OBSERVED CHANGES OF KÖPPEN CLIMATE ZONES IN SPAIN SINCE 1951

CAMBIOS OBSERVADOS EN LAS ZONAS CLIMÁTICAS DE KÖPPEN EN ESPAÑA DESDE 1951

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Abstract

Despite of having been originally formulated more than one hundred years ago, the Köppen classification is still nowadays the climate classification most widely used in climatological studies. Based on the empirical relationship between climate and vegetation, this climate classification provides an efficient and easy way to describe climate conditions and their seasonality by using a simple but ecologically meaningful classification scheme. This study examines the temporal evolution of the Köppen climate classification in Spain for the period 1951-2020, using high-resolution gridded datasets of monthly mean temperature and precipitation with 1 x 1 km spatial resolution. Climate classification maps for consecutive 30-year reference periods are compared, and the temporal evolution of each climate type in Spain is analysed, showing a progressive expansion of the arid climate zones and a contraction of the cold climate zones along the study period.

Keywords

Climate classification; Köppen; grid; climate change

Resumen

A pesar de haber sido originariamente formulada hace más de cien años, la clasificación de Köppen sigue siendo actualmente la clasificación climática más ampliamente usada en los estudios climatológicos en todo el mundo. Basada en la relación entre el clima y la vegetación, esta clasificación proporciona una forma eficiente y sencilla de describir las condiciones climáticas y su estacionalidad, usando un esquema de clasificación que resulta a la vez simple y consistente. En este estudio se examina la evolución temporal de los tipos de clima en España en el periodo

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1951-2020, usando rejillas de temperatura y precipitación de alta resolución, con celdas de 1 x 1 km. Se comparan los mapas de la clasificación climática obtenidos para periodos consecutivos de 30 años, y se analiza la evolución temporal de cada tipo de clima en España, poniéndose de manifiesto una expansión progresiva de los climas áridos y una contracción del área ocupada por los climas fríos en el territorio español en el periodo de estudio.

Palabras clave
Clsificación climática; Köppen; rejilla; cambio climático

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1. INTRODUCTION

Despite of having been originally formulated more than one hundred years ago, the Köppen classification is still nowadays the climate classification most widely used in climatological studies (Kottek *et al*., 2006) by researchers across a range of disciplines as a basis for climatic regionalisation of variables and for assessing the output of global climate models (Peel *et al.*, 2007). In the last decades, it has been also frequently used for climate change impact assessments (Beck *et al*., 2018).

Based mainly on the relationship between climate and distribution of the vegetation, the Köppen classification defines different types of climate based on the average monthly and annual values of temperature and precipitation, establishing thresholds for the delimitation of different types of climate (Essenwanger, 2001).

In this article, the observed variations in the areas of the Köppen climate zones in Spain during the 1951-2020 period are analysed, applying the classification scheme to the high-resolution gridded datasets of temperature and precipitation recently generated in the Climatology Area of the Spanish State Meteorological Agency (AEMET), following the same procedure used in other recent similar studies (Chazarra *et al.*, 2022; Chazarra *et al.*, 2023).

2. METHODOLOGY

We follow, almost exactly, the classification scheme proposed by Köppen in his last revision of 1936, sometimes known as Köppen-Geiger classification (Köppen, 1936). The only difference is that temperate C and cold D climates are distinguished using a 0 °C threshold instead of a 3 ºC threshold, following the suggestion of Russell, Trewartha, Critchfield and others (Essenwanger, 2001). This scheme was used in the updated world map of the Köppen-Geiger climate classification published in 2007 by Peel (Peel *et al*., 2007), and it is exactly the same that the one used in the climatic maps published by the Spanish State Meteorological Agency for the 1981-2010 reference period (Chazarra *et al*., 2018), and in the maps of the Climate Atlas of Spain and Portugal (AEMET, IM, 2011; 2012) for the 1971-2000 period.

The Köppen-Geiger classification scheme was applied to the high-resolution gridded datasets of temperature and precipitation generated in the Climatology Area of the Spanish State Meteorological Agency (Chazarra *et al*., 2020; Romero *et al*., 2020). These gridded datasets were generated by spatial interpolation of the monthly temperature and precipitation data currently stored in the Spanish National Climate Database of the AEMET. The method used for the spatial interpolation of the temperature data was regression kriging, using altitude, latitude and distance to the coast as independent variables, with an ordinary kriging for the interpolation of the residuals. The precipitation data were spatially interpolated by ordinary kriging.

The selected study period was 1951 to 2020, in order to cover the 30-year climatic reference periods 1951-1980, 1961-1990, 1971-2000, 1981-2010 and 1990-2020 established by the World Meteorological Organization for climate monitoring studies (WMO, 2017).

Two study areas were considered (Figure 1): the first one comprises continental Spain and the Balearic Islands, and the second one the Canary Islands.

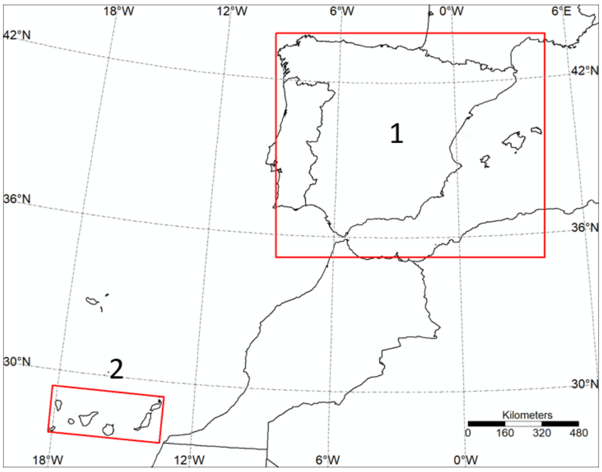


FIGURE 1. STUDY AREAS

Regarding the spatial resolution, 1 x 1 km cells were chosen for the temperature and precipitation grids.

The climatic boundaries were calculated by applying the Köppen-Geiger scheme to the monthly temperature and precipitation grids, using map algebra techniques through SAGA GIS (version 6.3.0) and R software.

With the purpose of analysing the temporal evolution of the climate zones, a 30-year moving windows procedure was applied over the study period, following the methodology used in other previous similar studies (Beck *et al*., 2005; Chazarra, 2012). Finally, in order to study the statistical significance of the observed trends, Spearman and Kendall rank correlation tests were applied to the series of the areas occupied by each climate, considering 30-year simple moving averages.

3. RESULTS

3.1. KÖPPEN-GEIGER CLIMATE ZONES IN 30-YEAR REFERENCE PERIODS

In Figure 2, the climate zones obtained for each 30-year reference period of the 1951-2020 period are shown. Four of the five main climates (B, C, D and E) are found in Spain in the study period.

All four of the arid climates are present in Spain. The dominant arid climate is BSk, covering wide areas of the southeast, centre and northeast of the Iberian Peninsula, Ibiza, southeast of Majorca and medium altitude areas of Tenerife and Gran Canaria islands. BSh type is located in small areas of the southeast of the Iberian Peninsula and the Canary Islands. At first glance, both BSk and BSh climates show an evident growth in the successive reference periods.

Regarding the desert climates, BWh type is observed in Lanzarote and Fuerteventura islands, in the south of Tenerife and Gran Canaria islands, and in small zones of Almería, Murcia and Alicante provinces in the Mediterranean coast. BWk type is located only in small areas of Almería and Murcia provinces. In the southeast of the Iberian Peninsula, the area occupied by BWh and BWk climates shows a slight net growth, although showing evident fluctuations in the different reference periods. In the Canary Islands, an expansion of the BWh type zone and a contraction of the area occupied by BWk climate are observed.

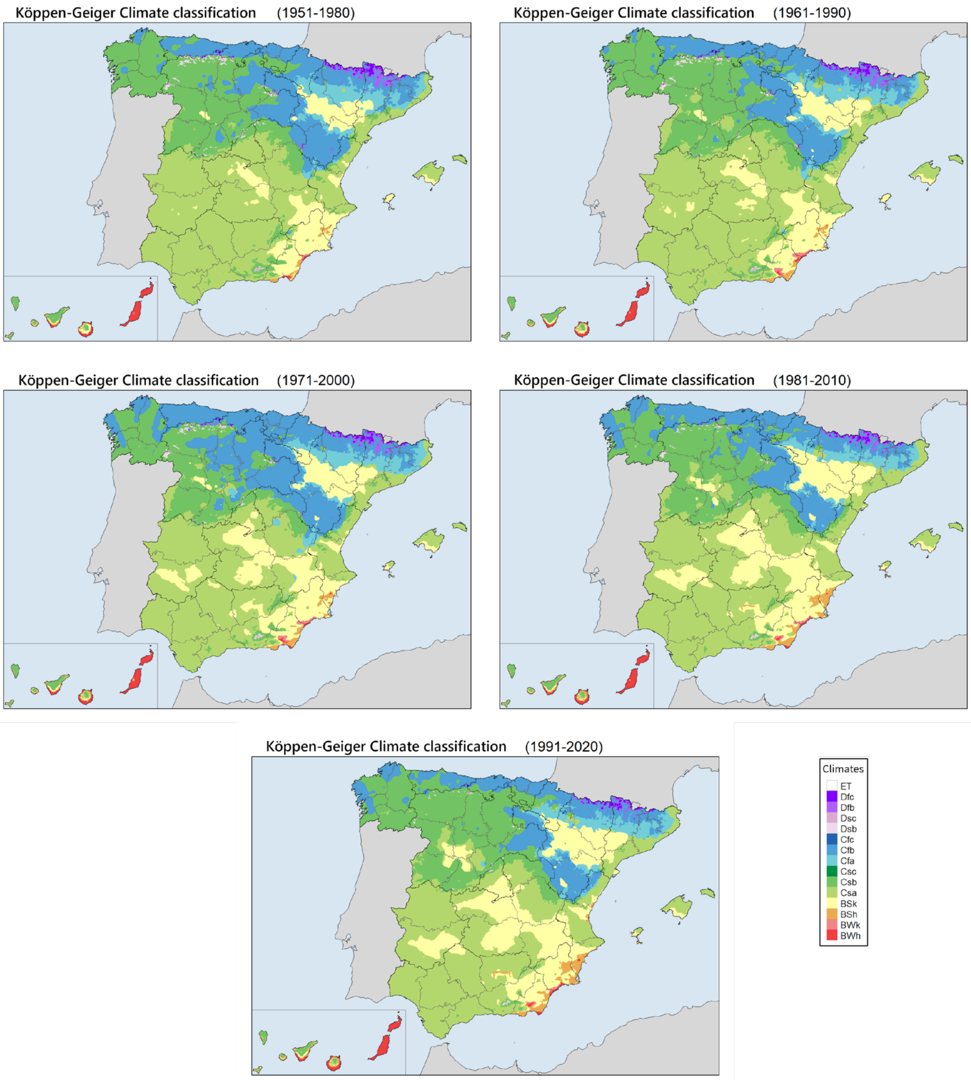


FIGURE 2. KÖPPEN-GEIGER CLIMATE ZONES IN SPAIN IN THE REFERENCE PERIODS 1951-1980, 1961-1990, 1971-2000, 1981-2020 AND 1991-2020

Six temperate climates are found in Spain: Csa, Csb, Csc, Cfa, Cfb and Csc. The dominant temperate climate type is Csa, which covers wide areas in the south of the Iberian Peninsula, northeast coastal zones of the peninsula, the Balearic Islands and small areas of the Canary Islands. This climate type shows and evident decrease in his area due to the expansion of the arid climates in the continental Spain. Csb type is located mainly in Galicia, northern plateau of the Iberian Peninsula, mountainous regions of the centre and south of continental Spain, and medium and high altitude zones of the Canary Islands. Csc type is observed only on the slopes of the Teide volcano during the 1971-2000 reference period.

Cfa type is mainly located in the northeast of the Iberian Peninsula, in a medium altitude range surrounding the Pyrenes and the Iberian System. Cfb type is observed in some areas of Galicia, Cantabrian region, the Iberian System and the Pyrenes, and also in the east of the northern plateau in some reference periods. Both Cfa and Cfb type areas show fluctuations between the different reference periods, with a net decrease along the study period. Cfc type is located only in small regions of the Cantabrian Mountains.

Four cold climate types are observed: Dsb, Dsc, Dfb and Dfc. Dsb and Dsc types are located in small high altitude areas of the Cantabrian Mountains, Central and Iberian Systems, Sierra Nevada and the Teide volcano, whereas Dfb and Dfc are observed in high mountain areas of the Pyrenes, Cantabrian Mountains and Iberian System. These four climate types show and evident decrease in their areas in the successive reference periods.

Finally, the polar climate type ET is observed only in the highest peaks of the Pyrenes in the two first reference periods, disappearing in 1981-2010 and subsequent reference periods.

3.2. TEMPORAL EVOLUTION OF THE MAIN CLIMATE ZONES USING 30-YEAR MOVING AVERAGES

In this section, the temporal evolution of the major climate zones is analysed using 30-year simple moving averages along the 1951-2020 study period. In the graphs (Figure 3), the percentage of the study area occupied by each climate zone

FIGURE 3. TEMPORAL EVOLUTION OF THE AREA OF EACH MAIN CLIMATE TYPE IN THE CONTINENTAL SPAIN AND BALEARIC ISLANDS ZONE, CONSIDERING 30-YEAR MOVING AVERAGES

in the successive 30-year windows is shown, being each window designated by the last year of the interval.

As shown in Figure 3, the arid B climate has experienced a remarkable expansion in continental Spain and the Balearic Islands zone, growing since 11 % of the territory in the first years to near 21 % in the last years, almost doubling his area. This growth is observed mainly in the 1990s and the 2000s, whereas the area of this climate remains approximately constant in the previous and posterior periods.

The temperate C climate shows almost exactly the opposite pattern compared to the B climate, having decreased his area since 87 % to near 78 % in the study period, due to the expansion of the arid climate. This shrinking has occurred mainly in the last decade of the twentieth century and the first decade of the twenty-first century.

The cold D climate also shows an evident shrinking, having decreased his area since 2 % to least than 1 %. For this climate, the decrease has been constant along the study period.

The polar E climate, which was located only in the highest mountains of the Pyrenes during the first years of the study period, shows a rapid retreat until became totally extinguished in the mid-1990s.

Having applied the Spearman and Kendall rank correlation tests to the series of the areas occupied by each main climate in the continental Spain and the Balearic Islands study zone, considering 30-year simple moving averages, a significant positive trend at a 99 % confident interval was found for the B climate, and significant negative trends at a 99 % confident interval for climates C, D and E.

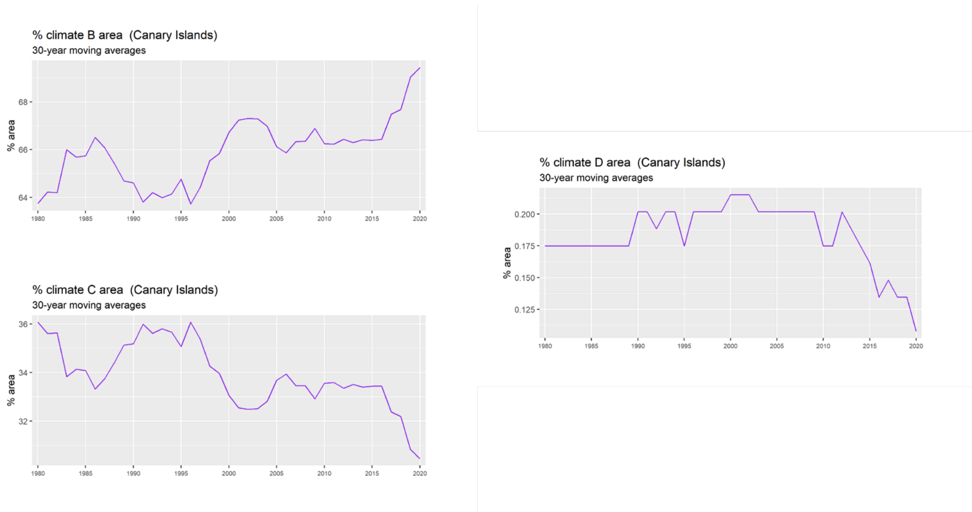


FIGURE 4. TEMPORAL EVOLUTION OF THE AREA OF EACH MAIN CLIMATE TYPE IN THE CANARY ISLANDS ZONE, CONSIDERING 30-YEAR MOVING AVERAGES

In the Canary Islands study zone, the arid B climate has also grown at expenses of the temperate C climate in the study period, but in this case the observed changes are not so pronounced: B climate shows an increase in his area from 64 % of the territory to 69 %, whereas C has experienced a decrease from 36 % to less than 31 % of the territory.

The cold D climate, observed only on the highest slopes of the volcano Teide, maintains an almost constant area except for the last decade of the study period, when decreases from 0.2 % to near 0.1 % of the territory.

Having applying the Spearman and Kendall rank correlation tests to the series of the areas occupied by each main climate in the Canary Islands study zone, a significant positive trend at a 99 % confident interval was found for the B climate, a significant negative trend at a 99 % confident interval was found for climate C, whereas there is no significant trend for D climate at a 95 % confident interval.

3.3. TEMPORAL EVOLUTION OF THE TEMPERATURE AND THE PRECIPITATION IN SPAIN ALONG THE STUDY PERIOD

To help understand the obtained results, the temporal evolution of the annual mean temperature and the annual total precipitation in each study zone in the 1951-2020 period has been represented (Figure 5), as well as the observed tendencies. This series has been generated using the high-resolution gridded series employed in this study for the climate classification.

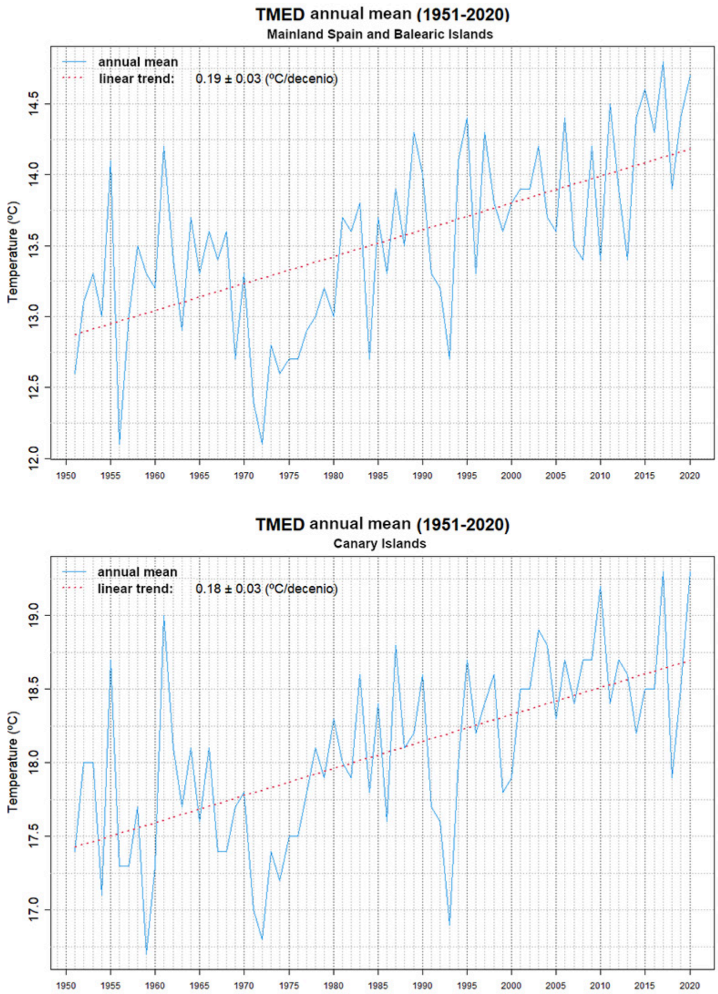
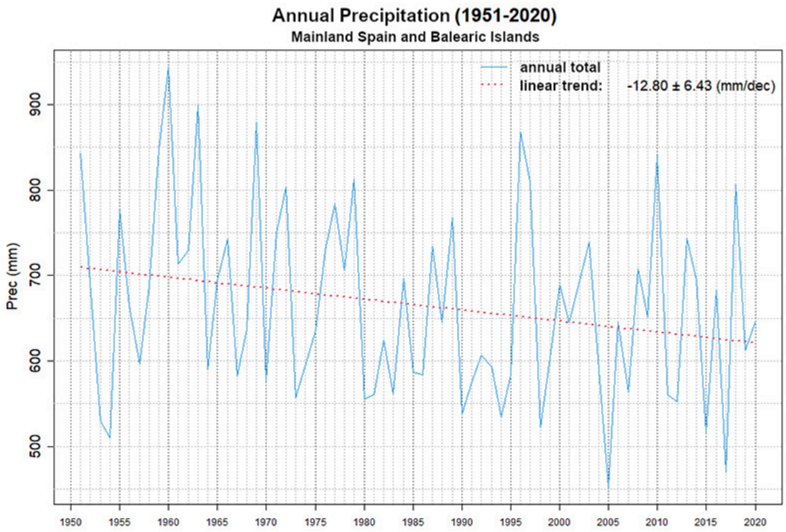
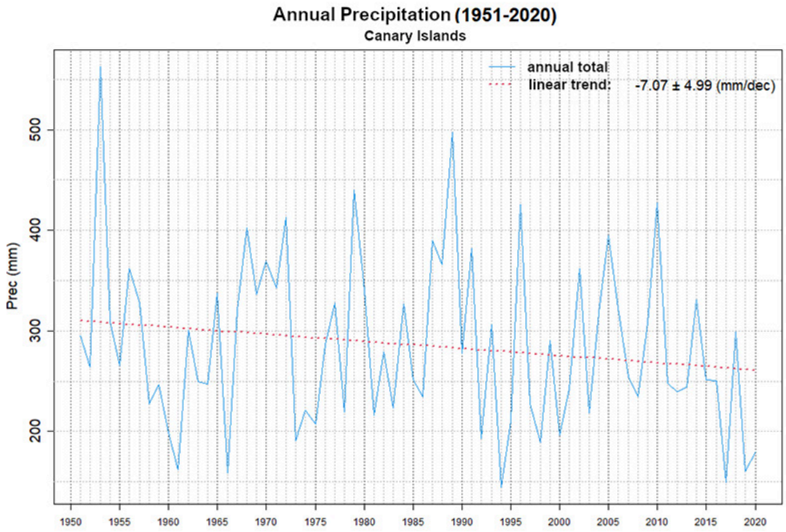


FIGURE 5. TEMPORAL EVOLUTION AND TENDENCIES OF THE ANNUAL MEAN TEMPERATURE AND THE ANNUAL TOTAL PRECIPITATION IN EACH STUDY ZONE IN THE 1951-2020 PERIOD





The annual mean temperature series show a positive tendency of 0.19 ± 0.03 ºC/decade in the continental Spain and the Balearic Islands study zone, and 0.18 ± 0.03 ºC/decade in the Canary Islands zone, both tendencies significant at a 99 % confident interval when applying the Spearman and Kendall rank correlation tests.

Regarding the precipitation, the other climatic variable considered in the Köppen-Geiger classification, a slightly negative trend is observed, -12.80 ± 6.43 mm/decade in the continental Spain and the Balearic Islands and -7.07 ± 4.99 mm/decade in the Canary Islands, but this tendencies are not significant at a 95 % confidence interval when applying the Spearman and Kendall rank tests, and they show, in addition, a considerable margin of error.

4. CONCLUSIONS

These results show a progressive and statistically significant growth of the arid B climate zone at the expense of the temperate C climate in both study areas during the study period 1951-2020, and a regression of the cold D climate in the continental Spain, being replaced by C climate.

It is also remarkable the rapid decrease of the cold E climate zone, which was located only in the highest mountains of the Pyrenes in the beginning of the study period, until became totally extinguished in the mid-1990s for the spatial resolution used in this study (1 x 1 km cell grids). This result coincides with the significant decrease of the glacier-covered area observed in the Pyrenees in the study period 1951-2020, which is near to 80 %, and it has accelerated since the early 1980s (Rico *et al.*, 2017), confirming the rapid decline of the mountain glaciers of the Pyrenes observed at the end of the 20th century and the beginning of the 21st.

The results of this study summarize the effects of the global warming observed in the last decades in the spatial distribution of the climate and vegetation zones in Spain, and they are consistent with the changes observed at a global scale over the period analysed (IPCC, 2021).

Considering the trend observed in the annual mean temperature in the study period, statistically significant at 99 % level of confidence, it follows that the decrease of the cold D and polar E climate zones, which boundaries are calculated taking into account the mean temperature of the coldest and the warmest month of the year, is a direct consequence of the warming observed during the study period in Spain.

Regarding the arid B climate zone, which boundaries depend on the monthly temperature and precipitation, we can conclude that the expansion of his area is mainly due to the observed rise of the temperature and, to a lesser extent, to a slight decrease of the precipitation, though this reduction of the precipitation amount is not statistically significant and should be considered with caution. There is a greater degree of evaporation due to the warming of the temperature that is not compensated with a higher precipitation rate, which leads to a diminution of the amount of the water available to plants and, as a consequence, to an expansion of the arid B climate zone and a reduction of the temperate C climate zone of the Köppen-Geiger classification.

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