# HOW THE CLIMATE MIGRATES. CASE STUDY FOR FOUR LOCATIONS IN THE CARPATHIAN-BASIN

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**ABSTRACT:**
One of the manifestations of climate change is that the climate of a given location becomes similar to the climate of another location. The detection and investigation of these migration effects is useful in several areas, such as tourism or agriculture. The present study attempts to monitor this location-related climate change. Based on daily temperatures and precipitation at four test sites, using the cosine similarity index shows how the climates of each site migrated in the Carpathian Basin. The study examines the similarity values for each location both for ten- and thirty-years periods. We can see that in most cases the climate not only migrates, but in many cases, it shrinks territorially or largely disappears from the study area. In order to be able to process the large amount of data, we used own developed R scripts, which can be reused and expanded in the context of new data or perhaps a more precise methodology.

***Key-words:*** *Climate change, Climate migration, Modeling, R automatization, Big data, Carpathian-Basin*

## 1. INTRODUCTION AND AIMS

Climate migration is one of the manifestations of climate change when the climate of a given location becomes similar to the climate of another location. It is important and useful to examine the reality of how the climate of a region has changed/is changing in recent decades (Thompson, 2009), how new, non-native plant cultures appear in certain areas (Gómez-Ruiz and Lacher, 2019), and whether these changes are trend-like or oscillating, because these effects must be analyzed and evaluated according to local characteristics. (Meresa et al., 2017). The change in the climate greatly affects the crops that can be grown on the given area, which is why many studies deal with the investigation of this phenomenon (Mabhaudhi et al., 2019; Malhotra, 2017; Reynolds and Ortiz, 2010). The aim of our research was to develop an automatized, parametrizable software tool which can properly identify areas with similar climate characteristics. This new analysis method and data visualization should be able to track climate change in space and time based on the climate similarity of different areas.

By this having the possibility to study the migration of the climate for several places in the Carpathian-basin, taking into account one of the warmest locations of it, Timișoara (Ács et al., 2020). The climate change in Carpathian basin were studied comparing to global climate change and it was expected to have higher temperature increases (Bartholy et al., 2009) and there are studies which aims to determine and quantify the effects of climate change in that region (Rakonczai, 2011).

To carry out the research a large dataset was necessary. Although the effective amount of data used depends on their spatial and temporal resolution, it was necessary to process a very large amount of data, which is unfeasible without automated analysis. After identifying the usable data source, the next step of the research was to read, aggregate and finally compare the meteorological characteristics for each raster cell (location). For this, a test software analysis module had to be developed, the ultimate goal of which is to be able to determine, for every location, the extent to which the different locations of the test area are similar to each other based on their meteorological characteristics. The parameter of the analysis module is not only the location, but also the test period.

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The software module created in this way provide the opportunity to carry out specific analyses. For this purpose, we selected four locations, namely Sâmboleni (RO), Timișoara (RO), Zagreb (HR) and Győr (HU), examining which of them show the greatest climatic similarity with other locations over time, thereby determining how the climate of the selected location "migrated".

## 2. DATA AND METHODS

### 2.1. Data

At the beginning we set up several selection criterions. In order to be able to model the migration of the climate, the temporal extent and temporal resolution of the data series were of primary importance, the longer daily data series were preferred. The second selection criterion was the diversity of the data. Based on the experience of our previous researches (Magyari-Sáska, 2021; Magyari-Sáska and Dombay, 2021, 2022), we would definitely prefer those data sources that, in addition to temperature and precipitation, also contain other weather elements (e.g. humidity, number of sunshine hours, etc.), since these also play a significant role in the examination of climate similarity. The third element that was considered in the selection of the data source was the spatial resolution of the dataset.

Examining the freely available raster-based databases, unfortunately, there was not much possibility to choose, because all four examined databases, which covered the area of the Carpathian Basin, had certain deficiencies in order to achieve the research goal. The WorldClim database contains the data aggregated to the level of months (Fick and Hijmans, 2017), in which it only contains the minimum, maximum and average values, which proved to be insufficient from the point of view of this research, and did not fulfill the first criterion I defined. At the same time, the last year of the available data was 2000, so the data of the last 20 years would have been missing.

The next database examined was the Euro-Cordex, which is a climate modeling database (Jacob et al., 2014), raw data is not available, so it is completely unsuitable for carrying out the type of studies that the present research aims to do. Next came ECLIPS 2, which has a very good spatial resolution (Chakraborty et al., 2021), but which is actually based on Euro-Cordex data, so it presents not raw, but processed, different climate scenarios.

In the end, the selected database was the E-OBS, the temporal extent of which is from 1950 to 2021, the temporal resolution is daily, the spatial resolution is 0.1 x 0.1 degrees, which corresponds to approximately 7-8 km in the examined area (Cornes et al., 2018). The metadata includes several meteorological characteristics, such as daily average, minimum and maximum temperature, rainfall, humidity, air pressure, solar radiation and wind speed. The only weakness of this data source was the spatial resolution, but from the point of view of climate analysis, this is not the most significant, a resolution of roughly 60 km2 is acceptable. What is a real disadvantage of the database is the incomplete temporal and spatial coverage of the other characteristics besides temperature and precipitation. In many cases, solar radiation and wind speed are not actually available in the database, so we could not use them in the research. Based on temperature and precipitation data, we used the 30 synthetic indicators to characterize the climate including average values and ratio of values in a given interval, such as the ratio of how many days the average daily temperature was between 10 and 20 degrees.

### 2.2. Methods

In order to be able to compare the climate of different areas a similarity index must be defined which expresses the joint similarity of the different weather characteristics of two aggregation periods.

The similarity index can be created in such a way that we try to condense the standardized values of the weather characteristics into a single value (e.g. using a linear combination), and then designate the difference between these values as the similarity index. In this case, the question can be raised as to what extent the various characteristics participate in the formation of the weather, what is their information content, is it necessary to weight them, and if so, what would these weights be.

The similarity index can be created without combining the weather characteristics into one value. There are several methods to determine the similarity between two vectors, each consisting of several values (in our case, weather characteristics). One of the most well-known is correlation, but many studies use the Jaccard index, the multidimensional Euclidean, Minkowski or Hamming distance (Thant and Shoe Moe, 2020), and cosine similarity (Tan et al., 2005).

We used the latter, since this indicator is often used in data mining (Han et al., 2012) and shows how much the values of the two vectors have the same orientation (Schubert, 2021). By definition, the cosine similarity index is the cosine of the difference between the resulting vectors defined in a multidimensional (the number of dimensions is the same as the number of features in the vectors) space.

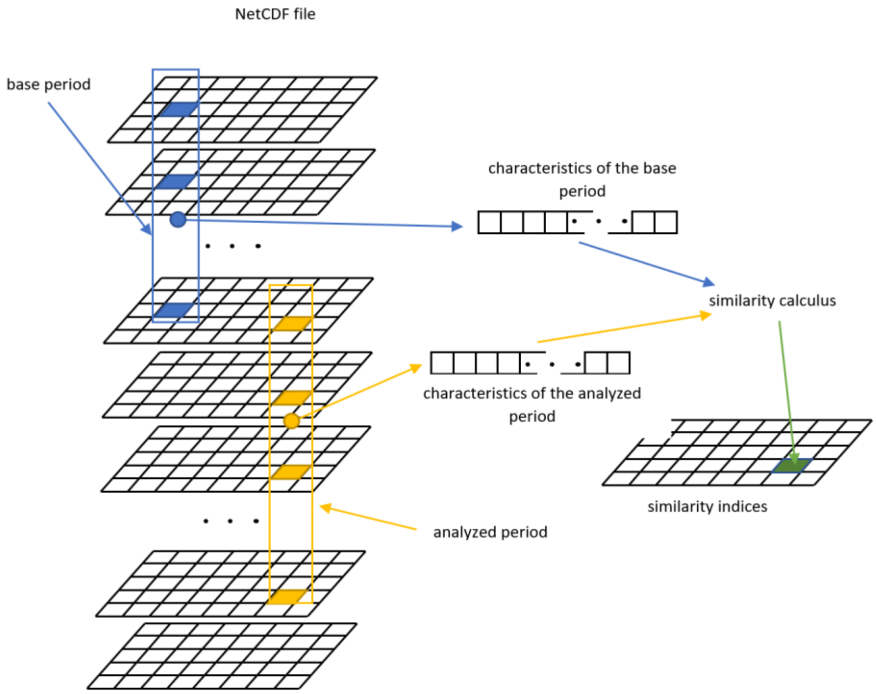


**Fig. 1.** – Data processing of a NetCDF file for obtaining the similarity value.

The analysis process follows the algorithm shown in **Fig**. **1** and it's based on the following steps:

- step 1: a reference location, a reference period which we called the base period, and an examination period are defined. The result of the analysis will show how similar is the climate at different locations during the study period is to the climate of the selected reference location for the base period.
- step 2: for the base period of the reference location, the data of that location are read from the data files, they are aggregated (Kabacoff, 2015) and the 30 indicators that we used are calculated from them.
- step 3: taking the base period into account, the similarity index is calculated for each area unit, this shows how similar the climate was to the reference location in the base period
- step 4: taking the study period into account, the similarity index is calculated for each area unit, thereby showing how similar the climate was to the reference location during the study period, taking into account the climate of the base period.

Based on the data structure and algorithm presented it can be seen that a large amount of data processing is required, and that the analysis itself allows for many parameterizations. It is almost impossible to carry out this research with traditional statistical or geospatial applications through their interactive user interface, since they require continuous human supervision, primarily to set up and start their repetitive calculations again and again. It was therefore necessary to develop our own analytical toolbox.

One of the most dynamically developing free analysis software of the last decade is R. The command-line application that initially enabled statistical processing (Ihaka and Gentlman, 1996) developed very quickly and gained great popularity among researchers. Today, there are several additional modules for almost every discipline, starting from the life sciences to the fields of geospatial, chemical or remote sensing research and applications.

Since R gives you the opportunity to create your own programmed analysis packages and efficiently manages large data structures, we used this programmable analysis software in this research as well. The created application package can be divided into two parts: the analysis module and the visualization module. We used the following R program packages to create the analysis and data display modules. To manage NetCDF files, we use the ncdf4 (Pierce, 2021) package. The rgdal (Bivand et al., 2022) and raster (Hijmans, 2022) program packages were used to manage raster layers, and the shiny (Chang et al., 2021) and shinyjs (Attali, 2021) packages to create the user interface.

## 3. RESULTS AND DISCUSSION

The analysis used data aggregated at the annual level. We used the period 1950-1980 as the base period, the climate emerging from the meteorological data of this period was the basis of comparison. For each settlement, we determined the following using the analysis module:

1. the similarity index for each cell based on the climate characteristics of the given settlement using the data between 1950-180. In the resulting raster layer, a cell value shows how similar the climate of the given area, based on data between 1950-1980, is to the climate of the settlement used, based on data from the same period.

2. the similarity index of each cell based on the meteorological data of five different periods, having as basis for comparison, the climate characteristic of the given settlement in the period 1950-1980. The five examination periods were 1981-1990 / 1991-2000 / 2001-2010 / 2011-2020 and 1990-2000. The first four periods show how the climate has changed in ten-year intervals, while the last study period spans 31 years, just like the base period. Here, based on the 30-year period often used in the study of climate changes, the raster file created for the base period and this 31-year study period serves as the basis for climatic comparisons. In this case a cell value of the raster files obtained as a result, shows how similar the climate of the given area is to the climate of the settlement used for the base period (1950-1980) based on the data of the study period.

In the following map representations, we have marked six categories of similarity: we have depicted the strongest similarity in green, here the value of the similarity index is above 0.998. The four categories that follow use an increasingly lighter shade of blue, where the lower the similarity, the lighter the color is. In these cases, the value difference of the successive similarity categories is 0.002. Areas with a similarity value lower than 0.992 are displayed without coloring.

### 3.1 Győr as reference location

Based on data from the period 1950-1980, Győr's climate was largely typical of extensive areas of the Carpathian Basin. This settlement is an excellent example for observing the migration of the climate. In the case of the successive decades, it can be clearly seen as if we had blown into the Carpathian basin from the south and south-east (**Fig. 2a**).

In the first decade of investigation, between 1981 and 1990, the number of areas with the greatest similarity in Timișoara region decreases. The area belonging to the highest similarity category is also thinning in the Southern Great Plain of Hungary, and these characteristics are congested to the north from the northern areas of Bosnia and Herzegovina. North of Vienna, in Lower Austria, a small spot also appears, indicating areas with a similarity value higher than 0.998 (**Fig. 2b**).

In the next decade (1991-2000), the impact of this blow will continue to strengthen. The areas in the vicinity of Belgrade that have been until now in the category of the greatest similarity to the climate of the base period, will disappear. This high similarity also disappears from the areas along the Szolnok, Kiskunfélegyháza and Tompa axes. At the same time, areas with a climate most similar to the climate of Győr's base period appear in the Prekmurje region and the number of areas with these characteristics also increases significantly in the western and northern neighborhoods of Vienna. (**Fig. 2c**).

Between 2001 and 2010, the similarity in most places weakens compared to the climate of the base period. Győr and Vienna are no longer among the locations whose climate is most similar to the climate of the base period. The locations most similar to the climate of the base period can be found in the areas north and south of Vienna. In the north-eastern region of the Carpathian Basin, Satu Mare and its surroundings fall out of the category with the greatest similarity (**Fig. 2d**).

In the last study decade, between 2011-2020, the climate that was typical for Győr and significant areas of the Carpathian Basin in the base period was completely blown out of the inner area of the Carpathian Basin. We only find small spots and islands with the climatic characteristics typical of the base period, such as Prešov, Zalău or Olomuc (**Fig. 2e**). It is also noticeable that outside of the Carpathian basin, in the Eastern parts, the climate of Győr's base period already appears in the period 1991-2000, which extends to larger and larger areas in the following two decades.

### 3.2. Sâmboleni as reference location

Sâmboleni is a small settlement in the Transylvanian countryside, whose climatic conditions could only be found in three larger areas during the base period. On the one hand, these areas covered the plains of Transylvania and the western Carpathians, but there were similar climatic conditions in the vicinity of the Nógrád and Gömör basins as well. On the western extremities of Hungary, we find similar climate conditions with the base period of Sâmboleni in an even larger area (**Fig. 3a**).

In the next four decades, we can witness the continuous "extinction" of Sâmboleni's climate in the Carpathian Basin. In the period 1981-1990 the areas with the greatest similarity already disappear from Hungary’s western part. In the north, the sites in the vicinity of the Nógrád and Gömör basins that belong to the highest similarity category are shrinking, and in Transylvania, these sites are retreating almost exclusively to the Transylvanian plain. In the east, beyond the Carpathian basin, the Pre-Carpathians show similar climatic conditions such as those that characterized Sâmboleni in the base period. In the following decade, between 1991 and 2000 only the climatic conditions of the Gömör basin resemble the climate of the Sâmboleni base period to a large extent. Areas with a high climatic similarity remain in the Transylvanian plain, as in the Pre-Carpathians. The next decade (2001-2010) will bring little change in terms of the similarity of the climatic conditions, the areas in the Târnava ridge that belonged to the highest similarity category will decrease.

In the last study decade, between 2011-2020, there is already a significant change compared to the climate of the base period. In Transylvania, in the hills of Bistrița-Reghin we find a few more cells that are very similar to the climate of the base period of Sâmboleni. Smaller spots that still have this quality can be found in the north around Râșnov, next to Baia de Arieș, south of Sibiu along the Olt and beyond the Carpathians in the areas of the Pre-Carpathians and Bucovina.

In addition to all of this, it is easy to notice that the climate of Sâmboleni that once characterized the Transylvanian plain has completely disappeared from the Carpathian basin in the last decade. If we look at the climate of the last 30 years, this disappearance is stronger in the northern part of the Carpathian basin and takes place more slowly in the Transylvanian plain (**Fig. 3b**).

### 3.3. Timișoara as reference location

The highest category of similarity indicators calculated for the base period of Timisoara includes the Great Plain, in its eastern extension as far as Satu Mare, the surroundings of Drava and Sava rivers, the surroundings of Komárom, as well as the south Pre-Carpathians (**Fig. 4a**).

In the four consecutive decades of the study period, compared to this base period, we can see the following. There are hardly any changes in the period 1981-1990. The highest similarity value is found in the vicinity of Nyíregyháza and Satu Mare, in the north the area with the highest similarity value is transferred from the vicinity of Komárom to the vicinity of Győr, and in the south beyond the Carpathian basin, the areas of the Oltenian Pre-Carpathians fall into the highest similarity category.

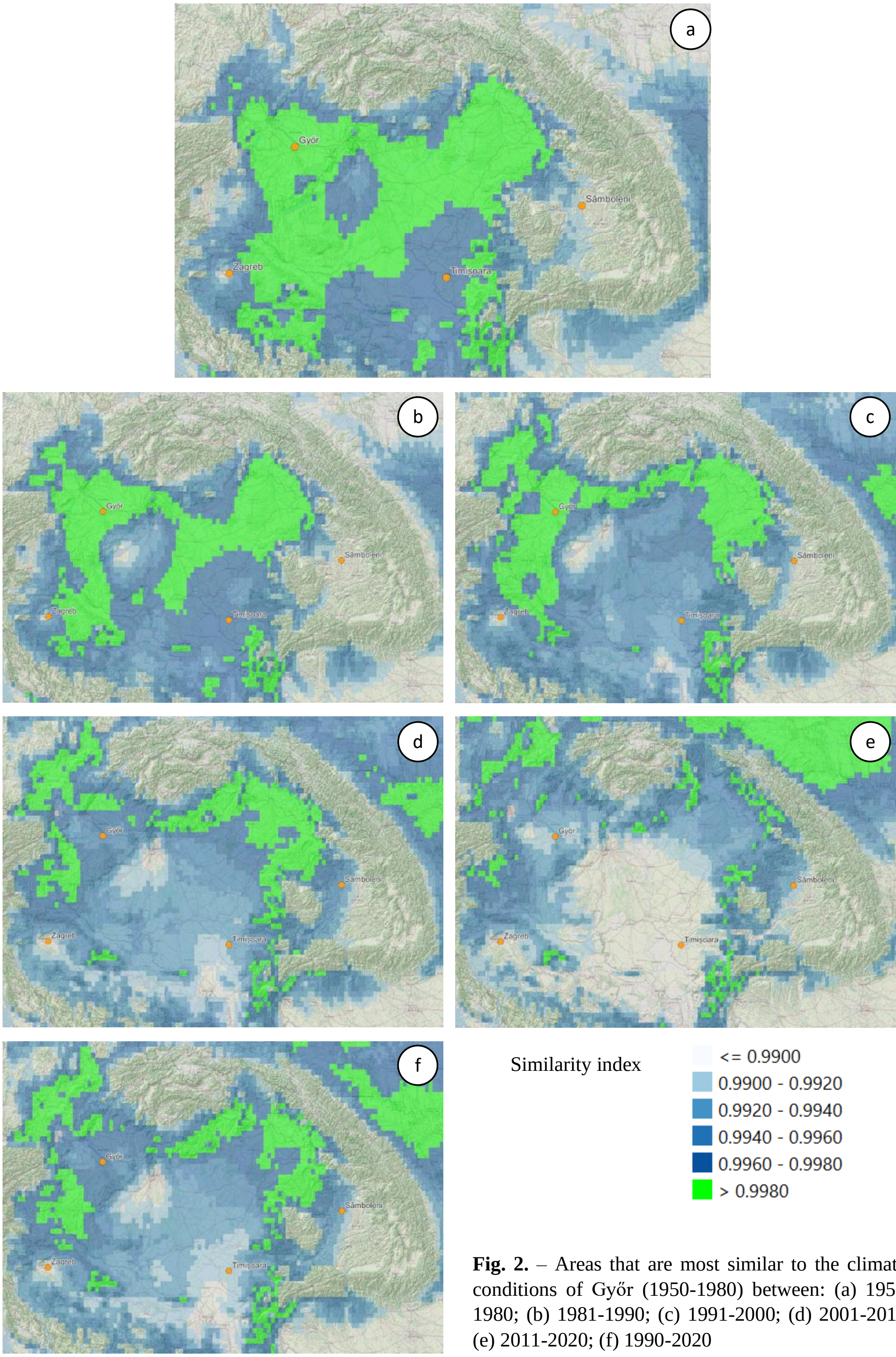


**Fig. 2.** – Areas that are most similar to the climatic conditions of Győr (1950-1980) between: (a) 1950-1980; (b) 1981-1990; (c) 1991-2000; (d) 2001-2010; (e) 2011-2020; (f) 1990-2020

The period 1991-2000 is the period of "expansion". The north-eastern tip of Hungary regains the status of the areas with the greatest similarity, and in the western part of the Carpathian Basin, Győr, Celldömölk, Nagyatád, Bjelovar, Banja Luka, a narrow band appears on the north-south axis, the areas of which have a high similarity with the similarity index calculated for the base period of Timisoara. In the 2001-2010 period, this expansion stalls and the previously unified, connected areas break up. Primarily, the areas of Drava River and Hernád, Timișoara and Cehu Silvaniei, Eger and Kosice, Banja Luka and Doboj come out of the category indicating the greatest similarity.

In the last study decade of 2011-2020, the areas with the highest similarity index show a decrease even more. Primarily, the southern and central parts of the south plain of Hungary and the Danube plain to the east of Pécs lose the status of the highest similarity category. In the south, the climate of the northern slopes of the Southern Carpathians becomes similar to the climate of the base period, in the east, the Moldavian plain and the Hotina ridge are among the areas indicating the highest category of similarity (**Fig. 4b**).

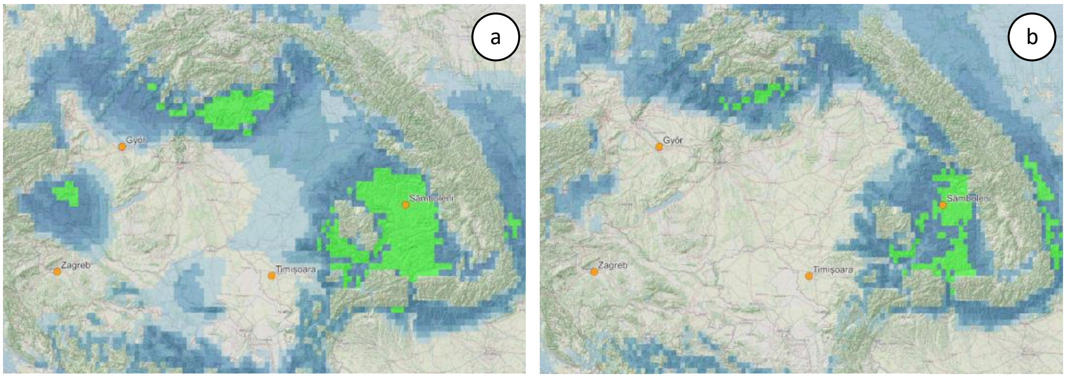


**Fig. 3.** - Areas of the Carpathian Basin that are most similar to the climatic conditions of Sâmboleni (1950-1980) in: (a) 1950-1980; (b) 1990-2020

Similarity index

<= 0.9900
0.9900 - 0.9920
0.9920 - 0.9940
0.9940 - 0.9960
0.9960 - 0.9980
> 0.9980

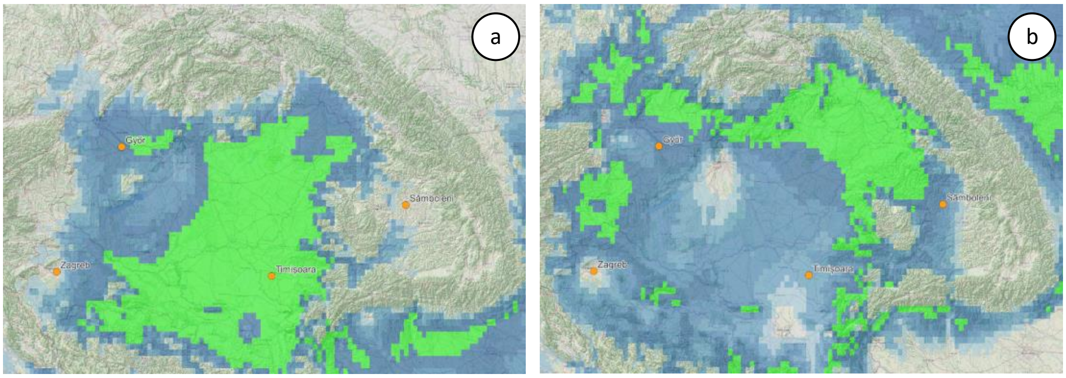


**Fig. 4.** - Areas of the Carpathian Basin that are most similar to the climatic conditions of Timișoara (1950-1980) in: (a) 1950-1980; (b) 2011-2020

Similarity index

<= 0.9900
0.9900 - 0.9920
0.9920 - 0.9940
0.9940 - 0.9960
0.9960 - 0.9980
> 0.9980

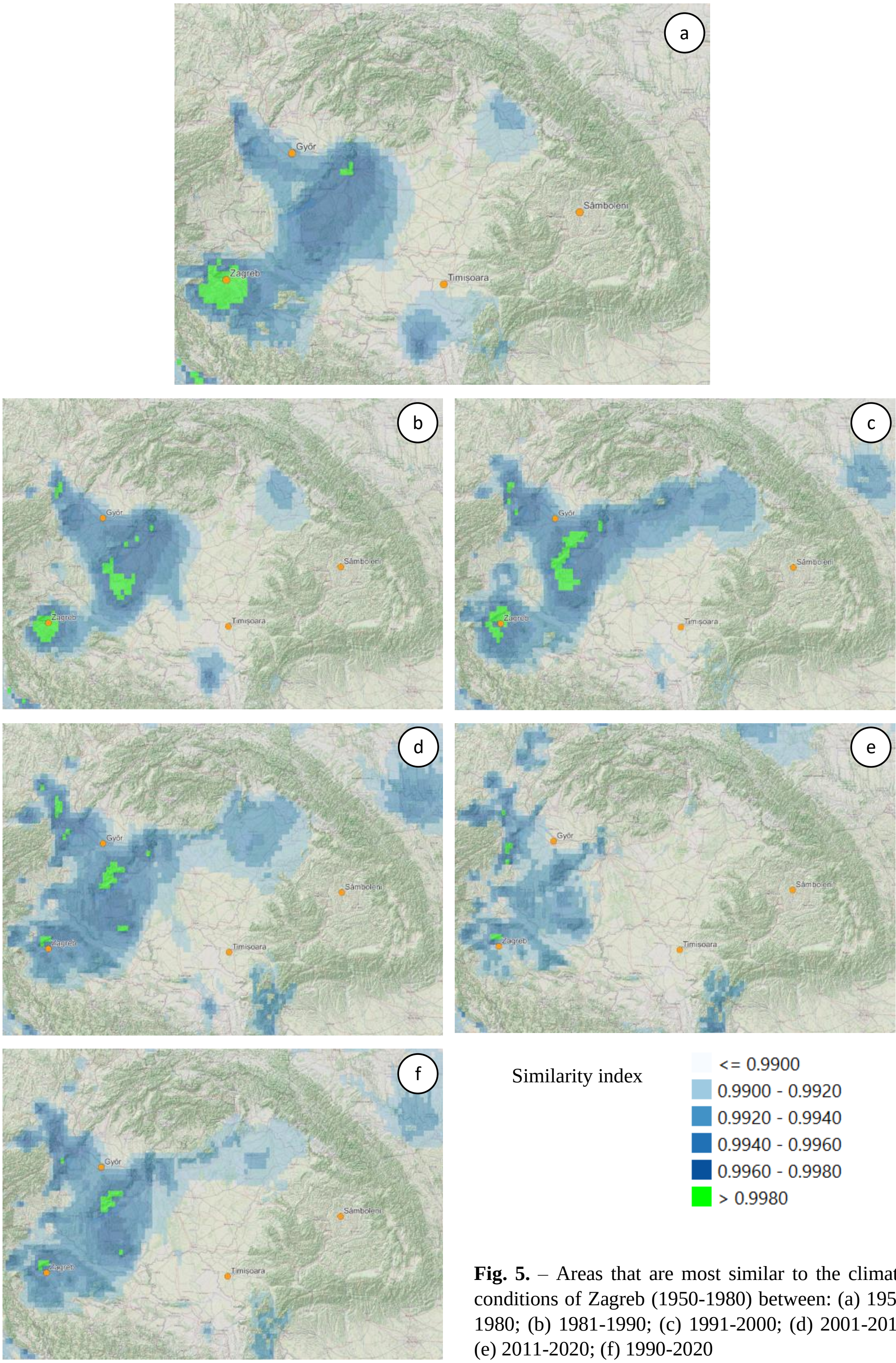


**Fig. 5.** – Areas that are most similar to the climatic conditions of Zagreb (1950-1980) between: (a) 1950-1980; (b) 1981-1990; (c) 1991-2000; (d) 2001-2010; (e) 2011-2020; (f) 1990-2020

### 3.4. Zagreb as reference location

The similarity indicators in the highest category calculated for the base period of Zagreb are almost exclusively limited to the surroundings of Zagreb, the Zagreb Basin (**Fig. 5a**). In the period 1981-1990, this area slightly decreases around Zagreb, and a new area appears north of Pécs in the area of the Transdanubia hills, whose similarity index is above 0.998, belonging to the highest similarity category (**Fig. 5b**). In the following decade, between 1991 and 2000, both of the previously mentioned areas migrated a little to the north and even extended in a northerly direction (**Fig. 5c**). In the following decade, the category with the greatest similarity to the base period almost completely disappears near Zagreb, but it appears north of Pécs and Vienna, as well as in the Bakony in the form of a small island (**Fig. 5d**). In the last study period, between 2011-2020, these small islands continue to shrink, and the climate of Zagreb's base period practically disappears from the Carpathian Basin (**Fig. 5e**).

## 4. CONCLUSIONS

In this research we examined how similar the periods 1950-1980, 1981-1990, 1991-2000, 2001-2010, 2011-2020 and 1990-2020 are to the climate experienced in each settlement between 1950-1980 (base period). We observed where the highest similarity category (above a similarity index of 0.998) appeared in the test periods. In the case of peripheral settlement - Zagreb, the former climate of it practically disappears from the Carpathian basin, and cannot be found in other areas. In the case of the other settlements, we can see primarily a migration, the direction of which basically takes place in the north, north-east direction. It can be clearly observed that in several cases, areas belonging to the highest similarity category also appear beyond the Eastern and North-Eastern Carpathians.

Based on the figures in the base period, the climate of Győr and Timisoara was the most typical among the investigated locations in the Carpathian Basin. Looking at the period 1990-2020 and taking into account the areas that have the greatest similarity compared to the base period, we can say that the climate of Timisoara's base period can still be found to the greatest extent in the Carpathian basin. This is the only settlement whose base period characteristics are present in a larger area today than in the 1950-1980 period.

Examining in percentage terms the extent on which the climate of the base period can be found in the Carpathian Basin in the last 30 years compared to the base period, we can see that the largest decrease occurs in the case of Zagreb. Compared to the base period, the areas which have very similar climate to the base period's is less than 32%. In case of Győr, this number is not much higher, around 38%, and in the case of Sâmboleni it does not reach 40%. As already mentioned, the climate of Timișoara is extending, considering the last 30 years, 105% of the original area has the climate of Timişoara's base period.

Although the present research is a first attempt in assessing the migration of the climate, it clearly shows that we can encounter at least two different situations. There are cases when a specific climate completely disappears from a given region, and there are situations when it conquers larger areas - even if in other locations.

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