Evaluating inter-model variability among CMIP6 projections of future Köppen–Geiger climate zones in Kazakhstan under SSP5-8.5

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Absztrakt

Tanulmányunk az SSP5-8.5 forgatókönyv szerint vizsgálja, hogy a jövőre nézve mennyire megbízható a több modellen alapuló Köppen–Geiger-féle éghajlat-osztályozási térkép. A CMIP6 projekt 32 modelljének felhasználásával a század végi állapotokra készítettünk osztályozási előrejelzéseket Kazahsztán területére. Létrehoztunk egy modális térképet, amely minden pixelhez a leggyakrabban előrejelzett éghajlati zónát jeleníti meg. Az előrejelzések bizonytalanságának bemutatására további térképeket készítettünk, amelyek a másodlagos zónákat is megjelenítik, ahol a valószínűségük egy meghatározott küszöbértéknél magasabb. Az osztályozás megbízhatóságának értékeléséhez három küszöbértéket vezettünk be, hogy megjelenítsük a magas, közepes és alacsony bizonyosságú zónákat. Ez a megközelítés kiemeli azokat a régiókat, ahol az éghajlati besorolás kevésbé megbízható, és ahol további modellezésre vagy adatgyűjtésre lehet szükség a megbízhatóság növelése érdekében. Megállapítottuk, hogy a modellkimenetek között jelentős különbség van, ezért hangsúlyozzuk, ezeket óvatosan kell kezelni.

Abstract

The focus of our study is the uncertainty of the inter-model Köppen–Geiger climate classification map for the future under the SSP5-8.5 scenario. We created classification predictions using 32 models from the CMIP6 ensemble for the end of the century across Kazakhstan. We created a modal map to display the most frequently predicted climate zone for each pixel. To indicate the uncertainties of the predictions, additional maps were created that also show the secondary zones where their probability is higher than a specified threshold. To evaluate classification confidence, we applied three thresholds to visualize zones of high, moderate, and low certainty. This approach highlights regions where the climate classification is less reliable and where further modelling or data collection may be needed to enhance confidence. Given the significant variability among model outputs, our findings emphasize the need for cautious interpretation.

1. Introduction

Kazakhstan is a landlocked country in Central Asia, characterised by cold desert, steppe, and continental climates. The climate varies across regions: the northeast has a continental climate with very cold winters and warm summers (Dfa, Dfb), while the southwest is mostly cold desert (BWk) and semi-desert or steppe (BSk). The Köppen climate zones present in the territory of Kazakhstan are illustrated in Figure 1.

Greenhouse gas emissions are the main driver of climate change (Callendar, 1938 and Keeling, 1965), and so, the rise of mean temperature is making a direct impact on the country's climate patterns. With ongoing climate change and rising global temperatures, many studies report on the impact of climate change. Hu et al. (2020) showed that a significant territory of Kazakhstan (approximately 76.1 %) is prone to desertification, with the western regions being the most affected due to climate change and human activities, particularly in agriculture and animal husbandry. Bissenbayeva et al. (2025) concluded that the northern part of Kazakhstan is the most vulnerable to desertification, particularly in areas where land is used for pasture. The study identified that precipitation is the main factor influencing desertification. Additionally, Li et al. (2025) demonstrated that global warming may have catastrophic effects on Central Asia by the end of the century, especially under scenarios of fossil fuel development. It shows that the Central Area are projected to be exposed to heatwaves over the century. Apart from that, the study also highlights a significant shift in Köppen–Geiger climate zones in the region, with a trend toward warmer climates. For example, a shfit from BWk (cold desert) to BWh (hot desert) is expected, indicating increased aridity and higher temperatures.

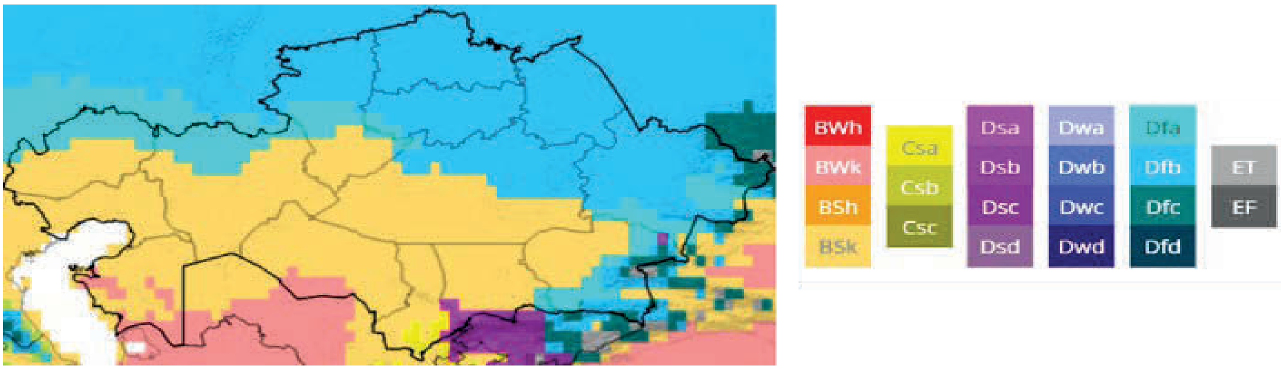

Figure 1. The Köppen climate map of Kazakhstan for 1991–2020 (World Bank, 2025)

Among other impacts of climate change, it is crucial to understand how the boundaries of climate zones will change in the future. This knowledge provides a broader understanding of the potential changes, their consequences for water and land management, agriculture, ecosystems and societal systems, furthermore, it offers insights into how we can mitigate or adapt to these changes effectively. Therefore, it is important to explore Kazakhstan's prospective climate zones, especially considering industrial development and global warming. There are several foundational studies in examining climate zones based on the Köppen–Geiger classification, including Kottek et al. (2006), who presented the digital classification map, and Peel et al. (2007), who updated the world's Köppen–Geiger climate map. Later, Beck et al. (2018) presented a high-resolution global Köppen–Geiger climate map at 1 km for the historical period and projected future maps using the Fifth Coupled Model Intercomparison Project (later: CMIP5) and Coupled Model Intercomparison Project Phase 6 data (later: CMIP6) (Beck et al., 2023).

This study is part of broader investigation on how the climate zones are changing in Kazakhstan and it aims to project the future climate zones of Kazakhstan using the Köppen–Geiger classification for the period 2071–2100, under the high-emission scenario Shared Socioeconomic Pathway (later: SSP) 5-8.5 (Riahi et al., 2017). The use of climate models (Thrasher, 2012), together with advanced tools like Google Earth Engine (GEE) and QGIS, allowed us to produce a projective modal Köppen–Geiger climate map and corresponding models' variability maps for Kazakhstan. Identifying vulnerable areas is crucial for developing sustainable adaptation and mitigation policies, protecting ecosystems and biodiversity, and assessing the economic impact of climate zone shifts.

2. Methodology and Results

In this study, the CMIP6 ensemble was used to generate Köppen–Geiger climate maps. CMIP6 is a collection of climate models utilized in climate studies, with data available from 1950 to 2100. The aim of this work is to explore how future climate zones will possibly/probably change by the end of the century, specifically by examining climate maps for the 2071-2100 period. Moreover, CMIP6 projects future climate through the SSP considering different scenarios. For this analysis, we selected SSP5-8.5, a worst-case scenario characterized by high economic growth and high greenhouse gas emissions.

The methodology for generating Köppen–Geiger climate maps is outlined in our work, 'Spatial and Temporal Analysis of Climatic Zones in Kazakhstan Using Google Earth Engine' (Yessimkhanova and Gede, 2025, under preparation). In that study, a web application was developed based on Google Earth Engine (GEE) that generates customizable Köppen–Geiger maps based on time, region, and emission scenarios. The code for generating these maps is available in our GitHub repository (Yessimkhanova, 2025). This methodology is currently in preparation for publication in an upcoming paper. Moreover, future Köppen–Geiger climate maps generated by this tool indicate areas where new emerging climate zones will appear by the end of the century. According to the projected climate maps, zones BWh (hot desert), BSh (hot semi-arid) and Csa (mediterranean) will feature in the southwest (BWh) and southern (BSh and Csa) part of Kazakhstan. For the current study, Köppen–Geiger climate maps were generated for Kazakhstan using each of the 32 climate models from the CMIP6 ensemble. The result is a 32-band raster image, indicating the climate zone classification result for each model at each pixel. The models used in the study are listed in Table 1 (Eyring et al., 2016).

All data processing was carried out in Google Earth Engine (later: GEE), as the platform provides the necessary data and functionalities to perform this task. GEE is a cloud-based service that enables complex computations and analysis of Earth Observation data. It provides the computational power to address challenging issues such as drought, deforestation, disasters, water management, food security, and more (Gorelick et al., 2017). As mentioned before, the algorithms for generating Köppen–Geiger climate maps were developed in GEE, and for further analysis of the projected climate maps, GEE functions were used to aggregate multiple values into a single result. Therefore, the modal map of Kazakhstan was generated using the ee.Reducer.mode() function (Google, n.d.). This reducer counts the frequency of each value, in this case a specific climate zone for a given pixel, and selects the most frequent one. By doing this, it is possible to identify the leading climate zone for each pixel (Figure 2).

Table 1. Climate Models Used in the Study

Model Name	Country of origin
ACCESS-CM2	Australia
ACCESS-ESM1-5	Australia
BCC-CSM2-MR	China
CESM2	USA
CESM2-WACCM	USA
CMCC-CM2-SR5	Italy
CMCC-ESM2	Italy
CNRM-CM6-1	France
CNRM-ESM2-1	France
CanESM5	Canada
EC-Earth3	Europe (Consortium)
EC-Earth3-Veg-LR	Europe (Consortium)
FGOALS-g3	China
GFDL-CM4	USA
GFDL-ESM4	USA
GISS-E2-1-G	USA
HadGEM3-GC31-LL	UK
INM-CM4-8	Russia
INM-CM5-0	Russia
IPSL-CM6A-LR	France
KACE-1-0-G	South Korea
KIOST-ESM	South Korea
MIROC-ES2L	Japan
MIROC6	Japan
MPI-ESM1-2-HR	Germany
MPI-ESM1-2-LR	Germany
MRI-ESM2-0	Japan
NESM3	China
NorESM2-LM	Norway
NorESM2-MM	Norway
TaiESM1	Taiwan
UKESM1-0-LL	UK

Considering that this is a future modal map, there may be a second leading climate zone close in frequency to the dominant modal zone. Since these are projections for the end of the century under high emission scenarios, different outcomes are possible. Therefore, areas where the second most frequent climate zone is close to becoming the leading modal zone were visualized. Following this, three maps were created to evaluate the projected modal climate zones. This evaluation provides insights into how climate models project future climate zones for a specific pixel

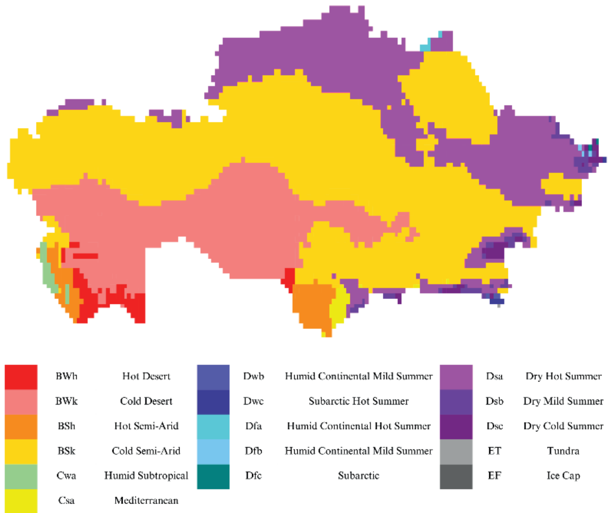

Figure 2. Modal Köppen–Geiger climate map of Kazakhstan (2071–2100, SSP5-8.5)

and help the assessment of the uncertainty in classification meaning the differences in the output produced by different models. It is important to note that this study does not assess the inherent uncertainty of the climate system itself, which is related to the structural characteristics and design of the climate models used. Consequently, to proceed with this evaluation, inter-model variability was investigated, which indicated areas with differing levels of classification uncertainty in assigning a specific climate zone to each pixel. Three different thresholds were used to represent areas of model variability with high, moderate, and low levels of uncertainty. These thresholds imply a different degree of uncertainty in representing the future Köppen–Geiger climate zone by visualizing model variabilities across models. Although the modal map already shows the most frequent zone at each pixel, there might be secondary zones that are similarly significant. To assess the uncertainty of predictions, the number of models predicting the various climate classes for each pixel was calculated, creating a new, 4-band image, with the following bands: the class with most predictions (best1), the number of models predicting best1 (best1cnt); the class with the second most predictions (best2), and the number of models predicting best2 (best2cnt). The certainty of prediction is characterized by the ratio of best1cnt and best2cnt. Next, the image created in GEE was exported and the visualization in QGIS, which offers more flexibility, was completed. The certainty of classification can be expressed by how many times the frequency of most leading zone is higher than the second one (best1cnt/best2cnt). The higher the number, the greater the certainty. For example, if a given pixel was classified as zone X by 15 models and as zone Y by 5 models, then the certainty is 3. Following this logic threshold 1.5, 2 and 3 were applied to identify areas with uncertainty. These thresholds are boundaries indicating areas where the frequency of the leading zone is less than 1.5, 2, or 3 times higher than the frequency of the second. The areas of high uncertainty (threshold 1.5) are illustrated through vertical line patterns as shown in Figure 3 (hatch colours indicate the two most probable zones).

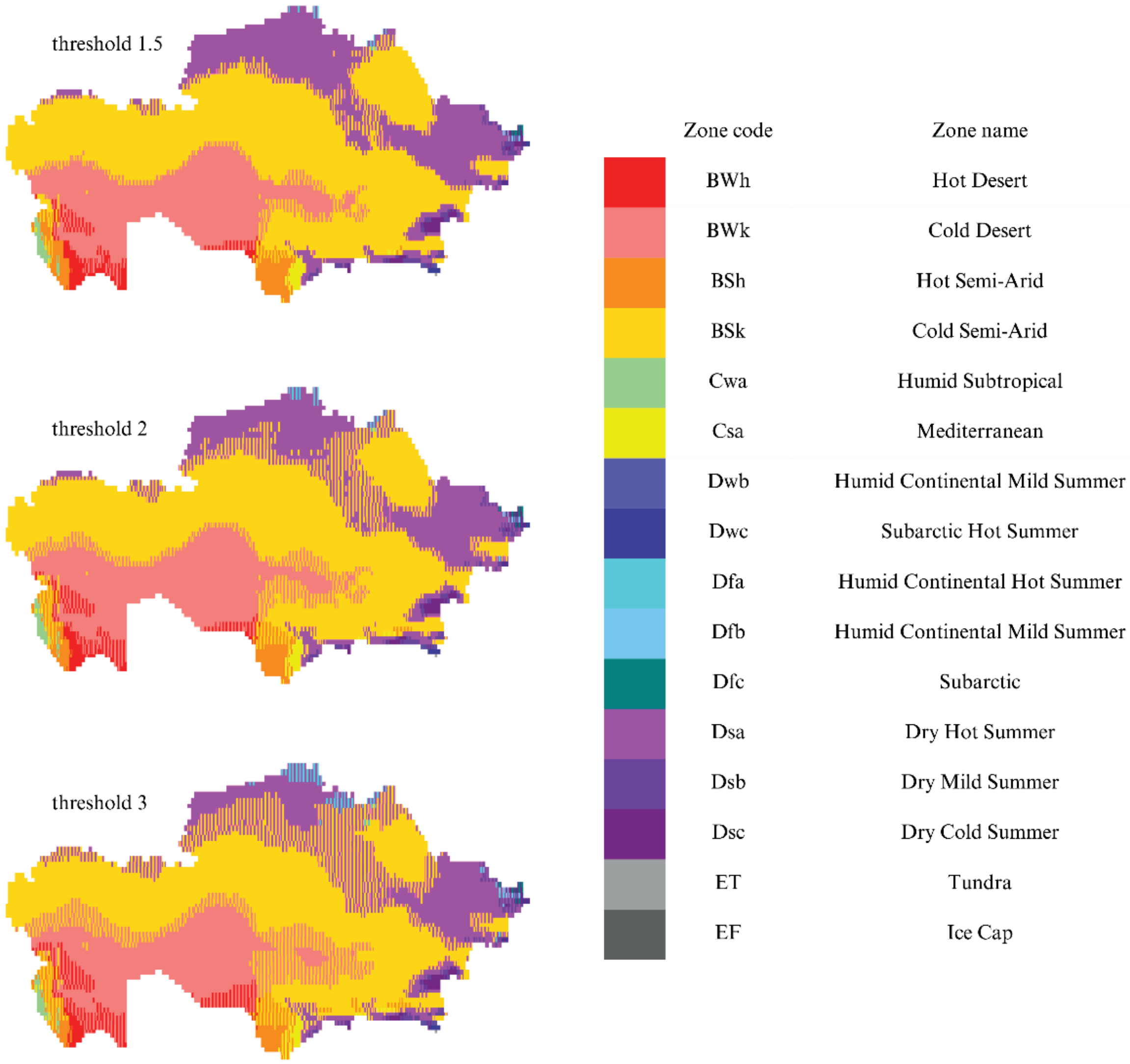

Figure 3. Modal Köppen–Geiger climate map of Kazakhstan (2071–2100, SSP5-8.5), with uncertainty areas shown in a linear pattern (high threshold < 1.5, moderate threshold < 2, low threshold < 3)

Consistent with the previous approach, threshold 2 is applied to visualize areas with moderate uncertainty, and threshold 3 is used for areas with low uncertainty. Figure 3 shows high variability (threshold < 1.5) of climate models at zone's borderlines, while the use of threshold 2 expands these areas of uncertainty. In these regions, the future climate zone is difficult to predict, and it could either remain the same as the leading zone or shift to the second frequent climate zone. As the threshold value increased to 3 (indicating low uncertainty), the areas shown in Figure 3 appear more consistent, with most models predicting the same climate zone – making misclassification unlikely.

3. Discussion

The modal Köppen–Geiger climate map of Kazakhstan for the time period 2071–2100 under the high-emission scenario SSP5-8.5 shows a significant transition of climate zones across the country. In particular, the northern part of Kazakhstan (including the North Kazakhstan region, the north of the Kostanay region, and the northeast of the Akmola region) as well as the eastern part (including the Abay and East Kazakhstan regions, with the southern part of East Kazakhstan transitioning to BSk (cold semi-arid climate)) are likely to experience a shift to a dry climate with hot summers (zone Dsa), replacing the current humid continental climate with hot and mild summers (zones Dfa and Dfb, respectively). This potential transition could significantly impact the agriculture sector, especially in the Akmola, Kostanay and North Kazakhstan regions, which are major wheat producer (U.S. Department of Agriculture [USDA], 2022). A dry climate may reduce precipitation, which can negatively affect crop yields.

Furthermore, the northeastern part of the country, specifically the Pavlodar region, is expected to transition into the BSk climate zone. There will also be a significant northward and north-eastward expansion of the BSk zone, including parts of East Kazakhstan, Aktobe, the central and southern parts of the Kostanay region, the east and south of the Akmola region, and the Karaganda region (with some areas in the northeast of the region transitioning to Dsa). The BSk zone will also expand into the Zhetysu, Almaty, and Zhambyl regions. In addition, a slight expansion of the Csa (mediterranean) climate zone is expected in the southern parts of the country, particularly around Shymkent city and its neighbouring areas. The BWk (cold desert) zone is predicted to expand northward from Aktau, Atyrau, Mangystau, and the south of the Aktobe region, as well as parts of Kyzylorda, west and south of Ulytau, and the surrounding areas. The expansion of arid climates poses significant challenges for affected regions, including desertification, reduced precipitation, and increased water scarcity.

Importantly, two new emerging climate zones are predicted by the end of the century under the SSP5-8.5 scenario. Zone BWh (hot desert climate) is expected to appear in the southwest along the Caspian shore, particularly in the Mangystau region and its southern parts. Another BWh zone will emerge in the south of Kyzylorda, near the border with Uzbekistan. The BSh (hot semi-arid climate) zone will also develop in the southern parts of the country, particularly in the Turkistan region. The projected emergence of new climate zones in southern Kazakhstan creates significant challenges to agriculture and food security. These regions, currently favorable for cultivating fruits, vegetables, cotton, and rice, may face adverse effects due to the transition to arid climates. Increased heatwaves and water scarcity could threaten crop yields and livestock productivity. Moreover, the broader climatic shifts across the country are likely to impact ecosystems and biodiversity, with reduced precipitation and more frequent heatwaves.

4. Conclusions

This study investigates how climate models project future Köppen–Geiger climate zones at the pixel level and assesses uncertainty using inter-model variability of CMIP6 ensemble under the SSP5-8.5 scenario in Kazakhstan. Different climate models may assign different future climate zones to the same pixel, and this disagreement is used as a measure of uncertainty in classification. A modal map was generated to show the most frequent climate zone for each pixel, along with the second most frequent zone to capture areas of disagreement. Three thresholds were applied to visualise high, moderate, and low confidence in zone assignment. These thresholds highlight areas with varying levels of confidence in future climate zone predictions. In particular, the analysis reveals that in the northern part of Kazakhstan, spanning from west to east, the most frequently projected climate zone is Dsa (Dry hot summer), with BSk (Cold semi-arid) being the second most frequent. In central Kazakhstan, from west to east and extending down to the south, the most frequent climate zone is BWk (Cold desert), with BSk (Cold semi-arid) being the second most frequent. At the northern border of the country, the second most probable zone is Dfa (Hot summer continental), with Dsa remaining the most frequent climate zone. In addition, the southern and southwestern parts of Kazakhstan show emerging climate zones such as BSh and BWh (Hot desert). The higher the threshold, the more dominant the most frequently predicted climate zone becomes over the second most likely zone. In areas with a threshold of 1.5, there is a smaller region of high uncertainty, meaning the climate zone could be either the most frequent one or another. As the threshold increases to 2 and 3, the areas of uncertainty expand, but these zones also reflect lower uncertainty, meaning the most frequently predicted climate zone is most likely the correct one. These thresholds indicate regions where there is strong consensus among the models, as well as areas with higher uncertainty, highlighting regions where climate classifications are less reliable. In those uncertain regions, additional modelling or data may be needed.

Future Köppen–Geiger climate maps should be interpreted with caution due to limitations of the methodology used in this study. In particular, the validation and correction of climate models were not performed, meaning that all models used in this research inherited biases in the projected maps and this should be taken into consideration. Additionally, the results were not compared with other methods, such as ensemble averaging or probabilistic methods. Regional Climate Models could also be used to further refine the results. Another limitation is the resolution of the data used in this study. Although the analysis covers the entire country to capture broad trends in climate zone transitions, higher-resolution data could be beneficial for smaller areas of interest. Despite these limitations, the findings of this study are still important for informing climate-related planning, policy-making, adaptation, and mitigation strategies in Kazakhstan, where spatially detailed research remains limited. These results could also serve as a foundation for further research by other scholars.

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