunits, such as the continents, or geographical regions. Its components interact with each other (Hantel and Haimberger, 2016) generating energy, as well as mass and momentum exchange processes across their boundary surfaces. Due to this, the climate system components are in a state of permanent change, where the spatiotemporal scales of the processes range from centimeters to thousands of kilometers and from seconds to millennia. All these changes are mainly driven by the energy of solar radiation.

The formation of the climate can be pictured in an easier way than the above by focusing mostly only on the atmosphere. The atmosphere is that climate system component where the changes are the fastest. The Earth's climate is determined by external astronomical forcing (conditions at the top of the atmosphere), plate tectonics (conditions at the bottom of the atmosphere), internal atmospheric processes and by the existence of the biosphere. Each of these factors varies over time, and, of course, how they change over time also differs. Among these external astronomical forcing is extremely important. The solar climate, that is, the spatiotemporal distribution of incoming solar radiation at the top of the atmosphere is determined by the Earth's obliquity and revolution around sun. Its distribution is strictly zonal and possesses strong seasonality (in the summer and winter periods Earth is tilted towards and away from the Sun, respectively). This strict zonal distribution is illustrated in Fig. 1a where the ISCCP[1] annual mean irradiance values are presented for the period 1991-1995.

Fig. 1a Area distribution of annual mean downward solar radiation at the top of the atmosphere for the period 1991-1995 (source: ISCCP-FD Radflux, taken from Hantel et al. (2005))

[1] ISCCP – The International Satellite Cloud Climatology Project is carried out in the scope of the World Climate Research Programme (WCRP) investigating the global distribution of clouds, their features and spatiotemporal variations. It was conducted in the period 1983-2010. More details can be found e.g. in the works of Rossow and Schiffer (1991, 1999) and Hahn et al. (2001).

Strong seasonality can be easily perceived by comparing the area distribution of air temperature in the summer and winter months periods (Figs. 1b and 1c) using CRU05[2] data products. Note that a tendency towards zonal distribution can be seen and is especially valid, for instance, above North America in the winter months, or over Russia in the summer months. Of course, this is rooted in the zonal distribution of incoming solar radiation at the top of the atmosphere.

Fig. 1b Area distribution of summer (June, July and August) mean air temperature over the continents for the period 1991-1995 (source: CRU05, taken from Hantel et al. (2005))

Fig. 1c Area distribution of winter (December, January and February) mean air temperature over the continents for the period 1991-1995 (source: CRU05, taken from Hantel et al. (2005))

Plate movement generating continental drift creates mountain ranges where the terrain effects act as strong climate-modifying factor. This is illustrated in Fig 2a, where not only the weather effects (convective clouds and their hourly lifetime) but also the changes in land cover type as a function of altitude can be seen (vegetation types and rocks, the magnitude of the speed of the shift is a few meters per year on average (e.g. Rubel et al., 2016)).

Figs. 2 a) and b) A natural and a cultivated upland area with convection raised clouds (source: created by the author)

Internal atmospheric processes contribute significantly to weather variability influencing, for instance, dynamic instability mechanisms. This can be quite well illustrated by showing the Earth's precipitation distribution. This is depicted using the GPCC[3] data products for the period 1991-1995 and is presented in Fig. 3. At first glance, it seems that wet and dry areas have a rather uneven distribution for which it is difficult to create a rule.

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[2] CRU05 – Climatic Research Unit, version 5 data. The data were created by the Climatic Research Unit at the University of East Anglia over the continental areas of the Earth without Antarctica for the period 1901-1998. The description of the data set can be found in the work of New et al. (2000).

[3] GPCC – Global Precipitation Climatology Center. The data were created by the Global Precipitation Climatology Center of the German Weather Service over land areas for the period 1951-2004. More information concerning the data set can be found in work of Rudolf et al. (2003) available at http://gpcc.dwd.de.

Fig. 3 Area distribution of annual mean land precipitation for the period 1991-1995 (source: GPPC full data product, taken from Hantel et al. (2005))

The biosphere with its extremely large surface/mass ratio is also an important climate-modifying factor. Photosynthesis basically determined the evolution of the Earth's atmosphere. In the deep past of the geological time scale the Earth's atmosphere was reductive, but has been oxidative already for eons because of the coupled evolution of life and atmospheric oxygen (Lenton, 2003). The biosphere also plays a crucial role in the exchange of trace-gases, which are, in the majority of the cases, greenhouse gases. Since the appearance of mankind, the biosphere obtained a new "player" often acting as an external disturbance. This is illustrated in Fig. 2b, where we can see drastic land-surface type conversion made by humans in a mountainous area. Figure 2a shows a natural environment, while as mentioned, Figure 2b presents a non-natural, manmade environment. In the natural environment aerobic, while in the non-natural environment anaerobic conditions prevail. Consequently, above dry areas carbon-dioxide (CO_2), while above water-covered areas methane (CH_4) is the main exchanging gas (Li, 2007) at the land-surface/atmosphere interface. Otherwise, both gases are greenhouse gases, but methane is the strongest. In Fig. 2b, the flooded areas are paddy fields, the crop which is determinant in Far East civilizations[4].

Among the factors mentioned, the zonal distribution of incoming solar radiation at the top of the atmosphere is an especially important factor since it is a very strong signal. This is visible in the distribution of the terrestrial biomes[5], especially in the northern hemisphere. Note that antique Greek culture was somehow aware of this fact (Sanderson, 1998), though there is no unequivocal proof that such an image of the worldly environment was based on strict scientific observation. One thing is sure: the Greeks knew that daylight period is more changeable to the north than to the south. What is more, Pytheas (330 BCE) was the first to suggest that the "length of longest day" and the climate[6] were related

[4] During human-rice interaction, rice developed a special tubing system called aerenchyma, which enabled it to grow well in flooded fields. Owing to aerenchyma submerged root tissues have an adequate supply of oxygen from the atmosphere irrespective of the anaerobic conditions which prevail in the muddy paddy field bed. Otherwise, the aerenchyma system can also be found in other cereal crops. Much more information about its characteristics and formation can be found, for instance, in the work of Yamauchi et al. (2013).

[5] An expression for denoting distinct ecological communities on the Earth. The area distribution of terrestrial biomes is closely related to the area distribution of the climate. It is commonly named via its most typical vegetation type (e.g. tropical rain forest, or temperate broad leaf forest).

[6] Climate as a notion was firstly introduced by the Ancient Greeks. With the word climate they allude to heat availability in a region that was determined by a region's position between the equator and the poles. It seems

(Sanderson, 1998). Poseidonius (135-51 BCE) was already thinking in terms of climate zones and distinguished seven on the earth's surface. Strabo (63 BCE - 23 CE) instead believed there were five zones as suggested by Pythagoras (sixth century BCE). Already at that time, Strabo was aware that the well-being of mankind is strongly determined by climate and its fluctuations due to crop production. Another Greek thinker, Ptolemy (87-150 CE), the astronomer and mapmaker, had the greatest influence on European renaissance culture, which is the cradle of the modern science. Ptolemy analyzed and determined the relations of three things on his maps: length of the longest day (horae deie longissimi), latitude in degrees (gradus latitudinis) and the climate designation number (numeri climatum). He clearly saw the relationship of climate and latitude, what is more, he treated these as being synonymous (Sanders, 1998). An important moment in evolution of climate science was Angelus' translation of Ptolemy's work into Latin in 1408 CE. In the middle of the sixteenth century, the medieval maps precisely denoted latitudes in degrees. The need to be able to make reference to the climate remained, but there were only thin meteorological data. With the development of meteorological instruments (e.g. thermometers and rain gauges in the seventeenth century) and the beginning of regular meteorological measurements (e.g. in Bavaria in the period 1781-1792 organized by the Societas Meteorologica Palatina), this gap was slowly closed. The first world map of monthly mean temperatures was published by the German botanist, Heinrich Dove in 1848. The first meteorological atlases were created at the end of the nineteenth century (e.g. Hann, 1887; Bartholomew et al., 1899). They contained many world maps, for instance, the world map of annual and monthly mean temperatures, annual and monthly mean pressures, monthly isohyets (lines of rainfall), monthly storm tracks and frequencies, and so on. As the collection of meteorological data increased, knowledge also increased. From the point of view of climate classification science, the accumulated knowledge in biogeography was particularly relevant. So, for instance, regarding vegetation, the scientist knew that its area distribution was a collective product of climate, phyto-geographic history, disturbance regimes and geographic isolation. Among these factors, Humboldt and Bonpland (1807) emphasized the role of climate. They were the first to reveal and discuss vegetation-climate covariation, which is clearly visible on global or continental scales.

Based on these meteorological and biogeographical results, Wladimir Köppen[7] (1900, 1918) created the first quantitative climate classification method

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that they introduced this notion on the basis of firsthand experience obtained in situ and in the course of voyages.

[7] Wladimir Köppen was an ethnic German born in Russia. Wladimir is an old Slavic name. "Great in his Power" was its original meaning, nowadays its meaning is "Peace Owner".

right at the beginning of the twentieth century. Köppen combined the ancient knowledge of the Greeks (the climate on Earth depends markedly on latitudes) and the two newest biogeographic findings (the area distribution of vegetation is closely related to the area distribution of climate and, the kind of vegetation that can develop on an area is determined mainly by the annual variations of temperature and/or rainfall on that area) into a unitary quantitative system based on simple algorithms applied mostly to temperature. It should be underlined that Köppen's aim was to construct a climate and not a vegetation type (e.g. Prentice et al., 1992) classification method on the global scale. One of Köppen's representations of global climate can be seen in Fig. 4.

Fig. 4 The world map of Köppen's climate classification (Symbols: A – tropical rain climates; BS – arid climate, steppe, grassland; BW – arid climate, warm desert; C – (warm) temperate rain climates; D – boreal forest and snow climates; E – cold snow climates, tundra, polar desert; s – summer dry season; w – winter dry season; moist climates with no marked dry season), (Fig. 4 is taken from Bolin (1980))

We can see that the so called Köppen's formulae are presented not only above terrestrial but also above ocean surfaces. Similar treatments, but with other datasets, can also be found, for instance, in the work of Walterscheid (2009) and/or Rohli et al. (2015). Of course, this is possible, but one thing should be emphasized: there is correlation only between Köppen's climate types and the terrestrial biomes. Regarding seas and/or oceans, such a correlation does not exist (Spalding et al., 2007). The climate does not really affect marine biomes much, though a broad latitudinal division of polar, temperate and tropical regions can be applied (Longhurst, 1998). We can also see, for instance, that the boundary between E and D climates (criterion: $T_{max} < 10$ °C, T_{max} is the highest monthly mean air temperature in summer) in Asia and North America is roughly positioned where the southward temperature interval 6-12 °C is located in Fig. 1b. Of course, there is a good overlap between the distributions of B climates in Fig. 4 and the extreme low precipitation areas in Fig. 3. Köppen worked for more than thirty years on his climate classification system and a presentation and discussion of the method can be read in Köppen's (1936) work. What is also important is that Köppen's legacy was continued by Geiger (1954, 1961).

Köppen's work (Köppen, 1884; 1900, 1936) had a great influence on the scientific community, though afterwards the way of thinking changed markedly. During the course of the twentieth century, scientific thinking in environmental disciplines, such as the climatology or geography, shifted towards physics[8], and used physical approaches (Hantel and Haimberger, 2016). This newest treatment is clearly visible, for instance, from the names of "physical climatology" (Budyko, 1963), "evapotranspiration climatonomy" (Lettau, 1969), "physical meteorology" (Bencze et al., 1982) and so on. Köppen's influence and the "new thinking" can be observed, for instance, in the United States. Carl Sauer, professor of geography at the University of California at Berkeley, knew German and as Thornthwaite's supervisor urged him to learn German and read Köppen[9]. So Thornthwaite did, what is more he carefully studied his climate classification system and worked out an own system (Thornthwaite, 1931; 1948), which can be treated as a kind of criticism of Köppen's work. He was the first to introduce the notion of "potential evaporation"[10] for characterizing both the thermal and moisture regimes of climate on a given location. With this new development, he improved the characterization of climate, at the same time increasing the complexity and the volume of calculations, as compared to Köppen. It should be emphasized that Thornthwaite's climate types are bioclimate types identified as areas with homogeneity in ombrotype (wet, dry moisture regimes) and thermotype (cold, warm thermal regimes) irrespective of vegetation type boundaries. It is interesting that Köppen (1936) knew about Thornthwaite's efforts (Thornthwaite, 1931) and clearly saw that his approach was much simpler, just because it is biogeographically based. He described Thornthwaite's (1931) approach in detail in section 6 of his work and noted that Thornthwaite created too many bioclimate types that were of only potentially use: "Freilich verzichtet Thornthwaite auf einen grossen Teil der möglichen 120 Kombinationen und begnügt sich mit 32, die er mit AA'r, AB'r, AC'r, … EC'd, nur die letzten mit den Einzelnbuchstaben D', E', F' bezeichnet.[11]" (In free translation: Of course, the number of combinations, that is, the maximum possible number of Thornthwaite's climate types is too high, about 120, it is obvious that many of them do not exist at all in reality. The number of the climate types actually used was 32 and the climate types were denoted as AA'r, AB'r, AC'r, … EC'd, and only the last ones with one character D', E', F'). It is obvious that Thornthwaite's (1931, 1948) method was too complex for classroom applications. In spite of this, the method was popular in the United States (e.g. Thornthwaite and Mather, 1955) and the drawbacks were progressively corrected over the years (e.g. Willmott and

[8] This is no wonder since the twentieth century was the century of physics.

[9] More precisely, it was Thornthwaite's friend, J.B. Leighly who recommended he read Köppen's work. Both of them were Carl Sauer's PhD students.

[10] Defining this notion, Thornthwaite did not suppose interaction between the surface and the atmosphere. He treated the atmosphere and the well-watered surface as mediums independent of each other. This view with its advantages and drawbacks was extensively discussed in work of Lhomme (1997).

[11] It should be mentioned that all works of Köppen were written in German.

Feddema, 1992). The greatest changes were made by Feddema (2005) who reformulated the method so that it became competitive with Köppen's. Feddema drastically simplified the calculation of moisture regime, for instance, the soil as a medium and climate representation via formulae were completely omitted. Of course, the bioclimate-based treatment remained, this was clearly elaborated, for instance, on page 454 of his work.

So far, these two methods, Köppen's method and the Thornthwaite-based Feddema method are the two most widely used generic, descriptive climate classification methods (e.g. Rubel and Kottek, 2011; Rohli et al., 2015). Of course, there are also other methods, for instance, the so-called genetic methods (e.g. Hettner, 1911), which differentiate climate on the basis of air masses and/or atmospheric circulations analyzing the causes and not the manifestation of climate. These methods were also known by Köppen and wrote the following in connection with this (Köppen, 1936): "Niederschläge, Bewölkung, selbst der Wind sind so komplizierte Dinge dass wir zunächst noch mit der Feststellung und möglichts übersichtlichen Gruppierung der Tatsachen genug zu tun haben. Es ist daher keine genetische, auf die Ursachen ihrer Entstehung gegründete Klassifikation der Klimate, die ich vorschlage, sondern eine, welche die Tatsachen und ihre Wirkung auf die übrige Natur nur zu einem möglichts klaren Bilde zusammenfassen will. Es können eben verschiedene Ursachen gleiche Wirkungen hervorrufen. Erst nachträglich wollen wir auch die Frage nach Entstehung dieses Bildes kurz streifen." (In free translation: Precipitation, cloudiness, the wind are, in themselves, complex phenomena, consequently their determination and classification is also a hard task. Having this in mind, I do not suggest the use of genetic climate classification, which deals with the causes of the phenomena, but instead classification that is based on the impacts imposed on nature, which are clearly visible and can be grouped into unique pictures. It is to be mentioned that different causes can result in the same effect and we are interested in knowing the causes only later.) It is interesting that already then, Köppen gave a clear answer to why he does not prefer and does not want to use such methods.

After Köppen and Thornthwaite, the "computer age" came, with the use of the new technology beginning at the middle and becoming intense at the end of the twentieth century. Modern computing capabilities combined with sophisticated and objective classification techniques such as principal component analysis (e.g. Davis and Kalkstein, 1990) and cluster analysis (e.g. White and Perry, 1989) represented major methodical advances over older methods, such as Köppen's. Otherwise, the classification techniques mentioned are also popular in synoptic climatology (e.g. Kalkstein et al., 1987) and climate-environment relationship analyses (e.g. Lund, 1963; Blasing, 1975). These methods may seem to be intellectually superior to generic methods, but, conceptually, they are much less striking (Mather and Gunson, 1995) and their biogeography or bioclimate related applications are as yet limited.

To date, climate classification applications were mostly macroscale applications. In the Middle Ages the so-called T-O type (the letter T within the letter O) map[12] was born for representing the World and its climatic zones (Sanderson, 1998). Note that Köppen's (1936) method is constructed and optimized exclusively for global scale applications. Thornthwaite's (1931) method, as Köppen's rival method, had a number of continental scale applications (e.g. Richard, 1962), but also many other methods, irrespective of the type of the method (e.g. Oliver, 1970; Wace, 1990), in most cases refer to the macro-scale.

1.2 What is good climate classification?

Köppen (1936) wrote the following in connection with this subject: "Hier ensteht die Frage, wie weit wir in der Unterscheidung von Klimaten gehen sollen. Dem narürlichen Wunsche nach Genauigkeit steht die Notwendigkeit gegenüber, ein möglichts einfaches, leicht erfassbares und die grossen Züge erkennbar lassendes System zu geben, von dem man auch erwarten darf, dass es Verwendung findet." (In free translation: The question arises, how many climate types should be differentiated. This is determined by the requirements and the accuracy of the classification. A climate classification method, which is balanced by these two factors, should be simple, easily applicable, and should be capable of reproducing the basic features of the system. Therefore it will be often used.). About two thirds of a century later, the basic requirements widened somewhat. After Essenwanger (2001), a method is the better 1) the fewer input data it uses, 2) the more simpler it is[13], 3) the more physically and less mathematically based it is, 4) the more the climate type is simply and unequivocally defined by it, 5) both annual and seasonal characteristics are considered and 6) the more the map presentation is transparent. As we see, Köppen already saw that the requirement for simplicity (simple method[14], as few input data as possible) is the basis of broad applicability. In my opinion, another two requirements should be added to the six already mentioned: the method should be applicable on any scale from the macro through

[12] The spherical World is divided into three continents (Europe, Africa and Asia) surrounded by oceans. On the map the points of the compass are also denoted.
[13] It can be said it should be as simple as possible.
[14] Note that the method cannot be simple if it is more mathematically and less physically based.

the meso to the microscale[15] and it should also be made suitable for climate change analyses.

Of course, there is no universal method that works well on every side, at all times, on all scales. The methods to be applied strongly depend on the goals, therefore it is these that should be defined as precisely as possible. Only precisely formulated goals and the best possible fulfillment of the abovementioned criteria can ensure climate classification that can reproduce the main features of the real climate.

1.3 New challenges in the twenty-first century

The twenty-first century will be strongly influenced by accelerating technological evolution and by climate change, of course, if global peace remains. Technological evolution will result in a superabundance of data, especially with respect to the turn of the nineteenth and the twentieth centuries. Superabundance of data means not only a plethora of predicted but also of measured data, and, necessarily, the type (e.g. Fanger, 1973) and the spatiotemporal resolution of data fields (e.g. Rubel et al., 2016) will enormously increase. This can be especially sensed in interdisciplinary sciences (e.g. Chan and Ryan, 2009). This data revolution together with climate change, which is happening (e.g. Naidu et al., 2011), represent a new challenge for the science of climate classification.

In the new situation, there is a plethora of new subjects, for instance, the structure, that is, the area distribution of climate on the mesoscale is unknown at many locations around the world. This is even truer when we are speaking about microscale structures. Or, a completely other subject: is there such a climate classification method that would be applicable on both the macro, and meso, and even the microscale? Similarly, is there such method that would be time-invariant[16]? Meanwhile we have made no mention of many classifications related to agriculture, the building industry, public health services and other domains of life. One thing is sure: data abundance is growing exponentially, as are the new challenges.

1.4 Which subjects will be dealt with?

[15] Note that scale dependence supposes hierarchical classification and structure, where small areas can be related to larger ones (e.g. Mather and Gunson, 1995)

[16] This subject is partly connected to those investigations that deal, for instance, with the applicability of Köppen's method to deep time (Zhang et al., 2016)

We still think that planet Earth is a unique planet because there is life on it. Life, or, put more scientifically, the biosphere actively participated in the creation of the evolution of Earth's climate. This fact is recognized, discussed and elaborated as the Gaia hypotheses by Lovelock (Watson and Lovelock, 1983; Lovelock, 1992). Regardless of this deep relationship, the climate is a resource for life and this is the reason it makes sense to classify it. Since today the existence of mankind is based on plant cultivation, climate classifications are mostly related to vegetation. So, the most popular Köppen (1936) classification is terrestrial biome distribution based classification. Recently, direct human being based approaches have also been published (e.g. Jendritzky and Tinz, 2009; Yan, 2005). In these studies, the human thermal environment is estimated and classified. Note that there also are such studies (e.g. Yang and Matzarakis, 2016) where these two approaches are combined.

In this book, we will use Feddema's (2005) approach, which is only indirectly related to vegetation[17]. The method used here is a product of a number of United States climatologists (Thornthwaite, 1948; Thornthwaite and Mather, 1955; Willmott and Feddema, 1992; Feddema, 2005; Elguindi et al., 2014). It is mainly applied to conditions in the United States (e.g. Grundstein, 2008) for both climate and climate change analyses. In Europe, it is less known and less popular, correspondingly, its European applications are not common, what is more, they are rare. We will apply Feddema's (2005) method to analyze climate and climate change processes in the European region on both the regional and continental scales. Analyzing climate, we will focus on its macro and mesoscale structures. We will try to answer the following important question: When and under what conditions is Feddema's (2005) method suitable for analyzing the mesoscale structure of the climate? Note that climate change processes can be unequivocally characterized using Feddema's (2005) method. Climate change processes in terms of annual and seasonal characteristics can be directly named, instead of describing climate type shifts, as for instance, when Köppen-Trewartha's classification method is used (e.g. Gallardo et al., 2013).

The climate and its reception by mankind is briefly elaborated in the *Introduction*, more precisely in section 1.1. Some thoughts regarding climate classification principles are presented in section 1.2. A subjective outlook related to some possible challenges in the science of climate classification in the twenty-first century are outlined in section 1.3. The motivation why precisely Feddema's (2005) method is chosen for analyzing European region's climate and climate

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[17] Feddema's method is based on estimating heat and water availability as simply as possible. These two factors can influence vegetation distribution, but they are not the only factors. Vegetation distribution also depends on edaphic factors, phytogeographic history, disturbance regimes and geographic isolation.

change is explained in section 1.4. Feddema's (2005) method is fully presented in the *Method* section (section 2). The meteorological data and the basic characteristics of the regions studied (European region and the Central-European sub-region) are briefly described in the *Regions and Data* section (section 3). All results will be presented in the *Analyses* section (section 4). The sensitivity of climate maps to the parameterization of potential evapotranspiration (PET) is discussed in section 4.1. Note that the Feddema' method can be fine-tuned. This important issue is analyzed in section 4.2. The climate of the European highlands is significantly determined by topography. This subject is analyzed in section 4.3 by comparing the climates of the European Alps in the Swiss-Austrian region and the Pannonian Basin. The climate in Europe and the climate change in the European region are discussed in detail in section 4.4. In doing so, we will focus on those climate characteristics that can be reproduced by Feddema but not using other generic climate classification methods. Lastly, the main conclusions and an outlook is given in section 5.

2 Method

Feddema's global climate classification scheme is presented in Feddema (2005). As mentioned, the method sorts bioclimate types, that is, areas with homogeneity in thermotype (cold, warm thermal regimes) and ombrotype (wet, dry moisture regimes) as simply as possible. Thermal regime is characterized via PET, while moisture regime via moisture index I_m. In his work, Feddema didn't mention, which calculation procedure is used for estimating PET. In this book, PET is calculated after Thornthwaite's (1948) formula as it was presented in McKenney and Rosenberg (1993). Accordingly, for the i^{th} month ($i = 1, \dots, 12$)

$$PET_i = 1.6 \cdot \left(\frac{L_i}{12}\right) \cdot \left(\frac{N_i}{30}\right) \cdot \left(\frac{10 \cdot T_i}{I}\right)^A, \quad (1)$$

where

$$I = \sum_{i=1}^{12} t_i, \quad (2)$$

$$t_i = \begin{cases} (\frac{T_i}{5})^{1.514}, if\ T_i > 0 \\ 0, \qquad if\ T_i \leq 0, \end{cases} \quad (3)$$

$$A = 6.75 \cdot 10^{-7} \cdot I^3 - 7.71 \cdot 10^{-5} \cdot I^2 + 1.792 \cdot 10^{-2} \cdot I + 0.49239\,. \quad (4)$$

T_i is the mean monthly temperature [°C] and L_i is the mean monthly daylight length [hours]. In our calculations, L_i is estimated by calculating L_i for the central day in the month. Thermal types, as annual characteristic, can be sorted on different ways. Feddema's (2005) categorization is given in Table 1.

Table 1 Thermal types used in Feddema's (2005) original scheme

Thermal type	**Annual PET (mm·year^{-1})**
torrid	>1,500
hot	1,200–1,500
warm	900–1,200
cool	600–900
cold	300–600
frost	0–300

As mentioned, moisture regime is estimated via moisture index I_m. I_m is defined via precipitation (P) and PET as follows:

$$I_m = \begin{cases} 1 - \frac{PET}{P}, if\ \ P > PET, \\ 0, \qquad if\ \ P = PET, \\ \frac{P}{PET} - 1, if\ P < PET. \end{cases} \quad (5)$$

P and PET can refer to both month and year depending on whether annual or seasonal characteristics are considered. Moisture types, as annual characteristics, can also be sorted on different ways. Feddema's (2005) categorization is given in Table 2.

Table 2 Moisture types used in Feddema's (2005) original scheme

Moisture type	Moisture index (I_m)
saturated	0.66–1.00
wet	0.33–0.66
moist	0.00–0.33
dry	-0.33–0.00
semiarid	-0.66–(-0.33)
arid	-1.00–(-0.66)

The characterization of seasonality is also an important feature of the method. Feddema's (2005) method treated this by determining a) the climatic variable that possesses seasonality and b) the magnitude of seasonal variability. The ratio between annual P range and annual PET range has to be calculated in order to determine which climatic variable possesses seasonality. The criteria used by Feddema (2005) in decision-making are presented in Table 3.

Table 3 Criteria for determining the climatic variable that possesses seasonality according to Feddema's (2005) original scheme

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

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 (Feddema, 2005). The magnitude of variability is estimated by calculating the annual range of I_m. I_m can range between -1 and 1. Feddema (2005) decided to subdivide this interval into four equal parts. The decision-making criteria used for both P and T can be seen in Table 4.

Table 4 The magnitude of seasonal variability according to Feddema's (2005) original scheme

Magnitude of seasonal variability	Annual range of I_m
low	0.0–0.5
medium	0.5–1.0
high	1.0–1.5
extreme	1.5–2.0

3 Regions and data

The analysis is not performed for the whole Europe ranging from Atlantic Ocean to the Ural Mountains, rather to somewhat less territory, but which north-south and west-east extension is large enough to perform a continental scale analysis. Such European region together with simple representation of relief can be seen in Fig. 5.

Fig. 5 European region and its basic elevation data. The elevation intervals are -200 – 0 m; 0 – 200 m; 200 – 1000 m; 1000 – 3200 m above sea level. The Central European sub-region (European Alps to the west and Pannonian Basin to the east) is denoted by red rectangular (source: created by Nóra Skarbit and Hajnalka Breuer)

The west (the Austrian-Swiss region of the European Alps) and the east (Hungary) part of the Central-European sub-region are separately treated in investigating the sensitivity to the scaling and topography.

Twentieth century is analyzed by using observed data. 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 well-known product of the Climatic Research Unit (CRU) of the University of East Anglia[18]. The used spatial resolution is 10'x10' (~18 km x 18 km). The data are chosen for the region between the -11°–32°/34°–72° longitude/latitude lines, which contains 31143 grid points. Climate and climate change analyses are performed by using thirty-year means, which means that a total of 71 mean temperature and precipitation fields

[18] https://crudata.uea.ac.uk/cru/data/hrg/timm/grid/CRU_TS_1_2.html is the internet link to the database.

are constructed. Twenty-first century is analyzed by using twenty-first-century projections data. They were constructed in scope of the project ENSEMBLES (van der Linden and Mitchell, 2009) by using RCM (Regional Climate Model) simulation results assuming A1B emission scenario, which hypotheses a rather convergent world with a reasonably rapid population and economic growth using all energy sources in a balanced way. The following RCMs were used: HadRM3Q, CLM, RCA, RegCM, RACMO2, REMO, HIRHAM5, HIRHAM and ALADIN. 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. Note that this region is somewhat different than the region used in the twentieth century. Further, these data were bias-corrected by using so-called E-OBS dataset[19] to ensure homogeneity between data referring to the twentieth and twenty-first centuries. All the RCM results were used. From these the ensemble mean of the P and T fields has also been created. We have also chosen the most extreme results by setting up precipitation and temperature differences between the periods 2071–2100 and 1971–2000. The model results showing the most extreme behavior regarding P and T fields are presented in Figure 6.

Fig. 6 Area distribution of precipitation (above) and temperature (below) differences between the periods 2071–2100 and 1971–2000 obtained using the HIRHAM, HIRHAM5 and HadRM3Q models, respectively (source: created by Nóra Skarbit)

Regarding precipitation, HIRHAM5 produced the largest increase, while HIRHAM the largest decrease. HIRHAM5's precipitation increase is easily observable on the Scandinavian Peninsula, especially in its southwestern parts. The decrease (up to -200 mm/year) is observable to the south from 45°N. In spite of this, HIRHAM produced much larger precipitation decrease, which can be observed up to 60°N. Note that temperature increase produced by HIRHAM is the smallest. This increase is about 4 °C or larger only in the regions to the north from 65°N. HadRM3Q produced the strongest temperature increase. In this case, large increases around or above 4 °C are typical not only in the northern but also in the southern regions of Europe.

[19]E-OBS dataset contains daily air temperature (minimum, maximum and mean), precipitation (Haylock et al., 2008) and pressure data (van der Besselaar et al., 2011) in a spatial resolution of 25 km x 25 km referring to the period 1950–2016.

4 Analyzes

As it was mentioned, Thornthwaite's (1948) method can be interpreted as a critical answer to Köppen's (1936) method since it used a completely new approach based on the notion of PET. Feddema's (2005) method is maybe[20] an end-product of the Thornthwaite-type approach. In these approaches, PET is the most important factor. Its use can be underdog and advantageous together. That is underdog that it has to be parameterized, which is not a simple task. At the same time the method is pretty sensitive to its changes. That is advantageous that thermal and moisture regimes, which are determined by PET, are defined by PET and I_m intervals. That is to be underlined: not by values rather by intervals, which can be subdivided or extended, and so actually the method can be fine-tuned. These two important aspects (PET parameterization and fine tuning) together with terrain effect will be analyzed in detail before the discussion of the European region's climate and climate change processes.

4.1 Sensitivity to PET

PET possesses crucial role in estimating both the thermal and moisture regimes irrespective whether annual or seasonal characteristics are considered. PET should be estimated always with caution, its verification is even harder problem. At the same time, Feddema's (2005) method can be sensitive in some extent to its changes. Some first-hand experiences related to this issue referring to Hungary will be presented below. Firstly, let we get acquainted with some PET parameterizations!

4.1.1 PET parameterizations

The spectrum of formulae for estimating PET is broad (e.g. Jianbiao et al., 2005). The simplest PET formulae use only T as input (e.g. Xu and Singh, 2001). The most data-intensive, physically based methods are based on Penman-Monteith equation (e.g. Choudhury, 1997). In between, there are methods, which use radiation and air temperature and/or humidity as information as simply as possible. Some of such methods will be presented below.

Priestley-Taylor formula

[20] The uncertainty behind the „maybe" will be revealed by future.

The Priestley-Taylor (1972) equation is a well-known equation, where the basic quantity is radiation,

$$PET_{PT} = \alpha_{PT} \cdot \frac{\Delta}{\Delta + \gamma} \cdot \frac{R_n - G}{\lambda}, \quad (6)$$

where α_{PT} is the Priestley-Taylor coefficient (its average value is 1.26), Δ is the slope of saturation vapor pressure curve at air temperature T [hPa·K^{-1}], γ is the psychrometric constant [hPa·K^{-1}], λ is the latent heat of vaporization [MJ·kg^{-1}], R_n is the net radiation of surface [MJ·m^{-2}·d^{-1}] and G is the heat flux at ground surface [MJ·m^{-2}·d^{-1}]. PET_{PT} is expressed in [mm·d^{-1}]. R_n and G are parametrized after Allen et al.'s (1998) work.

Hargreaves-Samani formula

Hargreaves-Samani formula (Hargreaves and Samani (1982, 1985)) depends on both temperature and radiation,

$$PET_{HS} = c_1 \cdot R^t \cdot T_d^{0.5} \cdot (T + 17.8), \quad (7)$$

where c_1 is an empirical coefficient (for its value we have taken 0.0023), R^t is the sun radiation at the top of the atmosphere [MJ·m^{-2}·d^{-1}], T_d is the difference between maximum and minimum daily air temperature [°C] and T is the daily average air temperature [°C]. PET_{HS} is expressed in [mm·d^{-1}].

Blaney-Criddle formula

In Blaney-Criddle formula (Blaney and Criddle, 1950) radiation is only implicitly therein via a relative potential sunshine duration term,

$$PET_{BC} = c_2 + c_3 \cdot rsd \cdot (8.128 + 0.457 \cdot T), \quad (8)$$

where c_2 and c_3 are empirical coefficients after (Schrödter, 1985) (c_2=-1.55 and c_3=0.96), *rsd* is the ratio between monthly mean daily potential sunshine duration and the annual sum of potential sunshine duration expressed in percentage and T is air temperature [°C]. PET_{BC} is given in [$mm \cdot d^{-1}$].

Antal formula

Antal formula (Antal, 1968) depends not only on air temperature T [°C] but also on vapor pressure deficit [hPa], that is

$$PET_A = 0.74 \cdot [e_S(T) - e]^{0.7} \cdot (1 + \alpha_{air} \cdot T)^{4.8}. \quad (9)$$

$e_S(T)$ is the saturated vapor pressure at T, e is the actual vapor pressure and α_{air} is the thermal expansion coefficient of air (for its value we have taken $3.7 \cdot 10^{-3}$). As in the previous formulae, PET_A is given in [$mm \cdot d^{-1}$].

4.1.2 Climate maps obtained by different PET parameterizations

The climate maps considered refer to the beginning of the twentieth century, more precisely to the period 1901-1930. Mostly annual thermal and moisture type characteristics will be considered to touch the spot. To be most effective, we will use important information presented in Fig 7, where Hungary's main geographical regions are denoted.

Fig. 7 Hungary with its main geographical regions and mountains. I Transdanubia (subregions: Ia Alpokalja region, Ib Little Hungarian Plain, Ic Transdanubian Mountain, Id Transdanubian Hills), II North Hungarian Mountains and III Great Hungarian Plain. Some major geographical designations are also denoted on the map (source: created by Hajnalka Breuer)

The climate of Hungary obtained by using PET_{PT} and Feddema's (2005) method is presented in Fig. 8. Here, the main climatic features of Hungary are more or less reproduced: the climate type "cool, dry" with extreme seasonality of T in the extensive lowland areas in the Great Hungarian Plain, the climate type "cool, moist" with high or extreme seasonality of T in the Transdanubia and/or in the

North Hungarian Mountains and the sporadic climate type “cold, moist” only in the upland areas.

Fig. 8 The climate of Hungary in the period 1901-1930 obtained by using PET_{PT} (Priestly and Taylor, 1972) parameterization and Feddema’s (2005) original scheme (source: created by Nóra Skarbit, modified by author)

Contrarily, the climate of Hungary obtained by using PET_{HS} and Feddema’s original scheme is much warmer and dryer. This climate map is presented in Fig. 9.

Fig 9 The climate of Hungary in the period 1901-1930 obtained by using PET_{HS} (Hargreaves and Samani, 1985) parameterization and Feddema’s (2005) original scheme (source: created by Nóra Skarbit, modified by author)

The climate type “warm, semiarid” is prevailing in the Great Hungarian Plain. Going towards Transdanubia it can be observed the “warm, semiarid” → “cool, semiarid” → “cool, dry” climate type transformation. Climate type “cool or cold, moist” does not exist at all. In the whole country, the seasonality type is “high seasonality of T”. Extreme warm and dry climate is obtained by using PET_{BC} parameterization. This climate map is presented in Fig. 10.

Fig 10 The climate of Hungary in the period 1901-1930 obtained by using PET_{BC} (Blaney and Criddle, 1950) parameterization and Feddema’s (2005) original scheme (source: created by Nóra Skarbit, modified by author)

In this case, the climate type “hot, semiarid” is the prevailing climate type. Climate type “warm, semiarid” can be sporadically found in Alpokalja region and in some upland areas in the Transdanubian Mountains and in the North Hungarian Mountains. As in the previous case, only seasonality type “medium seasonality of T” exists in the whole Hungary. The climate map obtained by using PET_A differs completely from the climate map obtained by using PET_{BC}. It can be seen in Fig. 11.

Fig 11 The climate of Hungary in the period 1901-1930 obtained by using PET_A (Antal, 1968) parameterization and Feddema's (2005) original scheme (source: created by Nóra Skarbit, modified by author)

It is pretty heterogeneous possessing climate types "warm, semiarid", "warm, dry", "cool, semiarid", "cool, dry" and "cool, moist". Interestingly, the climate in the Great Hungarian Plain is also fairly heterogeneous by climate types "warm, semiarid", "cool, semiarid" and "cool, dry" with high seasonality of T. It is also interesting that Alpokalja region in the Transdanubia is wetter than the areas in the North Hungarian Mountains.

4.1.3 Comparison of the climate maps

According to the results presented in Feddema (2005)[21], the climate type "cool, dry, with high seasonality of T" is the prevailing climate type in the Pannonian Basin. Unfortunately, the part of the twentieth century to which refers his result is not specified. Thermal type "cool" means that PET is between 600 and 900 mm·year^{-1}. This result is in accordance with the result obtained by Choudhury (1997)[22]. In our numerical experiments, PET changed between 300-600 ("cold, moist" areas in the region of Transdanubian Mountains for PET_{PT} parameterization, Fig. 8) and 1200-1500 ("hot, semiarid" areas for PET_{BC} parameterization, Fig 10) mm·year^{-1}. Hungary is not so large country to possess so large scatter of PET in the reality. Therefore, simulation results were checked by comparing them with measurement results obtained by Class U evaporation pan in the period 1901-1950 (Stelczer, 2000). Stelczer's (2000) results confirm that PET changes in Hungary at the beginning of the twentieth century were somewhere between 500 and 850 mm·year^{-1}. Both the domestic measurement results and the international simulation results confirm that PET is overestimated by PET_{HS}, PET_{BC} and PET_A parameterizations (Ács et al., 2015). At the same time, the sensitivity test shows that Feddema's (2005) method is pretty sensitive to the parameterization of PET.

4.2 Sensitivity to scaling (original versus fine-tuned)

4.2.1 Lowland – Hungary (ORIGINAL, climate:1901-1930 (figure); 1971-2000(figure), climate change: 1901-1930—1971-2000(figure); FINE-TUNED,

[21] Exactly: Fig. 12 on page 464.
[22] Exactly: Figure 13 on page 78.

climate:1901-1930 (figure); 1971-2000(figure), climate change: 1901-1930—1971-2000(figure); IN TOTAL 6 FIGURES)

4.3 Sensitivity to topography (upland versus lowland)

4.3.1 Upland – Swiss-Austria region of the European Alps (ORIGINAL, climate: 1901-1930 (figure); 1971-2000 (figure), climate change: 1901-1930—1971-2000), FINE-TUNED, climate: 1901-1930 (figure); 1971-2000 (figure), IN TOTAL 5 FIGURES)

4.4 European region's analyzes

4.4.1 Feddema [Skarbit et al., 2017 (IJC), Breuer et al., 2017 (Climatic Change))

climate maps: four in twentieth century (two annual and two seasonal) and four (two annual and two seasonal) in the twenty-first century, IN TOTAL EIGHT

climate change maps: two in twentieth century (one annual and one seasonal) and two in the twenty-first century (one annual and one seasonal), IN TOTAL FOUR

(the viewpoint: TO HIGHLIGHT THOSE FEATURES WHICH ARE FEDDEMA-SPECIFIC, latitude, longitude, altitude, relief, land-locked eastward directed water bodies)

4.5 Feddema versus Köppen

From the point of view of Essenwanger on both regional and continental scales

5 Main conclusions and outlook

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Climate as notion was firstly introduced by Ancient Greeks. Already from the beginnings, there was a need for its classification to understand the Earth. This is understandable since the human life, what is more, the life in general is strongly determined by it. Though the need for climate classification was great, the first quantitative climate classification method, that of Köppen, was born roughly twenty centuries later after Ancient Greeks. The method comprises on an own way the Acient Greek knowledge on the climate-latitude and the biogeographic knowledges on the vegetation-climate relationships.

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