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Climate evolution from the Miocene to the present in central and southeastern Kazakhstan: Evidence from Aktau Mountain and Kushuk localities

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ABSTRACT

Reconstructing past climate dynamics in Central Asia is essential for understanding the Cenozoic evolution of ecosystems and regional climate patterns. This study presents a comparative paleoclimate analysis of two coeval Early Miocene floras from Kazakhstan: Aktau Mountain (also known as Dzhungar Aktau, Ili Depression, Southeastern Kazakhstan) and Kushuk (Turgai Depression, Central Kazakhstan). Using the Coexistence Approach (CA), we reconstructed key climatic parameters including mean annual temperature (MAT), coldest and warmest month temperatures (CMT, and WMT), and mean annual precipitation (MAP). The results indicate that both regions experienced warm and humid conditions during the Miocene (MAT ~14 °C, and MAP ~900–1000 mm), favorable for the development of forested ecosystems. In contrast, paleoclimate simulations from CHELSA TraCE21k reveal that during the Last Glacial Maximum (~21 ka) both localities were characterized by colder and drier conditions (MAT < 0 °C, and MAP 88–350 mm). Modern climate assessments show strong discrepancies between global climate models (CHELSA v2.1), which significantly overestimate temperature and precipitation, and regional meteorological data (Kazhydromet), documenting a strongly continental and arid climate (MAT 11.8 °C, MAP 218 mm in Aktau; and MAT 2.5 °C, MAP 275 mm in Kushuk). Our findings highlight a long-term climatic trajectory from humid Miocene conditions through arid Pleistocene environments to the modern sharply continental climate of Kazakhstan. The study emphasizes the importance of integrating paleobotanical evidence, global climate models, and observational meteorological datasets to achieve reliable reconstructions of the past and present climate dynamics in Central Asia.

Keywords: climate dynamics, paleoclimate reconstruction, Miocene, Kazakhstan, Coexistence Approach.
Article type: Research Article.

INTRODUCTION

The study of paleoclimate in Central Asia is crucial for understanding the Cenozoic history of climate change and the factors that shaped the formation of modern ecosystems in the region (Sun & Wang 2005; Zhang *et al.* 2012). Of particular interest is the Early Miocene stage (approximately 23–16 Ma), which was characterized by large-scale tectonic processes, including the orogeny of the Tien Shan and the uplift of the Tibetan Plateau. These events had a profound impact on atmospheric circulation and the distribution of precipitation across Asia (Sun & Wang 2005; Zhang *et al.* 2012). Fossil floras represent one of the most important proxies for paleoclimate reconstruction, as plant communities are highly sensitive to changes in temperature and moisture (Mosbrugger & Utescher 1997; Utescher *et al.* 2014). Among the Miocene floras of Central Asia, two coeval localities are of particular significance for comparing climatic conditions in different geographic provinces: Kushuk in the Turgai Depression (Central Kazakhstan) and Aktau Mountain in the Ili Depression (Southeastern Kazakhstan; Fig. 1).

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The floras of the Turgai region have been the subject of extensive study (Kornilova & Lavrov 1949; Kornilova 1955, 1956, 1960; Kurlov & Perezhogin 2015). The potential of the Coexistence Approach (CA) for quantitative climate reconstruction based on regional floras has been demonstrated in several studies (Bruch *et al.* 2006; Popova *et al.* 2019; Nigmatova *et al.* 2023). Recent works on Kazakhstan's fossil floras have further applied this method to different stratigraphic levels, demonstrating the robustness of paleobotanical data for quantitative climate analysis. For instance, Zhamangara, *et al.* (2025) provided a detailed reconstruction of the Early Miocene climate in the Kushuk locality, while Akmagambet *et al.* (2024) applied the CA method to the Early Oligocene flora of Kyin-Kerish. Comparable approaches have also been used in the reconstruction of the Early Miocene paleoclimate of Erzhilansay (Zhamangara *et al.* 2024), and in applied ecological research on the introduction potential of Betula pendula in Northern Kazakhstan (Mukhtubayeva *et al.* 2024). These studies highlight the methodological value of integrating paleobotanical evidence with modern climatic datasets, forming a solid foundation for the present comparative analysis of the Early Miocene floras of Aktau Mountain and Kushuk.

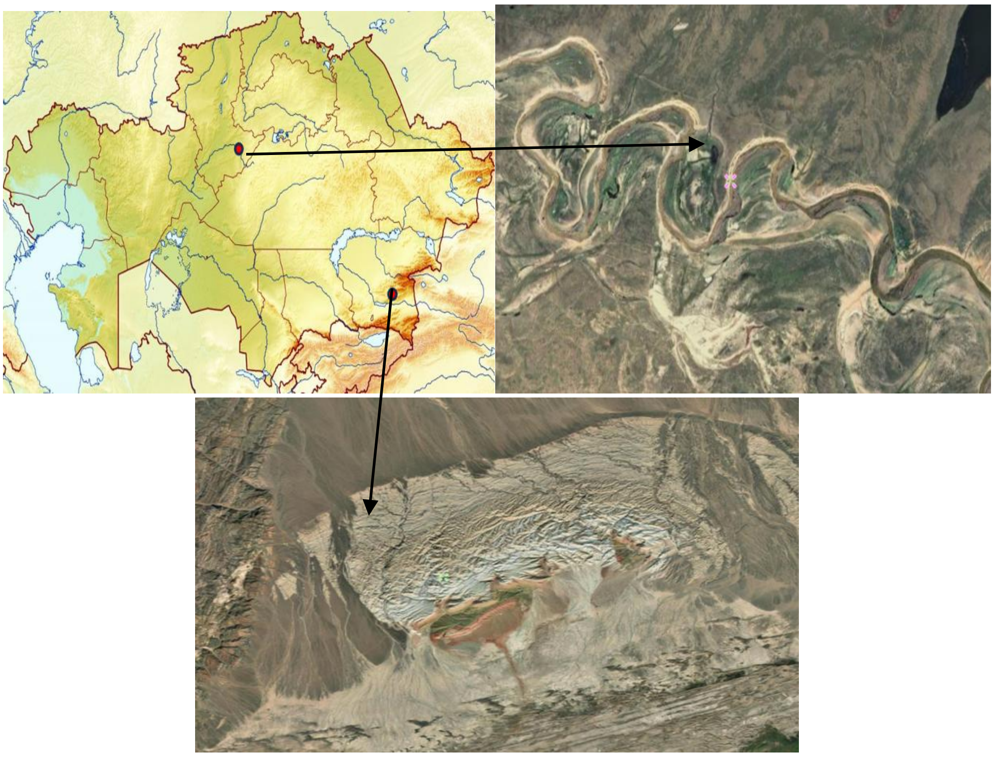

Fig. 1. Location of the studied localities; A: general view showing the position of the studied regions of Kazakhstan (scale ~300 km); B: Kushuk locality in the Turgai Depression (scale ~2 km; Esri, ArcGIS Imagery); C: Aktau Mountain locality in the Ili Depression (scale ~2 km; Esri, ArcGIS Imagery).

The principal aim of this study is to reconstruct the climatic parameters for these two localities using the Coexistence Approach and to conduct a comparative analysis between them. Furthermore, we contextualize these paleoclimatic estimates by comparing them with both modern climate conditions and simulated Late Pleistocene climates, thereby elucidating long-term climatic trends in the region.

Study localities

Kushuk locality (Turgai Depression, Central Kazakhstan)

The Kushuk locality (Fig. 2A) is associated with Lower Miocene deposits of the Turgai Depression, a large Cenozoic intracontinental basin (Fig. 1B). The sedimentary succession is dominated by continental siltstones, sandstones, and clays, deposited in lacustrine and floodplain environments (Kornilova 1960; Shi *et al.* 2016). The Kushuk flora comprises more than 40 species of higher plants, represented by leaf, fruit, and seed impressions. The assemblage is dominated by representatives of Betulaceae, Salicaceae, Ulmaceae, Fagaceae, and Juglandaceae, indicating mesophilic communities consistent with temperate broad-leaved forests under conditions of sufficient humidity (Kornilova 1955, 1956; Kurlov & Perezhogin 2015; Zhamangara *et al.* 2025).

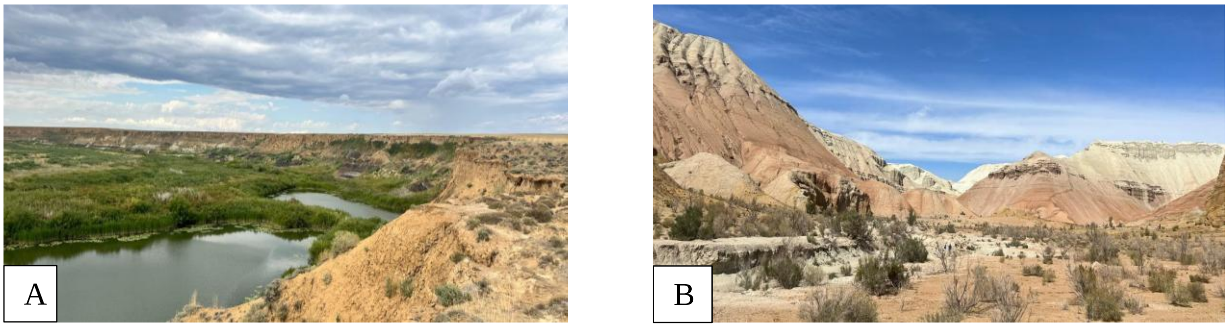

Fig. 2. Field views of the studied localities; **A:** General landscape view of the Kushuk locality (Turgai Depression, Central K

Aktau mountain locality (Ili Depression, Southeastern Kazakhstan)

The Aktau Mountain Mountains (Fig. 2B) feature a thick succession of Cenozoic deposits, including fluvial sandstones, lacustrine marls, limestones, and evaporite interbeds (Lucas *et al.* 2000; Nigmatova 2016; Verestek 2018), suggesting the existence of an extensive lacustrine system with variable water salinity. The flora comprises 56 plant species (Rayushkina 1993), dominated by *Betula, Populus, Salix, Ulmus, Berberis*, and *Ailanthus*, alongside shrub formations resembling Mediterranean sclerophyllous scrublands (maquis). This combination indicates transitional communities between riparian (Tugai) forests and arid shrublands, reflecting a gradual process of aridization in the region during the Early Miocene (Rayushkina 1993; Weber 2003; Nigmatova 2016). To better illustrate the differences between the two coeval localities, Kushuk (Turgai Depression) and Aktau Mountain (Ili Depression), their main geological, paleoecological, and floristic characteristics are summarized in Table 1. This comparative overview provides a concise framework for analyzing the environmental conditions and community types that prevailed in both regions during the Early Miocene.

Table 1. Comparative characteristics of the Kushuk and Aktau Mountain localities.

	Lower Miocene deposits of the Turgai Depression (Kornilova 1960; Shi *et al.* 2016)	Cenozoic deposits: fluvial sandstones, lacustrine marls and limestones, evaporites (Lucas *et al.* 2000; Nigmatova 2016)
	Lacustrine–floodplain systems with mesophilic conditions (Kornilova 1956; Kurlov & Perezhogin 2015)	Lacustrine system with variable mineralization, periodic paludification (Nigmatova 2016)
	> 40 species: Betulaceae, Salicaceae, Ulmaceae, Juglandaceae (Kornilova 1955, 1960)	56 species: Populus, Salix, Ulmus, Berberis, Ailanthus, shrubs resembling maquis (Rayushkina 1993; Weber 2003)
	Forest-steppe and tugai formations with sufficient humidity (Zhamangara *et al.* 2025)	Transitional communities: tugai and shrublands, reflecting aridization (Nigmatova 2016)
	Kornilova (1960), Zhamangara *et al.* (2025) — CA reconstruction	Rayushkina (1993) — taxonomy; first CA reconstruction in this stud

MATERIALS AND METHODS

Floristic analysis and paleoclimate reconstruction

To achieve the research objectives, this study was conducted in a series of sequential steps. First, the published floristic composition of the Aktau Mountain locality (Rayushkina 1993; Nigmatova 2016) was systematically analyzed and reviewed. This dataset was then compared with the well-established flora of Kushuk to identify key similarities and differences in taxonomic composition and ecological implications. Subsequently, a quantitative paleoclimate reconstruction for the Aktau Mountain flora was performed for the first time using the Coexistence Approach (CA; Mosbrugger & Utescher 1997). This method determines the climatic tolerances of fossil taxa based on the Nearest Living Relative (NLR) concept and identifies the range of climatic values where all tolerances overlap (the coexistence interval), providing robust estimates for key parameters. These results were then integrated with previously published CA-based climatic data for the Kushuk flora (Zhamangara *et al.* 2025) to enable a direct comparative analysis of Early Miocene climatic conditions between the two regions.

Comparative climate data analysis

To assess temporal climate dynamics, the reconstructed Miocene paleoclimate parameters were compared with modern and Late Pleistocene climatic conditions. For the modern climate baseline, data were sourced from the CHELSA v2.1 (Climatologies at High Resolution for the Earth's Land Surface Areas) database (Karger *et al.* 2017). This global dataset provides high-resolution (~1 km) bioclimatic variables (BIO1–BIO19) averaged for the period 1981–2010. For the geographic coordinates of each locality (Dzhungar Aktau: 44°01′N, 79°16′E; Kushuk: 51°12′N, 64°00′E), the following parameters were extracted: mean annual temperature (BIO1, MAT), mean temperature of the warmest month (BIO5, WMT), mean temperature of the coldest month (BIO6, CMT), mean annual precipitation (BIO12, MAP), and seasonal precipitation indices (BIO13, precipitation of wettest month; BIO14, precipitation of driest month). Data extraction and processing were performed programmatically in Python using the rasterio and pandas libraries. For the Late Pleistocene comparison, data from the CHELSA TraCE21k database (Karger & Zimmermann 2019) were used. This dataset provides downscaled bioclimatic variables based on transient climate model simulations (TraCE-21ka). We extracted data layers corresponding to the Last Glacial Maximum (LGM; ~21 ka) for the coordinates of the studied regions. To validate the modern climate model data and account for regional specifics, observational data from the Kazakhstan Hydrometeorological Service (Kazhydromet 2024) were incorporated for a critical evaluation of discrepancies between global model outputs and actual station measurements.

RESULTS AND DISCUSSION

Comparative analysis of Early Miocene climatic conditions

Paleoclimate reconstruction based on the floras of Aktau Mountain and Kushuk revealed both common features and regional differences in the climatic conditions within Central and Southeastern Kazakhstan during the Early Miocene. The floras of Kushuk (Turgai Depression) and Aktau Mountain (Ili Depression) are of the same geological age—the Early Miocene—making their comparison particularly informative. Despite a similar overall climatic regime (moderately warm and relatively humid), the quantitative parameters obtained using the Coexistence Approach (CA) indicate certain regional differences. For Kushuk, values for the mean annual temperature (MAT) were previously established within the range of 12.0–16.5 °C and mean annual precipitation (MAP) at about 700–1100 mm (Zhamangara *et al.* 2025). The new reconstruction for Aktau Mountain showed comparable but slightly different parameters: MAT = 13.3–15.6 °C and MAP = 879–1179 mm. Thus, the climate of Aktau was somewhat warmer and wetter than that of Kushuk. An important difference is precipitation seasonality. A more pronounced reduction in precipitation during the dry period was noted in Aktau (35–47 mm vs. 40–55 mm in Kushuk), indicating more marked arid tendencies in Southeastern Kazakhstan. At the same time, precipitation during the warm season in Aktau was higher than in Kushuk (107–141 mm vs. 100–140 mm), confirming a greater role of seasonal contrasts. These results lead to the conclusion that in the Early Miocene, Central Kazakhstan (Kushuk) was characterized by more stable humidity, while Southeastern Kazakhstan (Aktau) already demonstrated the first signs of aridization, associated with the onset of tectonic transformations in the region and changes in atmospheric circulation (Table 2). Table 2 summarizes the climatic parameters reconstructed for the two localities. The quantitative paleoclimate reconstruction for the Aktau Mountain flora shows that the Early Miocene climatic conditions of the region were generally similar to those of the Turgai Depression (Kushuk locality), but had several important differences. The Mean Annual Temperature (MAT) for Aktau Mountain was 13.3–15.6 °C (mean 14.5 °C), slightly higher than the reconstructed values for Kushuk (12.0–16.5 °C). The temperature of the coldest month (CMT) in Aktau varied from 0.7 to 5.2 °C, close to the values for Kushuk (–1.5–5.5 °C), confirming moderately mild winter conditions. The Mean Annual Precipitation (MAP) in Aktau Mountain was estimated to be within 879–1179 mm (mean 1029 mm), which is comparable to Kushuk (700–1100 mm). However, the seasonal distribution of precipitation differed. Aktau is characterized by a more pronounced decrease in moisture during the dry period: precipitation in the driest month was 35–47 mm, while in Kushuk this figure reached 40–55 mm. At the same time, Aktau receives slightly more precipitation during the warm season (107–141 mm vs. 100–140 mm for Kushuk). Thus, both localities demonstrate similar Early Miocene climatic conditions, reflecting a moderately warm and relatively humid regime with seasonal aridization. However, the Aktau Mountain flora records a more distinct manifestation of arid trends compared to Kushuk, which is consistent with the region's geographical position on the southeastern edge of Kazakhstan and the increasing influence of continental factors.

Table 2. Climatic parameters based on the Coexistence Approach.

Parameter	Kushuk (Turgai Depression) (Zhamangara *et al.* 2025)	Aktau Mountain (Ili Depression)
MAT (°C)	12.0 – 16.5	13.3 – 15.6 (mean 14.45)
CMT (°C)	–1.5 – 5.5	0.7 – 5.2
WMT (°C)	21.0 – 25.0	22.95 – 24.1 (mean 23.1)
MAP (mm)	700 – 1100	879 – 1179 (mean 1029)
MPwet (mm)	120 – 160	118 – 157 (mean 137.5)
MPdry (mm)	40 – 55	35.5 – 47 (mean 41)
MPwarm (mm)	100 – 140	107 – 141 (mean 124)

Note: For the Kushuk locality, the original publication (Zhamangara *et al.* 2025) provides only the coexistence intervals (ranges) for CMT and WMT without calculated mean values, which is why these cells are left without means in the table above.

Climate change dynamics to the present day

The Early Miocene climate parameters were reconstructed for the floras of Aktau Mountain (Ili Depression) and Kushuk (Turgai Depression) using the Coexistence Approach (CA). To assess temporal dynamics, the obtained data were compared with simulation results from the CHELSA TraCE21k database (Late Pleistocene, ~21 ka) and modern climatic conditions from the CHELSA v2.1 database (1981–2010), as well as data from Kazhydromet (Tables 3-4).

Table 3. Temperature parameters (MAT, CMT, and WMT) for different time periods.

Period	Region	MAT (°C)	CMT (°C)	WMT (°C)
Miocene (CA)	Dzhungar Aktau	14.5	2.95	23.6
	Kushuk	14.2	1.5	24.7
Pleistocene (~21 ka, CHELSA)	Dzhungar Aktau	-2.3	-3.6	-0.1
	Kushuk	-1.8	-3.2	0.3
Modernity (CHELSA)	Dzhungar Aktau	28.5	26.6	30.5
	Kushuk	27.9	25.7	30.3
Modernity (Kazhydromet)	Dzhungar Aktau	11.8	-2.2	25.9
	Kushuk	2.5	-16.0	21.5

As shown in Table 3, the comparative temperature data reveal a dramatic climatic evolution from the Miocene to the present. Both localities experienced mild conditions during the Miocene, but in the Late Pleistocene the climate deteriorated sharply: MAT dropped below 0 °C, indicating cold and continental conditions. In modern times, CHELSA data tend to overestimate temperatures, while observational data from Kazhydromet confirm the existence of sharply continental climates with strong seasonal contrasts. In addition to temperature dynamics, it is also essential to consider changes in precipitation over time. Table 4 summarizes the reconstructed and modeled values of mean annual precipitation (MAP) as well as seasonal extremes (Pwettest, and Pdriest) for the Miocene, Late Pleistocene, and the present day.

Table 4. Precipitation parameters (MAP, Pwettest, Pdriest) for different time periods.

Period	Region	MAP (mm)	Pwettest (mm)	Pdriest (mm)
Miocene (CA)	Dzhungar Aktau	1029	137.5	41
	Kushuk	898.5	138	25
Pleistocene (~21 ka, CHELSA)	Dzhungar Aktau	88	15	4
	Kushuk	350	50	17
Modernity (CHELSA)	Dzhungar Aktau	1953	303	82
	Kushuk	1981	208	119
Modernity (Kazhydromet)	Dzhungar Aktau	218	32	1
	Kushuk	275	45	7

According to Table 4, precipitation patterns underwent significant transformations from the Miocene to the present. In the Miocene, both Aktau Mountain and Kushuk experienced relatively humid conditions (MAP ~900–1000 mm), which favored the development of rich forest communities. By the Late Pleistocene, however, a drastic decline in precipitation was observed: MAP fell to only ~88 mm in Aktau and ~350 mm in Kushuk, indicating strongly arid conditions. In the modern period, CHELSA data tend to overestimate precipitation (1953–1981 mm), while Kazhydromet observations reveal much lower and more realistic values (218–275 mm). These results highlight not only the long-term trend toward increasing aridity since the Miocene, but also the critical discrepancy between global climate models and regional meteorological records.

Aktau Mountain (Ili Depression)

In the Miocene, the region's climate was characterized by mild winters (CMT ~2.9 °C), moderately warm summers (WMT ~23.6 °C), and a high level of humidity (MAP ~1029 mm). In the Late Pleistocene, the climate changed drastically: the mean annual temperature dropped to -2.3 °C, and the annual precipitation was only ~88 mm, indicating cold and arid conditions. Modern climate estimates from the CHELSA database showed overestimated values for MAT (28.5 °C) and MAP (1953 mm), while observational data from Kazhydromet reflect a sharply continental and arid climate: MAT ~11.8 °C, MAP ~218 mm, CMT -2.2 °C, and WMT ~25.9 °C. This underscores the necessity of combining global climate models with local observations.

Kushuk (Turgai Depression)

The reconstruction based on the Early Miocene flora showed climatic conditions close to those of Aktau: MAT ~14.2 °C, MAP ~898 mm, CMT ~1.5 °C, and WMT ~24.7 °C. In the Pleistocene, the region also experienced significant cooling (MAT ~-1.8 °C, and MAP ~350 mm). Modern climate indicators from CHELSA overestimate MAT (27.9 °C) and MAP (1981 mm). However, data from Kazhydromet for the Kostanay region provide a more realistic picture: MAT ~2.5 °C, CMT ~-16 °C, WMT ~21.5 °C, and MAP ~275 mm. These data indicate a cold and arid climate with pronounced seasonality and low humidity. In addition to the tabulated data, the temporal changes in mean annual temperature are more clearly illustrated in Fig. 1, which provides a graphical comparison of MAT values for Aktau Mountain and Kushuk from the Miocene to the present day, based on CA reconstructions, CHELSA model outputs, and Kazhydromet observations.

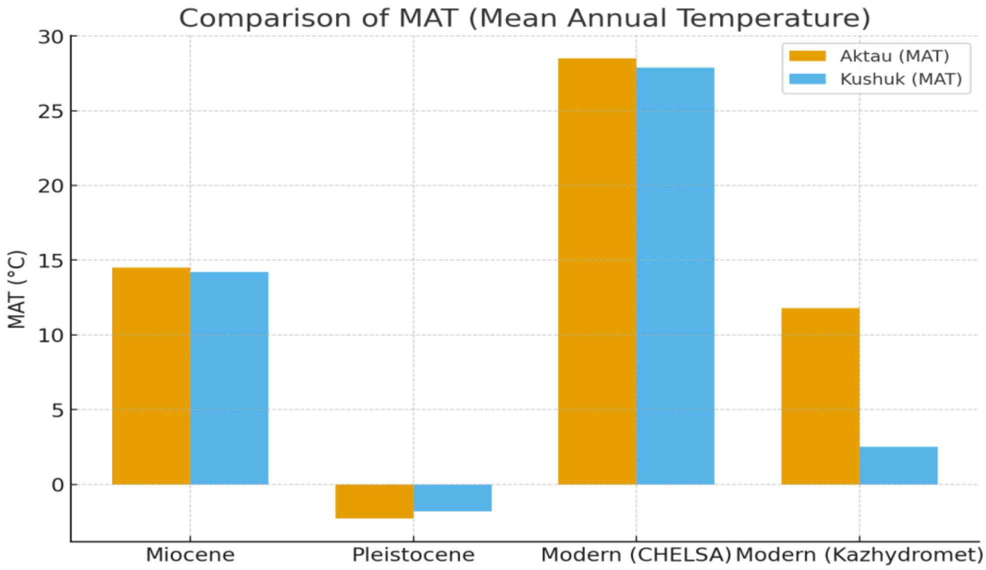

Fig. 1. Graphical representation of Mean Annual Temperature (MAT) changes from the Miocene to the present day for the Aktau Mountain and Kushuk localities.

As shown in Fig. 1, both regions exhibited relatively high MAT values during the Miocene (~14–15 °C), supporting the development of diverse forest ecosystems. In the Late Pleistocene, temperatures dropped sharply, with MAT falling below 0 °C, reflecting cold continental conditions. Modern estimates highlight a strong contrast: CHELSA data suggest unrealistically high MAT values (~28 °C), whereas Kazhydromet observations indicate much lower and more realistic values (11.8 °C for Aktau and 2.5 °C for Kushuk). This visual representation emphasizes both the long-term cooling trend since the Miocene and the divergence between modeled and observed modern climates. Alongside temperature dynamics, precipitation changes are more clearly illustrated in Fig. 2, which presents a graphical comparison of Mean Annual Precipitation (MAP) for Aktau Mountain and Kushuk from the Miocene to the present, based on CA reconstructions, CHELSA outputs, and Kazhydromet observations.

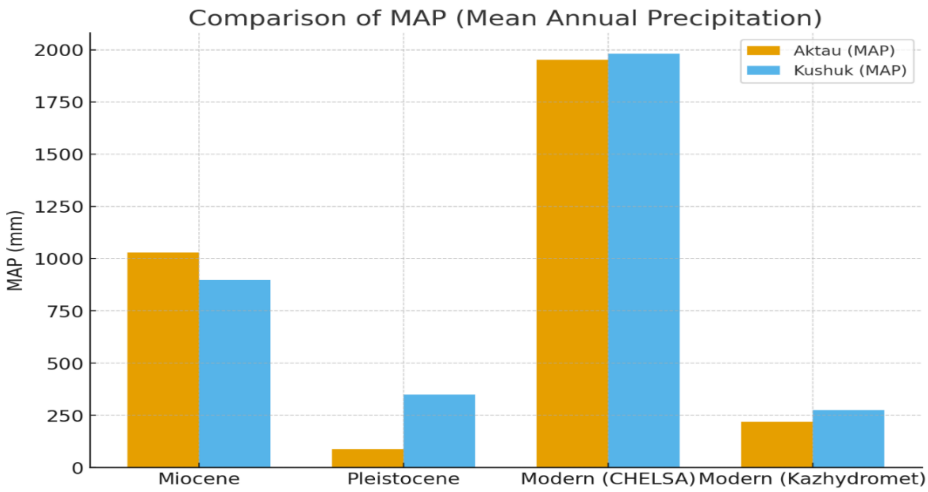

Fig. 2. Graphical representation of Mean Annual Precipitation (MAP) changes from the Miocene to the present day for the studied localities.

As shown in Fig. 2, both regions were characterized by high precipitation levels in the Miocene (~900–1000 mm), which supported the development of rich and diverse forest communities. In the Late Pleistocene, however, MAP declined drastically: only ~88 mm for Aktau and ~350 mm for Kushuk, reflecting strongly arid conditions. In modern times, the discrepancy between global climate models and observational data becomes evident: CHELSA indicates unrealistically high MAP values (>1900 mm), while Kazhydromet observations show much lower amounts (218 mm for Aktau and 275 mm for Kushuk). This visualization reinforces the trend of long-term aridization since the Miocene and highlights the critical importance of using local meteorological records to complement global datasets. Taken together, the quantitative reconstructions and graphical analyses demonstrate a pronounced shift from warm-temperate and humid conditions in the Miocene to cold and arid conditions in the Pleistocene and present. The comparison of Aktau Mountain and Kushuk highlights both shared regional trends and local differences, with earlier and stronger aridization signals recorded in the Ili Depression. Taken together, the quantitative reconstructions (Tables 2–4) and graphical analyses (Figs. 1–2) demonstrate a pronounced shift from warm-temperate and humid conditions in the Early Miocene to cold and arid conditions in the Pleistocene and the present day. Both Aktau Mountain (Ili Depression) and Kushuk (Turgai Depression) record similar overall climatic trajectories, yet with notable local differences. The flora of Aktau Mountain reflects earlier and stronger signals of aridization compared to Kushuk, highlighting the importance of regional geographical and tectonic settings in shaping climatic evolution. These results are consistent with previous paleobotanical reconstructions in Central Asia (e.g., Sun & Wang 2005; Utescher *et al.* 2014), which also document a trend toward increasing aridization since the Miocene. Comparable findings have been reported for the Tibetan Plateau and Tien Shan regions, where large-scale tectonic uplift intensified continentality and altered atmospheric circulation patterns (Zhang *et al.* 2012). However, the earlier onset of arid conditions in Aktau Mountain, relative to Kushuk, underscores the significance of its southeastern location and its proximity to zones of active tectonic reorganization. The integration of fossil-based reconstructions with climate modeling (CHELSA TraCE21k) and modern meteorological observations (Kazhydromet) provides a more comprehensive understanding of long-term climate dynamics. Importantly, the discrepancy between global climate models and local observations emphasizes the necessity of combining multiple data sources to achieve reliable paleoclimatic reconstructions.

CONCLUSION

In conclusion, the Early Miocene of Central and Southeastern Kazakhstan was characterized by relatively warm and humid conditions, supporting rich forest ecosystems. Subsequent climatic evolution involved progressive aridization, culminating in the sharply continental and arid climate observed today. This study highlights the regional differentiation of climate trajectories within Kazakhstan and demonstrates the value of integrating paleobotanical data with quantitative approaches (CA) and modern climatic datasets. Furthermore, the comparative analysis of the Aktau Mountain and Kushuk localities reveals that southeastern Kazakhstan exhibited earlier and more pronounced arid signals, likely linked to tectonic uplift and intensification of continental climatic regimes. These findings not only refine our understanding of regional paleoenvironments but also provide an important basis for assessing long-term climate–vegetation interactions in continental interiors. Future research should focus on expanding the geographical scope of comparative studies across Central Asia, incorporating additional fossil assemblages and multiproxy evidence (e.g., palynological, isotopic, and sedimentological data). Combining these datasets with high-resolution climate modeling will allow for a more nuanced reconstruction of paleoenvironmental dynamics and enhance our ability to place local records within the broader framework of global Cenozoic climate evolution.

Conflict of interests

The authors declare no conflict of interests regarding the publication of this article.

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