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Article

# Paleoclimate analysis of the Early Miocene in the Kushuk locality (Turgai Depression) based on the Coexistence Approach method

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**Abstract:** This article reconstructs the Early Miocene climate of the Turgay Trough in Central Asia, using the Coexistence Approach (CA) and paleofloristic data from Kushuk. Its main goal is to determine climatic parameters and ecosystem changes in the Early Miocene. Results indicate a warm-temperate climate with mild winters and sufficient rainfall, featuring a mean annual temperature of 14.2°C and mean annual precipitation of 898.5 mm. These conditions supported diverse forest ecosystems, including broadleaf and mixed woodlands. A comparison with the modern climate shows a strong contrast, suggesting increased continentality and reduced moisture availability. This evidence supports a gradual climatic cooling and drying during the Miocene, driven by global and regional factors such as tectonic uplift and oceanic currents.

The study underscores the climatic evolution of Central Asia and validates the CA method as an effective tool for paleoclimatic studies. Findings can be applied to climate modeling and assessing how shifts in temperature and precipitation influenced Neogene ecosystems. Planned research will examine the interplay of climatic and geological factors, focusing on how changes in precipitation patterns shaped habitat distribution and species composition. These data provide a basis for refining paleoclimatic models and reconstructing biosphere dynamics in the Neogene, thereby advancing our understanding of how climate influenced regional development and biodiversity.

**Keywords:** Lower Miocene, Turgai trough, paleoclimatic reconstruction, nearest modern analogues (NLR) method

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## 1. Introduction

The Kushuk locality, situated in the Turgai Basin of Kazakhstan, represents a crucial site for the investigation of Tertiary flora and the reconstruction of ancient climatic patterns in Central Asia (Kornilova, 1960; Nigmatova et al, 2023). The first studies of this place began in 1912. Since then, numerous excavations have revealed a rich diversity of flora and faun (Kornilova, 1960). In the middle of the XX century, Kornilova, V.S. made a significant contribution to the study of Kushuk's flora, providing valuable insights into the climatic and ecological conditions of the Miocene (Kornilova, 1960, 1949, 1956, 1955; Nigmatova, 2023).

Understanding the paleoclimatic evolution of regions like the Turgai Basin is crucial for contextualizing broader patterns of global climate change throughout the Cenozoic (Zachos et al., 2001; Wang, 2009). Furthermore, the unique characteristics of Central Asian deserts, as detailed by Graham (2011), underscore the importance of regional studies in unraveling the complex history of climate and ecosystem dynamics. Recent research, such as that conducted by Zhamangara et al. (2025) in the nearby Erzhilansay region, highlights the continued importance of utilizing modern methodologies to refine our understanding of Early Miocene paleoclimates in Central Asia. This emphasizes the evolving nature of paleoclimatic studies and the increasing precision achieved through contemporary techniques.

To accurately reconstruct the paleoclimate, this study uses the Coexistence Approach (CA). This method evaluates climatic parameters by comparing the ecological ranges of modern analogs with fossil flora. The CA method has proven to be a reliable tool for assessing temperatures and precipitation in paleobotanical research.

In 2024, a scientific expedition to Kushuk conducted detailed mapping and photographic documentation. Despite the absence of new floral remains, existing morphological descriptions from previous studies allowed for the application of the Coexistence Approach (CA). This research aims to determine the climatic conditions of the Lower Miocene and their role in the ecological evolution of the region.

This study aims to reconstruct the climatic conditions of the Lower Miocene in present-day Kazakhstan. The findings will enhance our understanding of regional climatic evolution and the role of vegetation in these processes.

## 2. Materials and methods

### *2.1. Location and geological context*

The study was conducted in the Kushuk tract, located in the Turgai depression in the territory of modern Kazakhstan. This place is one of the most significant for studying the tertiary flora and fauna of the region due to the unique geological conditions that contributed to the preservation of fossil remains (Kornilova, 1960, 1956). The outcrops along the banks of the Uluzhilanchik River are alternating layers of sands and clays with varying degrees of obliquity and leafiness, which indicates variable sedimentation conditions (figure 1). In some lenses stretched along the outcrops, there is a joint burial of fauna and flora, which makes this place especially important for paleontological and paleobotanical research.

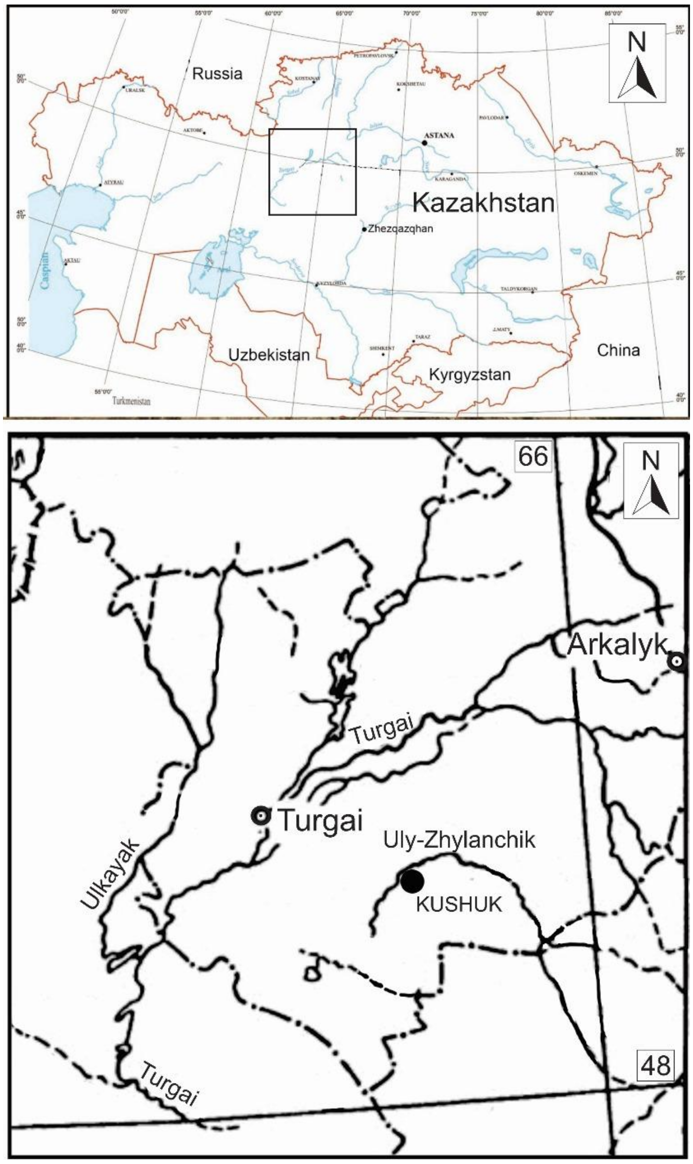


**Figure 1**. Location map of the Kushuk site in the Turgai Depression, Kazakhstan

During the 2024 summer expedition, field work was carried out, including mapping of outcrops, photo documentation of sections and collection of samples for subsequent analysis. In the course of field work, layers of light chocolate color containing highly decomposed plant residues were discovered. Unfortunately, no samples of floral remains have been found.

*2.2. Current Climatic Conditions*

The current climatic conditions in the Turgai region, located at coordinates 49.01°N and 65.30"E, are characterized by a mean annual temperature of 1-4°C, with an average temperature in the coldest month of January ranging from -15 to -17°C and reaching as low as -44°C (-47°C in some areas, such as Kushmurun). The warmest month, July, has an average temperature around 24°C in the southern parts of the region, but temperatures can reach up to 40-45.C on hot days. The duration of the warm period, when temperatures are above zero, averages 210-218 days in the southern half of the region. Annual precipitation decreases to 220 millimeters or less towards the southern areas, and the warm season (April-October) sees more precipitation than the cold season. Summer experiences significantly more rainfall than other seasons (Kazhydromet, 2024).

*2.3. Analysis of floral composition*

The work of Kornilova, V.S. (1960) presents data on the floral composition of the Lower Miocene in the region of the Turgai trough. Paleoclimatic reconstruction was performed based on the diversity and composition of fossil plants found at the Kushuk site. These data were supplemented with information from the Palaeoflora Database, which made it possible to determine the closest modern analogues (NLR) for each taxon (Utescher et al., 2024)

*2.4. Methods*

The Coexistence Approach (CA) was used for paleoclimatic reconstruction of the Lower Miocene of the Turgai Depression. This method is based on intersecting the ecological characteristics of modern analogs (NLR) of fossil plants to estimate climatic parameters under which the fossil flora could exist (Utescher et al., 2014). The method accounts for potential variability in the ecological ranges of modern analogs, ensuring more accurate reconstructions of ancient climatic conditions. Previous studies, such as Bruch et al. (2007), have demonstrated the effectiveness of CA in reconstructing Miocene climates in Europe, particularly in identifying temperature and precipitation patterns that shaped regional ecosystems (Bruch et al., 2007). These findings provide a comparative framework that strengthens the relevance of applying CA to the Turgai Depression. Similarly, Popova et al. (2019) successfully applied CA to analyze Early Miocene climates in Central Asia, revealing significant precipitation variability and its influence on vegetation. This study highlights regional climatic dynamics that align closely with the objectives of this research.

In addition to the CA method, this study also incorporates data on the leaf physiognomy of fossil leaves, which allows for a more accurate reconstruction of the paleoclimate (Jacques et al., 2011). This approach, based on the analysis of morphological features of leaves, is an important tool in paleobotanical research. Furthermore, to reinforce the data on paleoclimate reconstruction, the results of fossil mammal studies are used, which also provide valuable information about climatic changes in Eurasia (Fortelius et al., 2002).

Other paleoclimate reconstructions, such as those by Grimalt and Targarona (2017), Ivanov et al. (2011), and Liu et al. (2011), emphasize the integration of leaf assemblage data and climatic modeling. This approach enhances the reliability of CA results by providing robust datasets for validating reconstructed climatic parameters and understanding broader paleoclimatic trends. Ivanov et al. (2011) analyzed vegetation and climate dynamics in Eastern and Central Paratethys, while Liu et al. (2011) focused on Miocene climate evolution in North China. These studies underline the reliability and adaptability of CA for diverse geographic and temporal contexts.The reconstruction process involved several integrated stages. Fossil flora from the Kushuk site was analyzed using data from Kornilova's studies (1960) and the Palaeoflora Database (Utescher et al., 2024). These data provided the basis for matching fossil species with their closest modern relatives based on ecological and climatic similarities. Using the climatic ranges of these modern analogs, the climatic conditions of the Lower Miocene were reconstructed. This approach was further validated by referencing studies like Bruch et al. (2006, 2007), which highlighted temperature and precipitation patterns in Miocene Europe, and Popova et al. (2019), which provided insights into precipitation variability in Central Asia. Additionally, Ivanov et al. (2011) and Liu et al. (2011) emphasized the importance of vegetation-climate interactions in Eastern Paratethys and North China, respectively, offering comparative frameworks for this study. The data integration and analysis were conducted using manual calculations and cross-referencing with existing datasets, ensuring the effective utilization of both historical and modern sources. No new floral remains were found during fieldwork, but the extensive material previously collected and described in the literature provided a solid foundation for a comprehensive paleoclimatic reconstruction. The reliance on well-documented historical datasets ensured that the findings remain robust despite the absence of new samples.

**3. Results**

Based on the data presented in the work Kornilova, V.S. (Kornilova, 1960; Kurlov et al., 2015), work was carried out to determine the closest modern analogues (NLR) using the Palaeoflora Database (Utescher et al., 2024). This made it possible to carry out a more accurate climatic reconstruction, taking into account the temperature and precipitation ranges in which modern analogues of fossil flora existed.

The study of the flora of the Kushuk location made it possible to identify 42 species of plants belonging to 21 families (Kornilova, 1960). The main part of the flora consists of woody and shrubby plants, which indicates the existence of a warm temperate climate with pronounced seasonal fluctuations in temperature and precipitation. The main groups of plants are represented by the following taxa:

Paleofloristic analysis data indicate that the climate in the Lower Miocene in the Kushuk region was moderately warm, with distinct seasons. The predominance of broad-leaved forests, such as oak and walnut, indicates sufficient rainfall and mild winters. This is confirmed by the presence of species that require high humidity, such as Betula subpubescens and Alnus palaeojaponica.

The presence of species from the Fagaceae and Juglandaceae families suggests that summer temperatures were moderately high, which contributed to the growth of dense broadleaf forests. The combination of shrubby and herbaceous plants such as Rosa and Gleditsia indicates the presence of drier areas, especially in interfluves and open spaces.

Thus, the flora of Kushuk indicates the presence of ecosystems with a warm temperate climate, which are characterized by a variety of plant formations, including forest, shrub and aquatic ecosystems. This confirms the favorable climatic conditions that existed in the Lower Miocene.

To reconstruct the paleoclimatic conditions of the Kushuk location (Lower Miocene), the data on the floral composition presented in the work were used Kornilova, V.S. (1960), as well as the method of co-existence with the determination of the nearest modern analogues (NLR taxa) using the Palaeoflora Database (Utescher et al., 2024). Based on these data, the key climatic parameters for the reconstruction of the conditions of that period were determined.

**Table 1.** The main climatic parameters for the location of Kushuk

| Parameter | Minimum | Minimum |
|---|---|---|
| Mean Annual Temperature (MAT), °C | 12.8 | 15.7 |
| Coldest Month Temperature (CMT), °C | 0.7 | 2.2 |
| Warmest Month Temperature (WMT), °C | 24.3 | 25.1 |
| Mean Annual Precipitation (MAP), mm | 644 | 1153 |
| Precipitation in the Wettest Month (MPWET), mm | 108 | 168 |
| Precipitation in the Driest Month (MPDRY), mm | 20 | 30 |
| Precipitation in the Warmest Month (MPWARM), mm | 108 | 356 |

The analysis of temperature indicators allowed us to conclude that the climate in the Lower Miocene of the Kushuk region was warm and temperate, which contributed to the growth of mixed forests:

The average annual temperature (MAT) ranged from 12.8°C to 15.7°C, indicating the presence of a warm climate. The temperature of the coldest month (CMT) ranged from 0.7°C to

2.2°C, indicating mild winters. The temperature of the warmest month (WMT) was in the range of 24.3°C – 25.1°C, indicating a warm but not extremely hot summer.

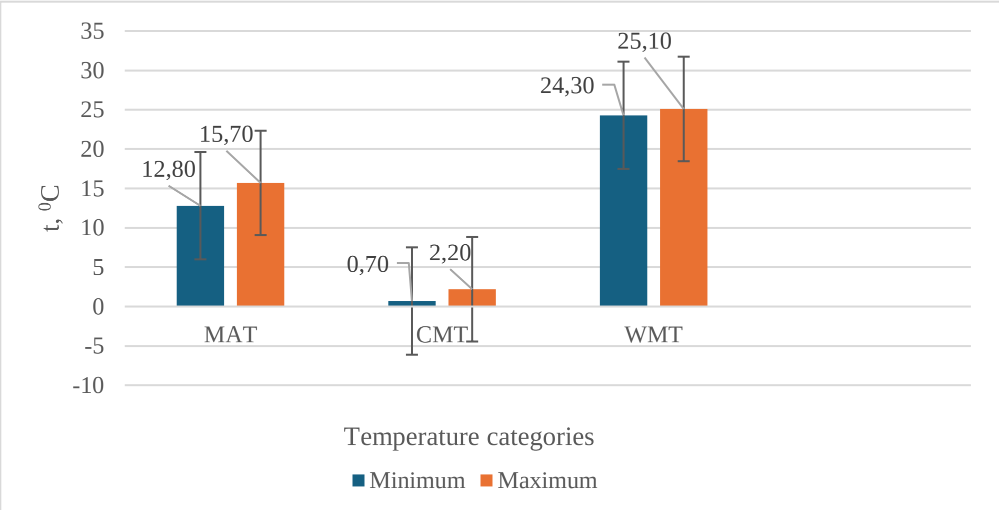


**Figure 2.** Temperature Regime for the Kushuk Site

Figure 2 clearly demonstrates the annual temperature fluctuations. It is evident that winter values do not drop below 0 °C, while in the summer months they reach around 25 °C, confirming the presence of a warm temperate climate in the region.

The paleoclimatic reconstruction of precipitation revealed the following characteristics:

The mean annual precipitation (MAP) ranged from 644 mm to 1153 mm, indicating moderately humid conditions.

Precipitation in the wettest month (MPWET) reached up to 168 mm, confirming the presence of a rainy season.

Precipitation in the driest month (MPDRY) was minimal, ranging from 20 mm to 30 mm, indicating brief dry periods.

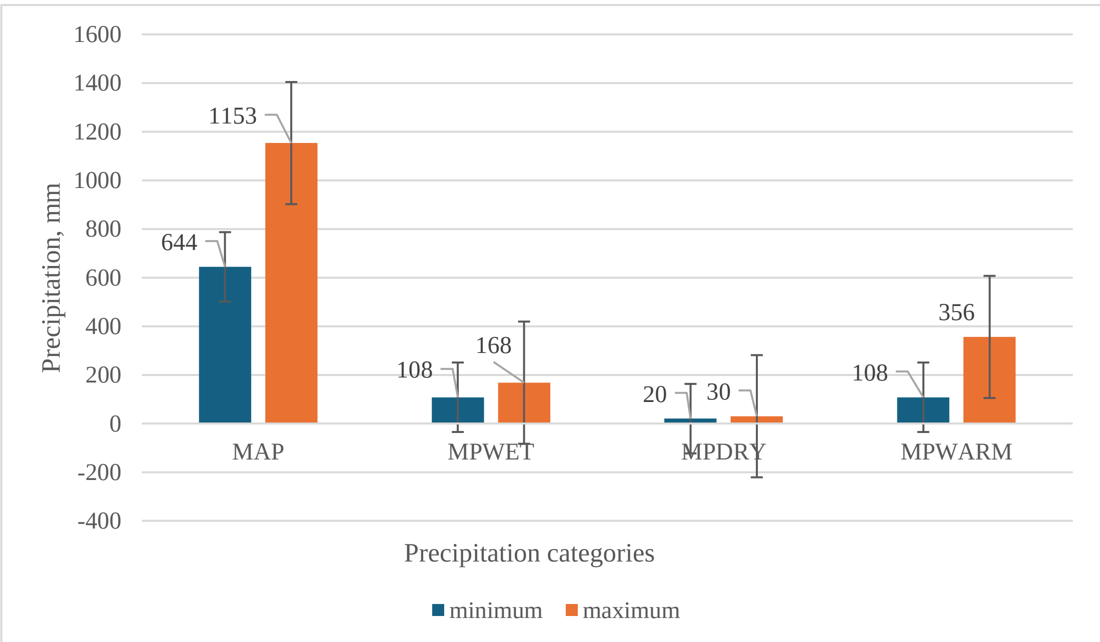


**Figure 3.** Precipitation distribution for the Kushuk Site

Figure 3 illustrates the seasonal fluctuations in precipitation, showing increased rainfall during the wettest months and decreased rainfall during the driest periods, thereby confirming the region's precipitation pattern.

An analysis of the correlation between temperature and precipitation regimes revealed a weak negative correlation (r = −0.02), indicating a lack of strong dependency between these two parameters.

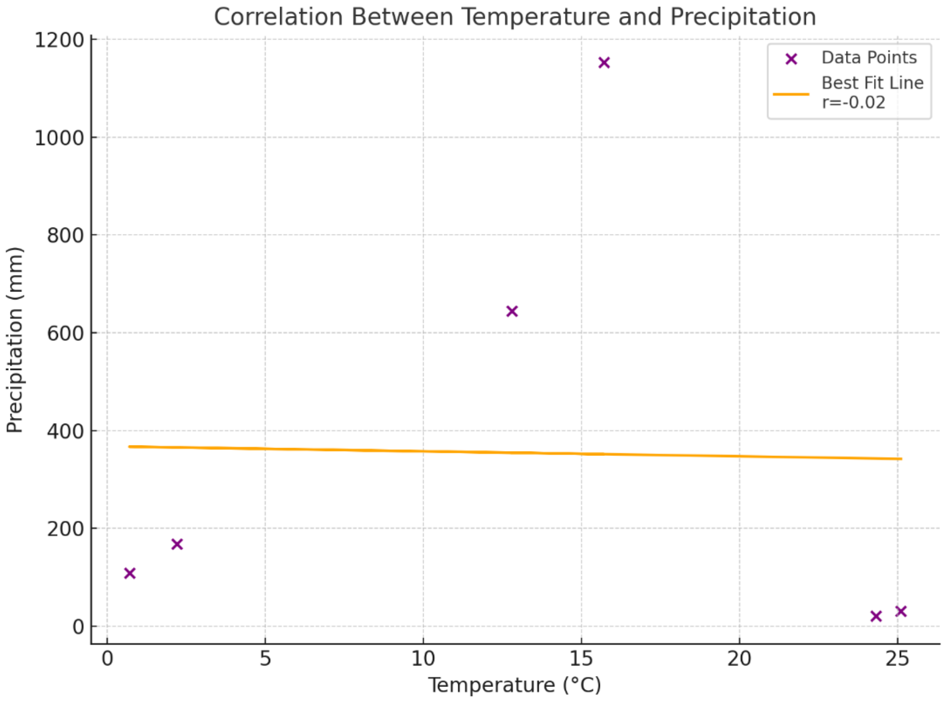


**Figure 4.** Correlation between Temperature and Precipitation

Figure 4 shows the correlation between temperature and precipitation regimes, highlighting their lack of dependence on each other. Based on the paleoclimatic reconstruction, the following conclusions can be drawn:

The climate in the Kushuk area during the early Miocene was warm-temperate, with mild winters and warm summers.

The annual precipitation was sufficient to support abundant vegetation, particularly during the rainy season.

The weak correlation between temperature and precipitation confirms their relative independence, which is typical of regions with moderately humid climates.

Thus, the climatic conditions of the early Miocene promoted the development of diverse ecosystems, including broadleaf forests and shrub formations, which supported the flora of the Kushuk region.

## 4. Discussion

The paleoclimatic reconstruction of the early Miocene using the nearest living relative (NLR) method provided detailed insights into the climatic conditions of the Turgai Depression during this period. A key aspect of this study was comparing the reconstructed data with contemporary climate indicators and examining it alongside the findings of other studies on paleoclimate. This section also includes graphs illustrating climate changes, allowing for a clear visualization of the region's climatic evolution.

*4.1 Paleoclimate Reconstruction of the Early Miocene*

The reconstruction revealed that during the early Miocene, the Turgai Depression was characterized by a warm temperate climate. The mean annual temperature (MAT) during this period ranged from 15.7°C to 17.8°C, significantly higher than present-day values. These findings align with those of Bruch et al. (2007), who recorded a mean annual temperature of approximately 15°C for the Oligocene-Miocene period in the Turgai Depression.

Our data also indicated that mean annual precipitation (MAP) ranged from 1150 mm to 1613 mm, suggesting a much wetter Miocene climate compared to current precipitation levels (220-330 mm). This shift reflects a notable decrease in regional moisture availability in modern times. Bruch et al. (2007) similarly reported evidence of a wetter Miocene climate, which corroborates our conclusions. These results demonstrate that the climate in the Turgai Depression during the early Miocene was considerably milder and more humid, supporting rich and diverse ecosystems, including forest formations and dense shrublands. Together with other studies, these findings contribute to a comprehensive picture of the region's climate change, highlighting the gradual cooling and aridification that have led to the present-day conditions characterized by steppe and semi-desert landscapes.

*4.2 Comparison with Contemporary Climate Conditions*

The modern climate of the Turgai Depression differs significantly from Miocene conditions. The current mean annual temperature ranges from 1°C to 4°C, indicating substantial cooling since the Miocene. Additionally, contemporary winter temperatures (CMT) can drop to -16°C or lower, whereas Miocene winter temperatures were considerably milder, ranging from 3.4°C to 8.1°C**.**

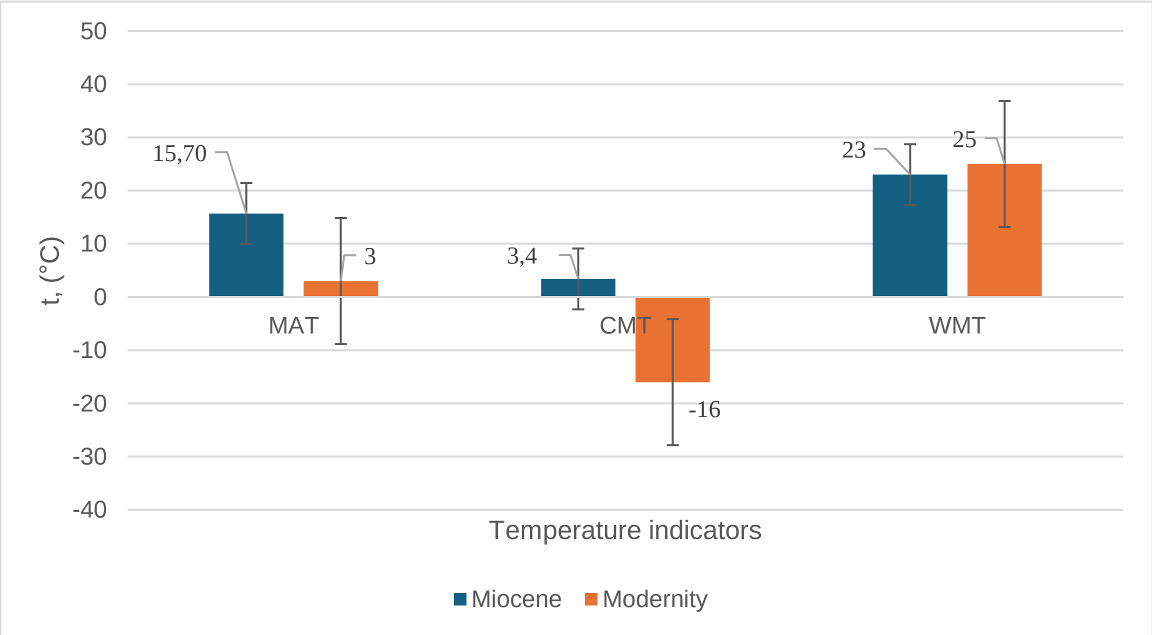


**Figure 5.** Comparison of Temperature Regimes in the Lower Miocene and Present Day

Figure 5 illustrates a significant cooling trend in the climate. The mean annual temperature (MAT) during the Miocene was approximately 15.7°C, much higher than the current 3.0°C. Changes are especially noticeable in the winter months: the coldest month temperature (CMT) in the Miocene was 3.4°C, whereas today it falls to -16°C, indicating a marked increase in continentality and winter severity.

Summer temperatures (WMT) have remained relatively stable, at 23°C in the Miocene and 25°C today. This suggests that the most pronounced climate changes occurred during the winter, while summer has retained relatively mild conditions over millions of years.

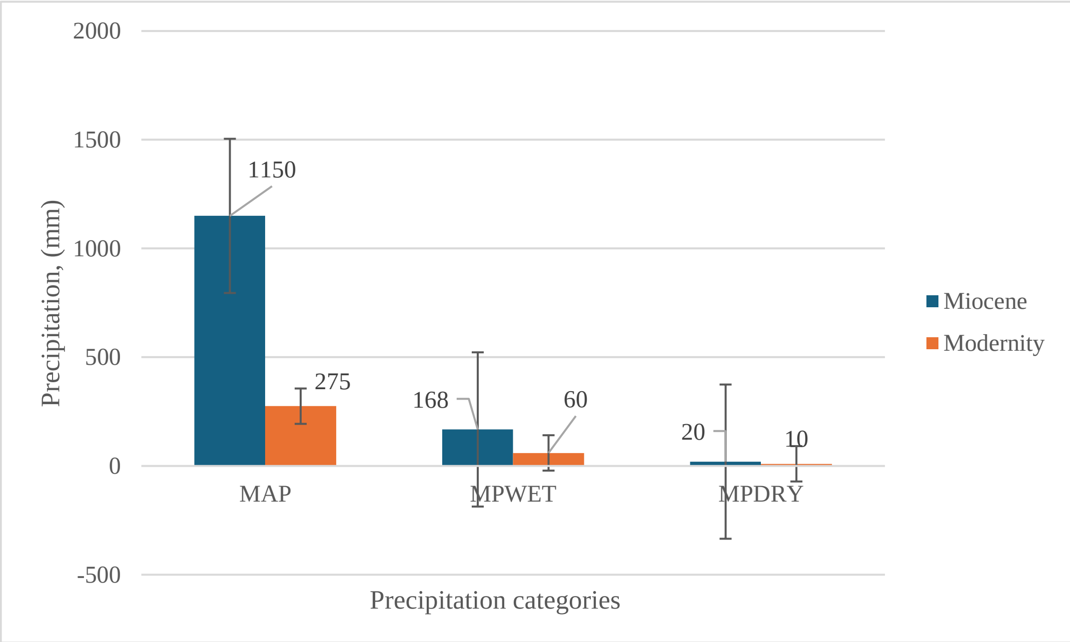


**Figure 6.** Comparison of Precipitation in the Lower Miocene and Present Day

Figure 6 highlights a substantial reduction in precipitation from the Miocene period to the present day. During the Miocene, mean annual precipitation (MAP) was approximately 1150 mm, whereas today it has decreased to 275 mm, indicating a shift toward a drier climate in the region. In the wettest months (MPWET), precipitation in the Miocene reached 168 mm, which is much higher than the modern 60 mm. Even in the driest months (MPDRY), precipitation in the Miocene was 20 mm, compared to the current 10 mm.

This reduction in precipitation led to a transformation of the region's ecosystems, with a shift from forests to steppe and semi-desert landscapes, as is evident from the region's current climatic and ecological conditions.

The comparison of early Miocene and modern climate conditions in the Turgai Depression reveals significant changes in temperature and precipitation patterns. The Miocene climate was considerably milder and wetter, with higher annual temperatures and greater precipitation, supporting extensive forest ecosystems. The modern climate of the region is marked by a sharp cooling, especially in the winter months, and a significant decrease in precipitation, leading to arid conditions and a shift from forested landscapes to steppe and semi-desert environments.

These climatic shifts illustrate the increased continentality of the region and a trend toward more extreme seasonal variations in temperature and precipitation, profoundly impacting the ecological and biological processes in the area.

Our findings align with other studies on the Miocene climate in Central Eurasia. For instance, research on the Kumyrtas flora in Western Siberia (Popova et al., 2012) presents similar climate conditions for that period, including mild winters and abundant rainfall. However, as noted in their work, the climate in Western Siberia was somewhat cooler than in the Turgai Depression, indicating spatial variations in regional climate. The results obtained indicate significant climatic changes in the Turgai Depression during the Miocene. Similar trends are observed in other regions, such as the Aegean Sea (Aksu et al., 1995), the Tarim Basin (Dupont-Nivet et al., 2007; Sun et al., 2010), and

Central Europe (Mosbrugger et al., 2005). The analysis of fossil Juglandaceae (Tiffney & Manchester, 2001) supports the data on the composition of vegetation. Comparison with the works of Bruch et al. (2006, 2007), Ivanov et al. (2011) also suggests that the early Miocene experienced wetter and more stable climatic conditions that supported dense forests. As these studies indicate, a gradual decrease in temperatures and precipitation occurred throughout the Miocene, leading to changes in the floral and faunal communities in the region. Additionally, studies such as Liu et al. (2011) and Grimalt and Targarona (2017) highlight similar climatic trends in North China and Central Asia, emphasizing the significance of vegetation-climate interactions during this period.

The paleoclimatic reconstruction of the early Miocene for the Turgai Depression region demonstrates that the climate during that period was considerably warmer and wetter than it is today. These shifts in climate conditions, including decreased precipitation and intensified seasonal temperature fluctuations, contributed to the transformation of the region's ecosystems. Our results align with these studies, supporting the hypothesis of substantial climate change from the Miocene period to the present day. By integrating findings from multiple studies, including those of Popova et al. (2019), our reconstruction reinforces the understanding of how Miocene climatic shifts influenced Central Eurasia's ecological and evolutionary pathways.

## 5. Conclusion

The Lower Miocene climate in the Turgai Depression was characterized by warm-temperate conditions, mild winters, and sufficient rainfall, supporting diverse forest ecosystems. These findings highlight a significant contrast with modern climatic conditions, where cooler temperatures and reduced precipitation dominate, contributing to the development of steppe and semi-desert landscapes.

The reconstructed climate parameters, such as a mean annual temperature (MAT) of 14.2°C and mean annual precipitation (MAP) of 898.5 mm, provide robust evidence of a wetter and milder climate during the Early Miocene. These results align with regional studies and reinforce the hypothesis of a gradual cooling and drying trend throughout the Miocene, driven by global climatic shifts and regional geographic factors.

This study contributes to a broader understanding of Central Asia's climatic evolution, offering insights into how ancient ecosystems responded to long-term climatic changes. The integration of the Coexistence Approach (CA) with existing paleofloristic data further demonstrates the reliability of this method for paleoclimate reconstruction and its applicability to other regions with rich fossil records. Future research could explore the interplay of climatic and geological factors to further refine our understanding of ecosystem transformations during the Neogene.

**6. Supplementary Materials.** No Supplementary materials.

## 7. Author Contributions

Conceptualization, methodology, and investigation – Sh.A.; supervision and project administration – A.Zh. and S.N.; validation and review – A.Zh. and S.N.; data curation and visualization – Sh.A. All authors have read and agreed to the published version of the manuscript.

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**11. Conflicts of Interest:** The authors declare no conflicts of interest.

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## Күшік мекенінің (Торғай ойпаты) ерте миоцен кезеңіндегі Coexistence Approach әдісі негізінде жүргізілген палеоклиматтық талдау

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**Аңдатпа.** Бұл мақалада Орталық Азияда орналасқан Торғай ойпатының ерте миоценінің палеоклиматтық реконструкциясы ұсынылған. Зерттеу Coexistence Approach (CA) әдісін қолдануға және Құшық орнынан алынған палеофлоралық деректерді егжей-тегжейлі талдауға негізделген. Жұмыстың негізгі мақсаты - ерте миоцендегі климаттық параметрлерді қалпына келтіру және экожүйе өзгерістерін бағалау. Нәтижелер ерте миоцен климаты жылы-қоңыржай жағдайлармен, жұмсақ қыспен және жеткілікті жауын-шашынмен сипатталғанын көрсетеді. Жылдық орташа температура 14,2°C, ал жылдық орташа жауын-шашын 898,5 мм-ге жетті. Бұл жағдайлар әртүрлі орман экожүйелерінің дамуына ықпал етті. Аймақтың қазіргі климатымен салыстыру айтарлықтай айырмашылықты көрсетеді, бұл континентальдылықтың жоғарылауын көрсетеді. Алынған деректер жаһандық және аймақтық факторлардың әсерінен миоцендегі климаттың бірте-бірте салқындауы мен құрғауы туралы гипотезаны растайды. Зерттеу Орталық Азияның климаттық эволюциясын түсінуге айтарлықтай үлес қосады және CA әдісінің сенімділігін көрсетеді. Нәтижелер климаттық өзгерістерді модельдеу және неогендегі экожүйелерге климаттың әсерін бағалау үшін қолданылуы мүмкін. Болашақ зерттеулер климаттық және геологиялық факторлардың өзара әрекеттесуін, сондай-ақ аймақтың биоәртүрлілігіне климаттық өзгерістердің әсерін бағалауға бағытталған. Климаттық ауысымдар мен гидрологиялық режимдегі өзгерістерді көрсететін өсімдіктер құрамындағы өзгерістерді талдауға ерекше назар аударылады. Алынған деректер палеоклиматтық модельдерді нақтылауға және неогендегі биосфералық процестердің динамикасын қалпына келтіруге бағытталған одан әрі зерттеулер үшін негіз бола алады.

**Түйін сөздер:** ерте миоцен, Торғай ойпаты, палеоклиматтық реконструкция, қазіргі заманғы жақын аналогтар (NLR) әдісі

## Палеоклиматический анализ раннего миоцена в местонахождении Кушук (Тургайская впадина) на основе метода совместного существования (Coexistence Approach)

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**Аннотация.** В данной статье представлена палеоклиматическая реконструкция раннего миоцена для Тургайской впадины, расположенной в Центральной Азии. Исследование основано на применении метода Coexistence Approach (CA) и детальном анализе палеофлористических данных из местонахождения Кушук. Основная цель работы -

реконструкция климатических параметров и оценка изменений экосистем в раннем миоцене. Результаты показывают, что климат раннего миоцена характеризовался теплоумеренными условиями, мягкими зимами и достаточным количеством осадков. Среднегодовая температура составляла 14,2°C, а среднегодовое количество осадков достигало 898,5 мм. Эти условия способствовали развитию разнообразных лесных экосистем. Сравнение с современным климатом региона выявляет значительный контраст, указывая на усиление континентальности. Полученные данные подтверждают гипотезу о постепенном похолодании и аридизации климата в миоцене, вызванном глобальными и региональными факторами. Исследование вносит существенный вклад в понимание климатической эволюции Центральной Азии и демонстрирует надежность метода CA. Результаты могут быть использованы для моделирования климатических изменений и оценки влияния климата на экосистемы в неогене. Планируется, что будущие исследования будут направлены на изучение взаимодействия климатических и геологических факторов, а также на оценку влияния климатических изменений на биоразнообразие региона. Особое внимание уделяется анализу изменений в составе растительности, которые отражают климатические сдвиги и изменения в гидрологическом режиме. Полученные данные могут служить основой для дальнейших исследований, направленных на уточнение палеоклиматических моделей и реконструкцию динамики биосферных процессов в неогене**.**

**Ключевые слова:** ранний миоцен, Тургайский прогиб, палеоклиматическая реконструкция, метод ближайших современных аналогов (NLR).