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REGIONAL CLIMATE CHANGES IN ALMATY REGION UNDER GLOBAL CLIMATE CHANGE

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Abstract. One of the global problems of our time is climate change. This problem is relevant not only at the level of individual states, but also on a global scale, having a significant impact on both natural ecosystems and socio-economic development of mankind. In the presented article, a comprehensive study of the impact of global warming on the climate of Almaty region, located in the south-east of the Republic of Kazakhstan, has been conducted. To analyze trends, the non-parametric Mann-Kendall test in the R Studio software environment was used, which allowed us to assess the statistical significance of changes. Additionally, using Climpact software, climatic indices were calculated from daily meteorological data reflecting extreme climatic events. Based on climate scenarios presented in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), modeling of possible multi-year changes in air temperature and precipitation in the region was performed using the QGIS geoinformation system. The obtained results indicate

the presence of stable trends of climate change in Almaty region and emphasize the need to take into account regional climatic changes. Projections based on various socio-economic scenarios show a possible increase in air temperature by the end of the 21st century, which emphasizes the relevance of integrating climate risks into the processes of strategic planning and natural resource management. The results of the study can be used for adaptation measures and decision-making in the fields of sustainable development, agriculture, water resources and environmental protection

Keywords: temporal changes in air temperature and precipitation, temperature and precipitation anomalies, climate indices, future climate change scenarios

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КЛИМАТТЫҢ ЖАҺАНДЫҚ ӨЗГЕРУІ ЖАҒДАЙЫНДАҒЫ АЛМАТЫ ОБЛЫСЫ КЛИМАТЫНЫҢ АЙМАҚТЫҚ ӨЗГЕРУЛЕРІ

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Аннотация. Қазіргі кездегі ғаламдық мәселелердің бірі — жаһандық жылыну салдарынан климаттың өзгеруі. Бұл мәселе жеке елдерде ғана емес бүкіл ғаламшарда өзекті болып табылады, сонымен қатар ол табиғи экожүйелерге әсер етіп қана қоймай, адамзаттың әлеуметтік-экономикалық дамуына да елеулі әсер етеді. Бұл мақалада Қазақстан республикасының оңтүстік-шығысында орналасқан Алматы облысының климатына жаһандық жылынудың әсері зерттеліп, сараптама жасалды. Алматы облысы бойынша 1937-2024 жылдар аралығындағы ауа температурасы мен жауын-шашынның аномалиялары есептеліп, соңғы жылдары ауа температурасы бойынша оң таңбалы, ал жауын-шашын бойынша теріс таңбалы аномалиялар байқалғаны анықталды. Трендтерді талдау үшін R Studio бағдарламалық ортасында

параметрлік емес Манн-Кендалл тесті пайдаланылды, бұл өзгерістердің статистикалық маңыздылығын бағалауға мүмкіндік берді. Сонымен қатар, Climpact бағдарламалық өнімін қолдана отырып, экстремалды климаттық құбылыстарды көрсететін тәуліктік метеодеректер бойынша климаттық индекстер есептелді. Климаттың өзгеруі жөніндегі үкіметаралық сарапшылар тобының (IPCC) алтыншы бағалау есебінде ұсынылған климаттық сценарийлер негізінде QGIS геоақпараттық жүйесін қолдана отырып, өңірдегі ауа температурасы мен жауын-шашынның ықтимал көпжылдық өзгерістерін модельдеу орындалды. Алынған нәтижелер – Алматы облысындағы климаттың өзгеруінің тұрақты үрдістерінің бар екендігін растайды және бейімделу мен салдарларды азайту стратегияларын әзірлеу кезінде өңірлік климаттық өзгерістерді есепке алу қажеттігіне назар аударады. Әр түрлі әлеуметтік-экономикалық сценарийлерге негізделген болжамдар XXI ғасырдың аяғында ауа температурасының жоғарылауын көрсетеді, бұл климаттық тәуекелдерді стратегиялық жоспарлау және табиғи ресурстарды басқару процестеріне біріктірудің өзектілігін аңғартады. Зерттеу нәтижелері бейімделу шараларын әзірлеу және тұрақты даму, ауыл шаруашылығы, Су ресурстары және қоршаған ортаны қорғау салаларында шешімдер қабылдау үшін пайдаланылуы мүмкін.

Түйін сөздер: ауа температурасы мен жауын-шашынның уақыттық өзгерулері, ауа температурасы мен жауын-шашынның аномалиялары, климаттық индекстер, климаттың болашақ өзгеру сценарийлері

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РЕГИОНАЛЬНЫЕ ИЗМЕНЕНИЯ КЛИМАТА АЛМАТИНСКОЙ ОБЛАСТИ В УСЛОВИЯХ ГЛОБАЛЬНОГО ИЗМЕНЕНИЯ КЛИМАТА

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Аннотация. Одной из глобальных проблем современности является изменение климата. Данная проблема актуальна не только на уровне отдельных государств, но и в мировом масштабе, оказывая значительное воздействие как на природные экосистемы, так и на социально-экономическое развитие человечества. В представленной статье проведено комплексное исследование влияния глобального потепления на климат Алматинской области, расположенной на юго-востоке Республики Казахстан. На основе метеорологических данных, охватывающих период с 1937 по 2024 годы, рассчитаны аномалии температуры воздуха и осадков, выявлены устойчивые положительные аномалии температуры и отрицательные аномалии осадков в последние десятилетия. Для анализа трендов использован непараметрический тест Манн-Кендалла в программной среде R Studio, что позволило оценить статистическую значимость изменений. Дополнительно, с использованием программного обеспечения Climpact рассчитаны климатические индексы по суточным метеоданным, отражающие экстремальные климатические явления. На основе климатических сценариев, представленных в Шестом оценочном докладе Межправительственной группы экспертов по изменению климата (IPCC), с применением геоинформационной системы QGIS выполнено моделирование возможных многолетних изменений температуры воздуха и осадков в регионе. Полученные результаты свидетельствуют о наличии устойчивых тенденций изменения климата в Алматинской области и акцентируют внимание на необходимости учета региональных климатических изменений при разработке стратегий адаптации и смягчения последствий. Прогнозы, основанные на различных социально-экономических сценариях, демонстрируют возможное повышение температуры воздуха к концу XXI века, что подчеркивает актуальность интеграции климатических рисков в процессы стратегического планирования и управления природными ресурсами. Результаты исследования могут быть использованы для выработки адаптационных мер и принятия решений в области устойчивого развития, сельского хозяйства, водных ресурсов и охраны окружающей среды.

Ключевые слова: климатические изменения, Алматинская область, температурные аномалии, осадки, климатические индексы, IPCC, моделирование, QGIS, R Studio, сценарии изменения климата

Introduction. Global warming is the process of gradually increasing the average annual temperature of the Earth's atmosphere and the surface of the world's oceans due to various factors. The concept of global warming and the greenhouse effect was first introduced in the 1960s, and since the 1980s, this issue has been

actively discussed at the United Nations (UN) level. The World Meteorological Organization, the UN Environment Programme, the Intergovernmental Panel on Climate Change (IPCC), and regional organizations such as Kazhydromet are the main institutions conducting research on global climate change and providing scientific information to governmental organizations at different levels.

According to the IPCC, climate change is associated with both natural internal processes and external factors, such as variations in solar cycles, volcanic eruptions, changes in atmospheric composition, and human activities related to land and ocean use. The Sixth Assessment Report of the IPCC states that anthropogenic climate change has led to an increase in the frequency and intensity of heatwaves since the 1950s. Further increases in air temperature will continue to amplify the frequency and intensity of heatwaves. Rising temperatures and heatwaves, in turn, contribute to an increase in diseases and mortality, food insecurity, and the extinction of local plant and animal populations. Every additional rise in temperature exacerbates extreme events. For example, an additional 0.5°C of global warming leads to increased intensity and frequency of extreme temperatures, as well as prolonged heatwaves. Heatwaves intensify droughts, fuel wildfires, and lead to electricity shortages and agricultural losses. According to the World Meteorological Organization, record levels have been reached in greenhouse gas concentrations, land surface temperatures, sea level rise, ocean acidification, and ice cover in Antarctica. Additionally, 2023 was recorded as the warmest year on record, with an average global land surface temperature reaching 1.45°C above pre-industrial levels (with an uncertainty of ±0.12°C).

Climate change, particularly global warming, has resulted in an increase in average air temperature by 0.5–0.7°C and a rise in sea level by 10–20 cm, exceeding the average values observed over the last 3,000 years. Since 1950, the volume of sea ice in the Northern Hemisphere has decreased by 10–15%, while the duration of ice cover on lakes and rivers has been reduced by two weeks in the last decade. Over the past 50 years, Arctic sea ice thickness has declined by 40%, and in the last 150 years, glaciers in non-polar regions have retreated significantly. Scientists have been discussing these changes and their potential consequences with growing concern. According to World Meteorological Organization (WMO) studies, the average global temperature increased by 0.85°C from 1880 to 2012, accompanied by a 10–20 cm rise in sea level. The study "Global Warming of 1.5°C" found that exceeding a 1.5°C increase in global temperature could lead to abrupt weather changes, reduced water availability, and an increased risk of extinction for many animal and plant species.

The research paper "The Impacts of Climate Change on Terrestrial Earth Surface Systems" discusses the impact of global warming on land surfaces, including its effects on vegetation, soil, and water resources. It highlights that climate change may lead to soil degradation, declining water quality, and reduced biodiversity (Jasper Knight et al., 2013). Air temperature and atmospheric precipitation are critical

meteorological parameters for assessing climate conditions and predicting weather. These parameters are key factors in scientific research and practical applications across various industries, including agriculture, transportation, construction, and hydrometeorology. Between the 1980s and 2019, the average global land surface temperature increased at a rate of 0.320°C per decade, while in the Northern Hemisphere, the annual mean land temperature increased at a rate of 0.362°C per decade (Beibei Shen et al., 2022).

The global warming hiatus from 1998 to 2012 has generated significant public interest in recent years. A study analyzing air temperature across 622 meteorological stations in China found that during this period, national and regional warming slowed significantly. The air temperature trend from 1998 to 2012 declined by -0.221°C per decade, which was 0.427°C per decade lower than the long-term trend from 1960 to 1998. This indicates that the warming hiatus was more pronounced in China compared to the global average. However, after 2012, air temperatures began to rise rapidly and are expected to continue increasing (Du Q et al., 2019). Five major global temperature datasets—three based on surface temperature records (NASA/GISS, NOAA/NCDC, and HadCRU) and two based on lower troposphere satellite measurements (RSS and UAH)—have been analyzed since 1979. All five datasets show consistent global warming trends ranging from 0.014 to 0.018 K per year. The lower tropospheric temperature trends are more influenced by El Niño/ Southern Oscillation events and volcanic activity compared to surface temperatures. The adjusted datasets indicate an ongoing warming trend with minimal data errors. The two warmest years recorded in the datasets were 2009 and 2010 (Foster et al., 2011).

According to data from Kazhydromet, over the past 81 years, a general increase in annual and seasonal land surface temperatures has been observed in Kazakhstan. Between 1936 and 2016, the average annual temperature in Kazakhstan increased by 0.27°C per decade. Additionally, 2016 was recorded as the wettest year since 1936 in terms of total annual precipitation. In recent decades, climate change has also been observed in the Almaty Region, particularly in changes in temperature and precipitation. Many climatologists attribute these changes to an increase in atmospheric carbon dioxide (CO_2) concentrations caused by human activities (Munaitpasova et al., 2024). The Almaty region is located in the southeastern part of the Republic of Kazakhstan. It borders the Zhambyl region to the west, the Karaganda region to the northwest, the East Kazakhstan region to the northeast, the People's Republic of China to the east, and the Kyrgyz Republic (Chu and Issyk-Kul regions) to the south. The geographical characteristics of the region are highly complex, with diverse terrain. The natural conditions include five climatic zones, ranging from deserts to perpetual snow.

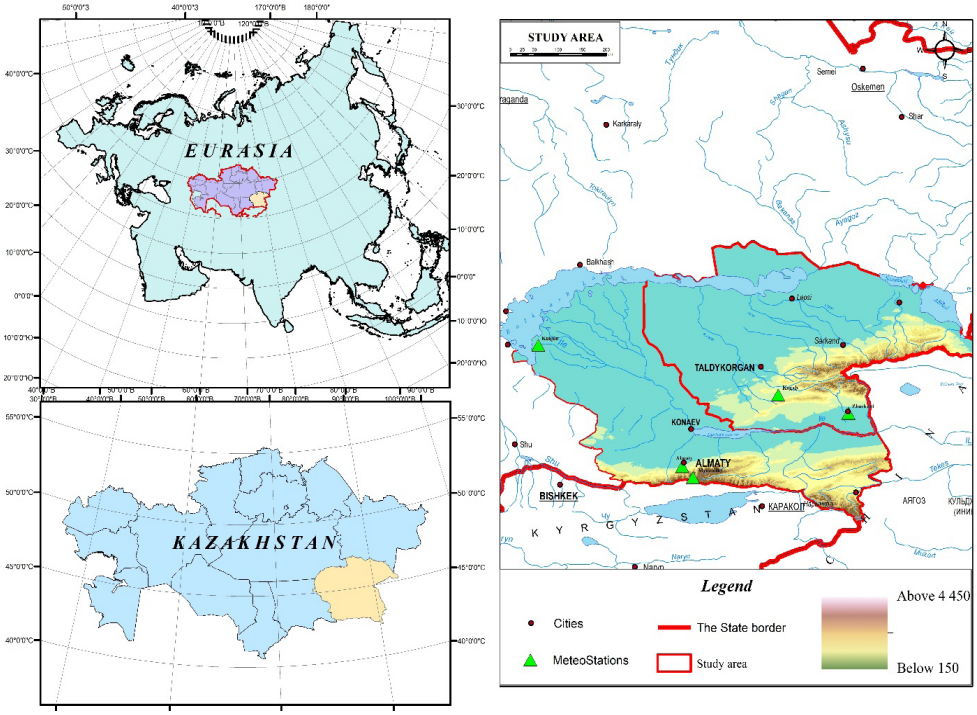

Figure 1. Map of meteorological stations in Almaty region

The northwestern part of the region consists of a semi-desert plain that slopes gently towards Lake Balkhash and is intersected by ancient river channels of the Ili, Karatal, Aksu, Koksu, Lepsy, and Ayagoz rivers. Mountain ranges extend across the southern and eastern parts, including the Ile Alatau and Dzungarian Alatau (part of the Tien Shan mountain system). The middle course of the Ili River is located at the confluence of the gradually descending mountain slopes. In the south, the region is bordered by the Northern Tien Shan ranges, while in the northwest; it is adjacent to Lake Balkhash. To the northeast, it is bordered by the Ili River, and to the east, it meets the People's Republic of China (Vilesov et al., 2009).

Table 1. Brief physical-geographical description of meteorological stations in the study area

№	Mete-orological stations	Observation period	Station elevation, metres (m)	Lati-tude	Lon-gitude	Ground-water level, metres (m)	Soil type
1	Kuygan	from 1929 y. to the present	344 m	45^0 22/	74^0 08/	2-4m	Meadow soils, highly saline with predominant sand, takyr-like in the south
2	Zharkent	from 1911 y.- to the present	642,5 m	44^0 10/	80^0 00/	10 m	gray soil with an admixture of sand, in places patches of solonchak

3	Almaty	from 1915 y. to the present	847 m	43^0 15/	76^0 54/	> 15 m	dark chestnut, loamy, in places gravelly
4	Kogaly	from 1927 y. to the present	1410 m	44^0 28/	78^0 39/	3-5 m	mountain-valley soil.
5	Mynzhylky	from 1935 y. to the present	3017 m	43^0 05/	77^0 04/	> 15 m	loamy, stony, in depressions loam with an admixture of gravel and pebbles.

Materials and Methods. Climate change has become one of the most pressing issues of our time. This phenomenon not only affects natural ecosystems but also has a significant impact on the socio-economic development of humanity. In Kazakhstan, studying global climate change has become a critical topic. For this purpose, five meteorological stations in the southeastern part of the country—Almaty, Kogaly, Kuigan, Zharkent, and Mynzhylky—were selected for analysis. The study examined annual and monthly average temperature and precipitation data from these stations over the period from 1937 to 2024. To understand the overall climate changes in the Almaty region, widely used meteorological methods such as mathematical analysis, statistical analysis, and climate deviation assessment were applied. The Mann-Kendall non-parametric test was used to check the normality of temperature trend lines. This test, which identifies monotonic trends in time series data, was applied using R Studio software (mkttest(x)).

The Mann-Kendall trend test is a non-parametric test that assesses whether there is a statistically significant trend in a dataset. The null hypothesis assumes no trend in the data, while the alternative hypothesis suggests a monotonic trend. A comparative analysis of temperature characteristics was performed using daily data in the Climpact software. Additionally, climate projections based on SSP1, SSP2, SSP3, and SSP5 scenarios from the IPCC Sixth Assessment Report were analyzed for the selected meteorological stations in the Almaty region.

Results and discussion. Global warming and climate change have significantly affected the Almaty region of Kazakhstan. Observable climate changes can lead to severe consequences such as drought, shifts in vegetation structure, and threats to biodiversity. Changes in global air temperature and climate models are already posing risks to agricultural systems and human settlements. These risks include an increase in the frequency of extreme heat events, greater variability in precipitation, an increase in hazardous weather phenomena, and rising sea levels. Given the importance of temperature and precipitation as key climate factors, the long-term dynamics of these elements were analyzed for the Almaty, Kogaly, Kuigan, Zharkent, and Mynzhylky meteorological stations over the period from 1937 to 2024 (Figures 2, 3).

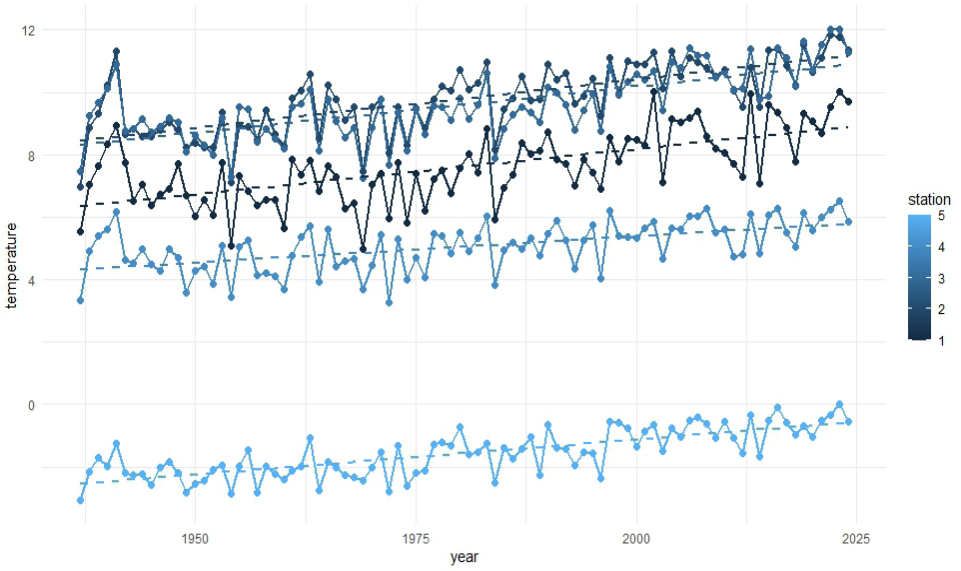

Figure 2. Dynamics of air temperature changes in Almaty region (1937–2024)
*1 - Kuygan, 2 - Zharkent, 3 - Almaty, 4 - Kogaly, 5 - Mynzhylky

According to the study by K.K. Duskaev et al., the average annual air temperature at the Almaty meteorological station was 9.0°C in 1935–1944, rising to 10.7°C in 2005–2014 (Duskaev et al., 2018).

Overall, the analyzed meteorological stations in Almaty Region show a trend of air temperature change by 0.2–0.3°C per decade between 1937 and 2024.

The study of long-term precipitation changes is one of the key issues. Precipitation undergoes spatial and temporal variations influenced by atmospheric circulation patterns, physical-geographical conditions, and seasonal factors. These factors interact closely, shaping the spatial and temporal distribution of precipitation both throughout the year and from year to year (Litvinova et al., 2010).

The precipitation regime across different regions of Kazakhstan is highly diverse. Except for high mountain areas, Kazakhstan is classified as a region with insufficient precipitation. In desert zones, precipitation levels are extremely low. Therefore, a defining characteristic of Kazakhstan's steppe climate is pronounced aridity, primarily due to its location in the center of Eurasia.

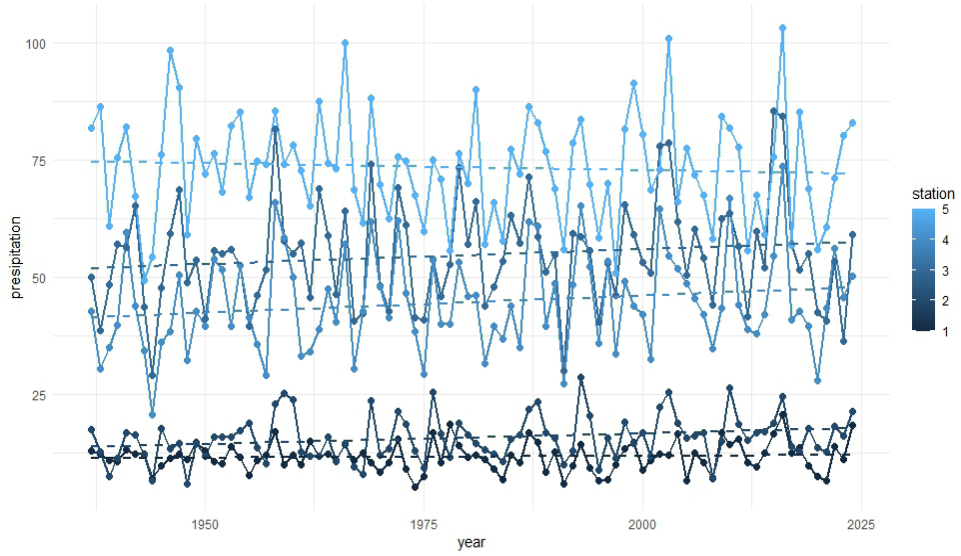

Figure 3. Dynamics of precipitation changes in Almaty region (1937–2024)
*1 - Kuygan, 2 - Zharkent, 3 - Almaty, 4 - Kogaly, 5 – Mynzhylky

Figure 3 presents the distribution of annual average precipitation dynamics for the studied locations. The highest precipitation levels are recorded at the Mynzhylky station, while the lowest levels are observed at the Kuigan and Zharkent meteorological stations. Over the study period, precipitation at Mynzhylky showed a decreasing trend of 0.5 mm per decade, whereas in Almaty, Zharkent, and Kogaly, precipitation increased by 0.4–0.8 mm per decade. At the Kuigan station, no significant trend was observed. Topography plays a crucial role in precipitation distribution. Due to the influence of mountain slopes, precipitation tends to increase in mountainous areas while decreasing at lower elevations.

During the second half of the 20th century, precipitation trends across Kazakhstan were influenced by synoptic processes within the general warming trend. However, it was found that precipitation increased during the cold season while decreasing during the warm season (Muratova et al., 2014). In 2021, the average annual air temperature anomaly in Kazakhstan was recorded at +1.6°C above the 1961–1990 average (5.4°C), which was 0.3°C lower than in 2020. Since the 1960s, each subsequent decade in Kazakhstan has been warmer than the previous one. During the most recent decade (2012–2021), the average annual air temperature was recorded at +6.6°C, exceeding the climate norm by 1.2°C, marking the highest decadal anomaly on record. The previous warmest decade was 2001–2010, with an anomaly of +1.1°C.

The most recent five-year period (2017–2021) was also the warmest on record, with an average annual air temperature of +6.7°C, which was 1.3°C above the climate norm.

Table 2. Warmest years in observation history and corresponding averaged annual air temperature anomalies (°C)

№	Global (since 1850)	Kazakhstan	Almaty region (1941–202)	Average annual air temperature anomaly averaged across Kazakhstan (jan.-dec.)	Average annual air temperature anomaly averaged across Almaty region (jan.-dec.) (1937-2021)
1	2020	2020	2016	1,9	2,0
2	2016	2013	2013; 2019	1,9	1,9
3	2019	1983	2002	1,8	1,8
4	2017	2015	2006; 2007	1,6	1,8
5	2015	2021	2021	1,6	1,7
6	2021	2002	2015	1,6	1,6
7	2018	2004	2008	1,5	1,6
8	2014	2019	2004	1,5	1,6
9	2010	2016	1997; 1941	1,5	1,6
10	2005	2007	2017	1,5	1,5

Table 2 presents the ranked series of annual mean temperature anomalies for the selected meteorological stations in the Almaty region from 1937 to 2021. On a global scale, all ten of the warmest decades have occurred in the last century. According to the 2021 report by the World Meteorological Organization, 2021 was one of the seven warmest years on record. The global average air temperature in 2021 was approximately 1.1°C higher than the 1850–1900 baseline period.

The following tables (Tables 2 and 3) provide data on temperature and precipitation deviations for different decades in the Almaty region from 1937 to 2024.

Table 3. Air temperature variations in different periods

Station	Air temperature variations in different periods, °C								
	1937-1946	1947-1956	1957-1966	1967-1976	1977-1986	1987-1996	1997-2006	2007-2016	2017-2024
Kuigan	-0,3	-0,8	-0,5	-1,0	-0,2	0,3	1,1	1,0	2,4
Zharkent	-0,7	-1,2	-0,3	-0,7	0,3	0,40	1,1	0,9	2,3
Almaty	-0,3	-0,8	-0,5	-0,8	-0,2	0,0	1,0	1,1	2,2
Kogaly	-0,2	-0,5	-0,4	-0,6	0,2	0,2	0,6	0,6	1,1
Mynzhylky	-0,6	-0,6	-0,5	-0,6	0,2	0,0	0,8	0,8	1,3

According to Table 3, the warmest decades in the Almaty region from 1937 to 2021 were observed in the last 30 years, with air temperature increases ranging from 0.6°C to 1.5°C. The most significant warming was recorded at the Almaty station (1–1.5°C), which can be explained by its urban location. The increase in greenhouse gas emissions from vehicles and thermal power plants contributes to additional heat accumulation.

The least noticeable temperature changes were recorded at the Kogaly and Mynzhylky stations. This is due to their higher elevation in mountainous areas, where air temperatures tend to be more stable.

Table 4. Precipitation variations in different periods

Station	Precipitation variations in different periods, mm								
	1937-1946	1947-1956	1957-1966	1967-1976	1977-1986	1987-1996	1997-2006	2007-2016	2017-2024
Kuigan	-0,3	0,0	-0,5	0,9	0,0	-1,1	0,2	1,8	-1,6
Zharkent	-2,5	-1,2	0,3	-0,2	-1,1	1,8	1,6	2,0	-1,5
Almaty	-5,3	-3,2	3,9	-3,4	1,2	-1,6	5,5	5,6	-5,5
Kogaly	-6,3	-0,4	1,1	1,0	-3,2	4,9	2,2	3,4	-5,5
Mynzhylky	0,1	2,4	5,3	-2,8	-3,8	0,0	3,1	-0,1	-7,6

According to Table 4, the annual average precipitation levels in the Almaty region from 1937 to 2021 did not show a clear trend, with both increases and decreases fluctuating significantly. During the period from 1997 to 2016, all analyzed stations recorded an increase in precipitation ranging from 0.2 to 5.6 mm. However, in the most recent period from 2017 to 2024, a decreasing trend in precipitation (1.6–7.6 mm) was observed across all stations. According to Kazhydromet data, precipitation shortages (30–40%) were recorded in the western and southern regions of Kazakhstan.

One of the main objectives of many environmental monitoring programs is to identify changes or trends in the concentration of various components over time. In Kazakhstan, statistical indicators related to these trends can be studied in more detail. These include basic correlation and regression analysis, time series analysis, and methods based on non-parametric statistics.

The Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975; Gilbert, 1987) is used to statistically determine whether a variable of interest exhibits a monotonic increase or decrease over time. A monotonic trend, whether linear or not, indicates a consistent increase or decrease in the variable over time. Instead of performing parametric linear regression analysis to determine whether the slope of the regression line is significantly different from zero, the MK test can be used. The Mann-Kendall test is a widely applied non-parametric test for detecting time trends. However, the standard p-values obtained from this test are constructed based on the assumption of independence among observations (as the Kendall theory is based on correlation).

The results of the Mann-Kendall trend test are presented in Tables 4 and 5.

Table 5. Air temperature trend analysis using the Mann-Kendall Test

Month	**Kuigan**		**Zharkent**		**Almaty**		**Kogaly**		**Mynzhylky**	
	z-stat	**p-value**	**z-stat**	**p-value**	**z-stat**	**p-value**	**z-stat**	**p-value**	**z-stat**	**p-value**
January	1.809	0.070	3.515	0.0004	3.302	0.0009	1.056	0.291	2.145	0.0319
February	2.466	0.014	3.846	0.0001	3.821	0.0001	1.298	0.194	1.914	0.0555
March	2.888	0.004	4.096	0.00004	3.941	0.00008	2.560	0.009	3.739	0.0002
April	4.067	0.00004	3.555	0.0004	3.667	0.0002	3.267	0.001	3.509	0.0005
May	2.968	0.003	2.589	0.0096	2.741	0.0061	1.832	0.067	2.975	0.0029
June	4.703	0.000003	4.654	0.000003	4.720	0.000002	4.332	0.00001	5.698	0.00000001
Jule	3.377	0.0007	2.716	0.0066	3.258	0.0011	1.999	0.045	3.969	0.00008
August	4.369	0.00001	2.104	0.0354	2.568	0.0102	1.898	0.058	3.945	0.00008

September	3.369	0.0008	3.120	0.0018	2.720	0.0065	1.897	0.058	3.781	0.0002
October	3.729	0.0002	3.228	0.0012	2.362	0.018	2.503	0.012	2.767	0.0056
November	3.169	0.002	4.189	0.00002	3.547	0.0004	2.747	0.006	4.211	0.00003
December	1.773	0.076	2.566	0.0103	2.754	0.0059	1.348	0.178	2.838	0.0045

Table 5 presents the results of the Mann-Kendall test, which examined temperature trends in the southeastern region of Kazakhstan from 1937 to 2024. Significant trend variations were observed in March, June, August, and September across the meteorological stations in Almaty, Mynzhylky, Zharkent, Kogaly, and Kuigan.

The Mann-Kendall test results indicate that warming during the spring and autumn months is evenly distributed across the Almaty region (Talipova et al., 2021). According to the non-parametric Mann-Kendall test, the Z statistic reached 5.698 at the Mynzhylky station in June. At the Almaty and Kuigan stations, the trend lines in June showed values of 4.654 and 4.703, respectively. The most significant warming was recorded at the Mynzhylky station during the summer months.

Table 6. Precipitation trend analysis using the Mann-Kendall Test

Month	**Kuigan**		**Zharkent**		**Almaty**		**Kogaly**		**Mynzhylky**	
	z-stat	**p-value**	**z-stat**	**p-value**	**z-stat**	**p-value**	**z-stat**	**p-value**	**z-stat**	**p-value**
January	0.245	0.806	0.155	0.877	0.962	0.336	1.211	0.226	-0.483	0.629
February	0.757	0.449	1.546	0.122	2.717	0.007	2.137	0.033	1.507	0.132
March	0.919	0.358	1.067	0.286	0.987	0.323	1.287	0.198	-0.105	0.917
April	-0.396	0.692	1.279	0.201	0.937	0.349	0.951	0.341	-0.378	0.705
May	0.303	0.762	0.029	0.980	-0.551	0.581	-0.894	0.371	-1.564	0.118
June	-0.869	0.385	-0.278	0.781	-1.114	0.265	-0.263	0.792	0.306	0.759
Jule	1.673	0.094	1.045	0.296	0.378	0.705	0.638	0.524	-0.584	0.559
August	0.779	0.436	0.274	0.784	0.843	0.399	0.919	0.358	-0.768	0.443
September	-0.682	0.495	1.362	0.173	-0.083	0.933	-0.533	0.594	0.382	0.702
October	0.890	0.373	2.209	0.027	0.039	0.968	0.861	0.389	0.923	0.356
November	0.083	0.934	1.474	0.140	-0.065	0.948	1.171	0.241	-0.800	0.424
December	-1.842	0.065	0.797	0.426	1.132	0.258	0.609	0.542	0.018	0.985

According to Table 6, the Mann-Kendall test was used to analyze precipitation trends in the southeastern region of Kazakhstan from 1937 to 2024. The non-parametric Mann-Kendall test showed that the Z statistic reached 2.717 at the Almaty station in February, while in Kogaly and Zharkent, the trend values were 1.546 and 2.137, respectively. However, no significant overall trend changes in precipitation were observed. Long-term annual precipitation changes exhibited both positive and negative trends, with a noticeable decline in precipitation during August and September at the analyzed meteorological stations.

Meteorological data is collected, processed, and analyzed to monitor climate change trends. In line with modern requirements, meteorological data processing has been simplified and is now carried out with the help of specialized software. The ClimPACT software uses daily weather data as a basis for calculating climate

indices, ensuring data consistency and quality control. Several methods are available for verifying data homogeneity, with the RHTest software being a recommended open-access and user-friendly tool. To compute all ClimPACT indices, time series of daily minimum temperature (TN), daily maximum temperature (TX), and daily precipitation (PR) are required.

Table 7. Key ET-SCI Indices (according to the 2011 decision)

Abbreviated тame	Full name	Description	Unit	Sector
TXx	max TX absolute maximum	Warmest daily TX	°C	AFS
TNn	min TN absolute minimum	Coldest daily TN	°C	AFS
TXge35	very hot days	number of days per year with maximum daily temperature TX> 35 ºC	day	H, AFS
TNltm20	TN below -20 °C	Number of days with TN<(-20) °C	day	H, AFS

According to Table 7, the characteristics of ClimPACT indices and their application across economic sectors are presented. These sectors include H (Healthcare) and AFS (Agriculture and Food Security).

Using ClimPACT indices, an analysis was conducted based on data from the Almaty BGM meteorological station. The study examined the absolute maximum and minimum values of daily temperatures, as well as the number of days per year when:

- The daily maximum air temperature exceeded TX > 35°C
- The daily minimum air temperature dropped below TN < -20°C

The results of these analyses are illustrated in Figures 3–6.

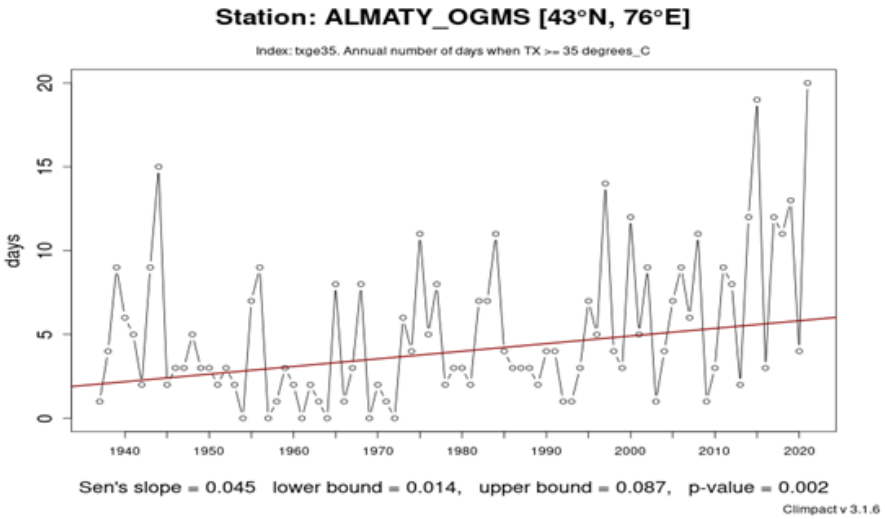

Figure 4. TXge35 Index at Almaty BGMS meteorological station

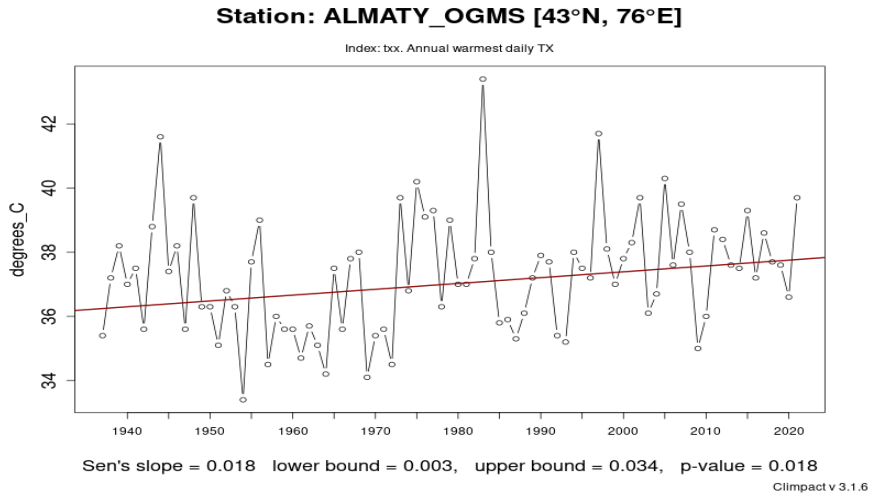

Figure 5. TXx Index at Almaty BGMS meteorological station

Figure 4 presents the number of days per year with a daily maximum air temperature exceeding TX > 35°C at the Almaty BGM meteorological station from 1937 to 2024, as calculated using the ClimPACT software. In recent years, the number of days with TX > 35°C has increased, reaching 20 days in 2023. Figure 5 displays the absolute maximum values of daily maximum temperatures recorded at the Almaty BGM meteorological station from 1937 to 2024 using the ClimPACT software. During this period, the absolute maximum temperature fluctuated between 34°C and 42°C, with the highest recorded value of 43°C in 1983.

The warm season of 2021 was characterized by exceptionally high daily maximum temperatures. Across Kazakhstan, temperatures exceeded 30°C and 35°C (except in mountainous regions). In southern regions, the number of days with temperatures above 35°C (TXGE35 index) ranged from 80 to 120 days. In 2021, the daily maximum temperature (TXx index) reached 36–40°C in northern, northeastern regions, and the western part of the Karaganda region. In other areas (excluding mountainous regions), maximum temperatures exceeded 40°C, while in some western and southern regions, temperatures exceeded 45°C.

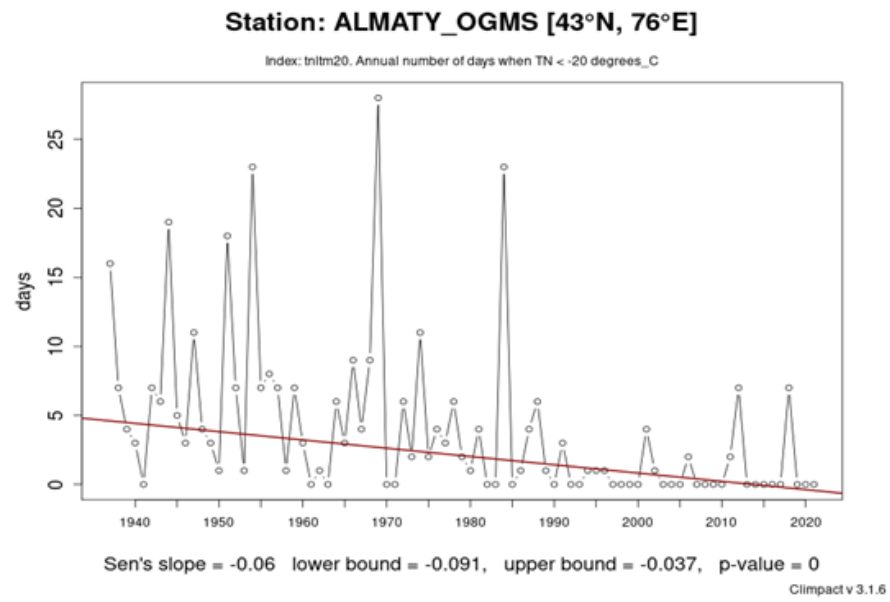

Figure 6. TNltm20 Index at Almaty meteorological station

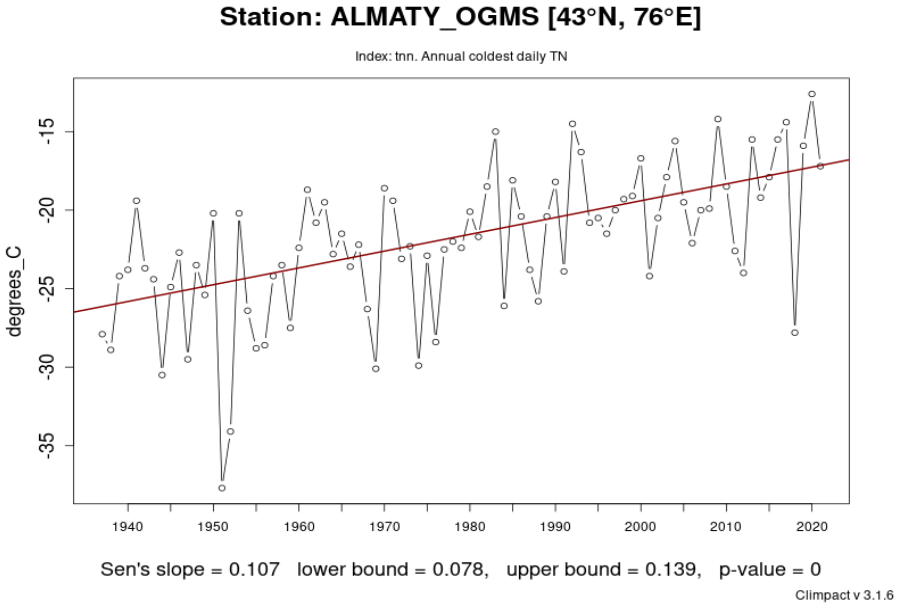

Figure 7. TNn Index at Almaty meteorological station

Figure 6 presents the number of days per year with a daily minimum air temperature below TN < -20°C at the Almaty meteorological station from 1937 to 2024, as calculated using the ClimPACT software. In the last three years

(2020–2022), the number of days with temperatures below -20°C dropped to zero, which can be considered a clear indicator of global warming. Figure 7 displays the absolute minimum values of daily minimum temperatures recorded at the Almaty meteorological station from 1937 to 2024 using the ClimPACT software. The absolute minimum temperatures fluctuated between -35°C and -15°C, with recent years showing a trend where the absolute minimum has not dropped below -25°C. In January 2021, typically the coldest month of the year, significant negative anomalies were recorded in northern and northeastern Kazakhstan. The daily minimum temperature (TNn index) dropped to -35°C to -40°C, and in some locations, it fell below -43°C.

In the context of global climate change, forecasting future climatic conditions is crucial for adaptation and mitigation of its consequences. Various socioeconomic development scenarios, developed within the framework of the Shared Socioeconomic Pathways (SSP) programs, are used to assess potential climate changes. These scenarios include different greenhouse gas emission trajectories based on assumptions about demographic growth, economic development, technological progress, and environmental policy. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) plays a crucial role in understanding future climate change and its potential impacts. This report examines various scenarios that outline possible pathways for societal and economic development, as well as their effects on the climate. Shared Socioeconomic Pathways (SSP) scenarios serve as a fundamental tool for modeling and analyzing climate change. This scientific study considers four key scenarios: SSP1, SSP2, SSP3, and SSP5.

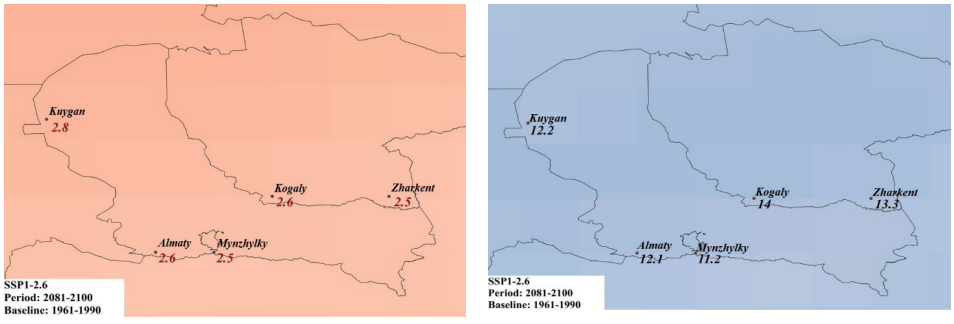

Figure 8. Changes in air temperature and precipitation under the SSP1-2.6 scenario

Figure 8 illustrates the SSP1-2.6 scenario, which aligns with sustainable development goals and presents an optimisticoutlook on temperature and precipitation changes. In this scenario, the maximum temperature increase is projected at the Kuigan station, reaching up to 2.8°C, while at the remaining stations, temperature changes are expected to range between 2.5°C and 2.6°C. A rising trend in precipitation is observed, with an expected increase of 11.2% to 14%.

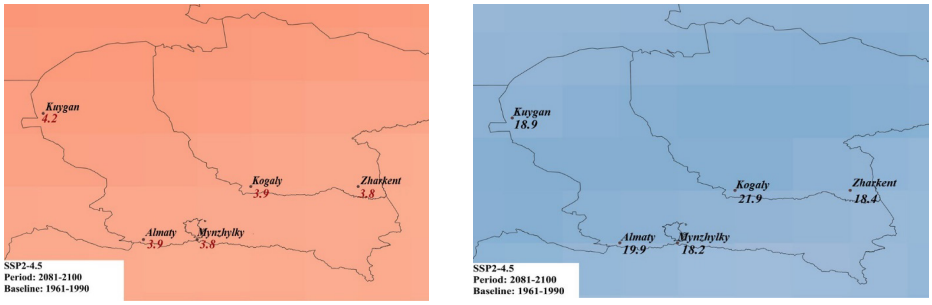

Figure 9. Changes in air temperature and precipitation under the SSP2-4.5 scenario

Figure 9 illustrates the SSP2-4.5 scenario, which assumes that socio-economic development will continue at a steady pace without significant disruptions. Under this scenario, air temperature is expected to increase by 3.8–4.2°C, while precipitation levels are projected to rise by 18.2–21.9%.

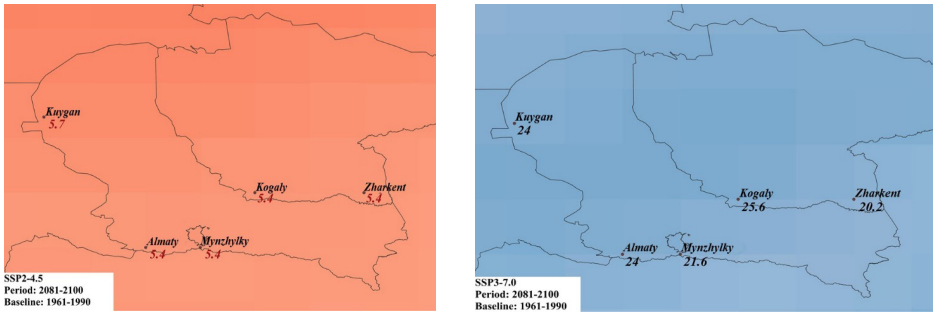

Figure 10. Changes in air temperature and precipitation under the SSP3-7.0 scenario

The SSP3 scenario is characterized by regional conflicts and high levels of competition, leading to a lack of global cooperation and scientific progress. According to this scenario, air temperature could rise to a maximum of 5.7°C at the Kuigan station, while the Kogaly station may experience the highest increase in precipitation, reaching 25.6%.

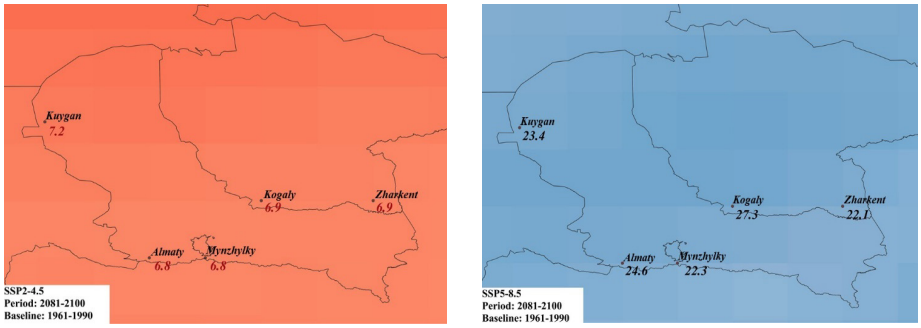

Figure 11. Changes in air temperature and precipitation under the SSP5-8.5 scenario

The SSP5 scenario represents a future of high economic growth driven by intensive fossil fuel consumption. Under this scenario, the maximum temperature increase is projected to reach 7.2°C at the Kuigan station, while at other stations, temperatures may fluctuate between 6.8°C and 7.2°C. A significant increase in precipitation is also expected, ranging from 22.1% to 27.3%.

Conclusions. Based on an analysis of temperature and precipitation data from the Kogaly, Kuigan, Zharkent, Mynzhylky, and Almaty meteorological stations in the Almaty region of Kazakhstan from 1937 to 2022, the following conclusions were drawn:

The ranked series of annual mean temperature anomalies from 1937 to 2024 shows that the ten warmest years on a global scale have all occurred within the last century, with this trend being particularly evident in Kazakhstan.

The warmest decades have been observed in the last 30 years, with temperature increases ranging from 0.8°C to 1.5°C, particularly noticeable at the Almaty station.

The Mann-Kendall test was used to assess the normality of temperature and precipitation trends. The results indicate that temperature trends exhibit significant changes during the warmer months, while precipitation trends have remained relatively stable.

Climate indices calculated using the ClimPACT software show that the number of days with a maximum temperature above 35°C (TXge35 index) has increased to 20 days, while the number of days with minimum temperatures below -20°C (TNltm20 index) has decreased.

The IPCC Sixth Assessment Report suggests that the future trajectory of climate change depends heavily on the chosen socio-economic development pathway. The SSP scenarios provide essential insights for decision-making and the development of climate mitigation and adaptation strategies. Depending on the selected economic scenario, temperature increases could range from 2.5°C to 7.2°C.and increase the effectiveness of measures to predict and reduce damage from possible earthquakes.

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