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ARTICLE

The Impact of Intensified Aridization Caused by Moisture Deficit on the Productivity of Grain Crops in Northern Kazakhstan

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ABSTRACT

The article examines the impact of increased aridization of the territory due to an increase in air temperature, reduced precipitation, and the formation of moisture deficiency on grain yields in Northern Kazakhstan. The most important result of the work is the revealed inverse relationship between grain yields and the temperature of the growing season: low-yielding years are associated with high temperatures and droughts, and high-yielding years are associated with lower temperatures and an optimal ratio of heat and moisture. The novelty of this study is the use of the method of hydrological and climatic calculations in identifying the nature of temperature variability and precipitation in the territory of Northern Kazakhstan for the modern period (1991–2020) compared with the base period (1961–1990). At all the studied meteorological stations, there is a tendency for the average annual temperature and the temperature of the growing season to increase: in the forest-steppe zone with an average warming intensity of 0.3–0.33 °C per decade; in the steppe zone by 0.2–0.43 °C per decade; and in the growing season by 0.2–0.7 °C per decade. The air temperature in the steppe zone is rising more intensively than in the forest-steppe zone, and precipitation in the forest-steppe zone has changed more than in the steppe zone. An increase in the average annual air temperature during the growing season (May–August), combined with a shortage of atmospheric moisture or a constant amount of it, led to an increase in the degree of aridization of the territory, an increase in the frequency of droughts in the steppe zone of Northern Kazakhstan.

Keywords: Aridization; Air Temperature; Precipitation; Moisture Deficiencies; Crop Yield; Northern Kazakhstan.

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1. Introduction

The intensification of aridization caused by a deficit of moisture is largely determined by the growth of temperatures during the modern period (1991–2020) compared to the basic period (1961–1990).

The climate aridity is the result of the interaction of natural processes that cause moisture deficit due to spatial and temporal variability of climatic characteristics and the need for moisture for the functioning of geosystems.

In temperate latitudes, aridity of territory is observed in natural zones with low precipitation levels and high evaporation rates. On such territories, the establishment of aridity over a long period of time becomes one of the factors of their aridification, leading to climate change.

Moisture deficits influence the productivity of agricultural crops, therefore, studies in this direction have been ongoing for many years by various scientists.

The impact of climate change has a particularly acute impact on human economic activity, on the development of agriculture, and on the state of the environment. Climate forms the fundamental basis for the formation, development, and existence of the natural environment and humanity. Therefore, today studying the climate and conducting systematic monitoring and observations of climate change in Northern Kazakhstan is one of the priorities of the scientific community in the region.

High air temperatures and a lack of atmospheric moisture lead to unfavorable agro-climatic conditions such as a shortage of soil moisture, a decrease in river runoff, drought, etc.

Moisture deficiency is defined as a complex natural phenomenon with the greatest temperature and humidity anomalies (precipitation, soil moisture content) on a regional scale; that is, it is a phenomenon that represents a decrease in environmental humidity compared to its average state over a short time interval.

In the current period, scholars A. A. Chibilyov, A. N. Zolotokrylin, M. E. Belgibaev, and G. Kirchengast have highlighted the role of climatic changes in the intensification of aridization [1–3].

In the works of scientists V. V. Paromov, V. A. Zemtsov, S. G. Kopysov, N.G. Ganeshi and G.V. Belonenko who studied the changes in the climate of Western Siberia, the stage of inertia of warming in 1986–2015 was determined, and a forecast of hydroclimatic resources was made until 2030 [4–7]. As a result of these scientists' research, it was revealed that, over the territory of Western Siberia, for the past 30 years, the average annual air temperatures, compared to the norm of the previous period for the same interval of time, have increased everywhere.

In the works of scientists K.A. Akshalov, S.S. Baisholanov, and others [8], it was revealed that in Northern Kazakhstan, during the growing season in the forest-steppe and steppe zones, the territory is "not arid," and in the dry-steppe zone, "slightly arid." In the forest-steppe and steppe zones, there are more optimally moisture-rich and non-arid years, and in the dry-steppe zone, more dry years with a lack of moisture have been identified. And also in the research of S.S. Baisholanov and D.K. Baybazarov, assumptions were made that in the northern part of Kazakhstan, in the context of climate warming until 2050, the agro-climatic conditions for grain crops will significantly deteriorate, and their yields will decrease by 37–49% [9].

Moisture deficiency is a condition in which available moisture levels (precipitation, groundwater) does not meet the needs of plants and ecosystems. The lack of moisture leads to a decrease in agricultural productivity, soil degradation, and vegetation changes. Studies by J.A.Tusupbekov et al. [10] show that the occurrence of moisture deficiency directly affects the intensification of climate aridization in the regions. Aridization is the process of increasing the dryness of the climate, which is characterized by an increase in the frequency and duration of dry periods, a decrease in precipitation, and an increase in evaporation. This process is of global importance and is especially relevant for steppe and semi-desert regions. The main aspects of the work of these scientists can be distinguished as follows:

– Changes in climatic parameters: Aridization is accompanied by an increase in temperature and a decrease in precipitation. This leads to a decrease in the water equivalent of the radiation balance and an increase in evaporation.

– Impact on the water balance: A decrease in precipitation and increased evaporation disrupt the natural water balance of territories. This leads to a decrease in the groundwater level and a reduction in the availability of moisture for plants.

– Environmental consequences: Aridization leads to structural changes of vegetation and soil cover. Many plant species cannot adapt to new conditions, which leads to their extinction and replacement with more drought-resistant species.

– Economic consequences: The lack of moisture has a negative impact on agriculture, reducing yields and worsening the quality of agricultural land. This requires the development of new methods of water resources management and the adaptation of agricultural technologies.

Understanding the relationship between moisture deficiency and aridization makes it possible to develop effective adaptation strategies to changing climatic conditions, the main directions of which are monitoring and forecasting climate change; developing and implementingsystems for the rational use of water resources; and usingsustainable agricultural technologies such as drip irrigation and drought-resistant crops.

It is necessary to understand the importance of an integrated approach to water resources management under aridization conditions, which minimizes the negative effects of moisture deficiency and ensures the sustainable development of regions.

This study employs the method of hydrological and climatic calculations proposed by V. S. Mezentsev [10], which involves calculating the coefficient of humidification and other hydrological and climatic characteristics based on standard meteorological data for various time intervals, taking into account corrections to precipitation readings and the redistribution of moisture over time– within the year and between years.

2. Materials and Methods

Meteorological data were obtained from operational weather stations located across northern Kazakhstan and adjacent territories the southern part of Western Siberia. The dataset spans a 31-year period from 1990 to 2020, inclusive. Variables included daily measurements of temperature (°C) and precipitation (mm). All station coordinates and elevation data were recorded to ensure spatial consistency in analysis.

Raw data underwent rigorous quality control: missing values were flagged and imputed using a nearest-neighbor temporal interpolation. Variables were aggregated to monthly and annual averages to align with analysis requirements.

Three main statistical approaches were applied. Simple Linear Regression: Explored long-term trends by regressing each variable's monthly means against time (in years). Evaluated slope significance using t-tests on regression coefficients. Analysis of Variance (ANOVA): Investigated differences in seasonal and interannual variations by fitting one-way ANOVA models (e.g., comparing seasonal temperature means). Employed F-tests to assess significance at $\alpha = 0.05$. Regression Equation Significance Testing: Tested the overall quality of regression fits using the mean approximation error (MAE). A regression model was deemed valid if MAE fell below a predefined threshold (calculated based on historical variability). Multivariate Correlation and Regression Analysis: Implemented multiple linear regression incorporating several predictors (e.g., precipitation, air temperature) to explain variability in a response variable (e.g., yields). Conducted Pearson correlation analysis to pre-select variables showing $|r| > 0.3$ at $p < 0.05$. Validated regression models by examining variance inflation factors (VIF < 5) to avoid multicollinearity. Data preprocessing and analysis scripts are thoroughly annotated and include parameter settings (e.g., interpolation windows, α levels).

The method of hydrological and climatic calculations (HCC) proposed by V.S. Mezentsev in 1957 in Omsk was applied in this study. Hydrological and climatic methods represent one of the most physically sound approaches to assessing the heat and moisture availability of territories. According to the method of hydrological and climatic calculations by V.S. Mezentsev, in the case of an inequality of atmospheric humidification to the optimal value obtained using the water equivalent of heat and energy evaporation resources, their difference expresses the amount of moisture deficits (or surpluses) [10].

To determine the water equivalent of thermal energy resources ***Zm***, formulas (1,2,3,4) proposed by

I.V. Karnatsevich [11] were used, according to which the evaporation rate is calculated depending on the sum of the average monthly positive air temperatures.

$$\mathrm{Zm} = \frac{\mathrm{TZ}}{\mathrm{L}} \quad (1)$$

$$\mathrm{TZ} = 17.6 \times \sum \mathrm{t} + 400 \quad (2)$$

where ***Zm*** is the maximum possible evaporation (the water equivalent of the heat and energy resources of evaporation), mm;

TZ – thermal energy resources of total evaporation in MJ/(m^2 year);

L – 2,512 MJ/(m^2·mm) – specific heat of vaporization;

$\sum t$ – is the sum of the positive average monthly temperatures of the growing season.

The calculations of the total evaporation values were performed by the method of hydrological and climatic calculations (HCC) proposed by V.S. Mezentsev [10,11]. The system of equations of the HCC method is the most general and universal from the point of view of use for the required calculation period and mathematical model of moisture transformation processes at the level of the active surface of the catchments of any territory.

The indicator of the moisture deficit of the territory Δ***KX*** is calculated as the difference between the values of atmospheric precipitation ***KX*** and the water equivalent of heat and energy resources ***Zm***.

KX is atmospheric precipitation, corrected by the correction factor for the underestimation of the precipitation measuring device in mm:

$$\triangle \mathrm{KX} = \mathrm{KX} - \mathrm{Z_m} \quad (3)$$

The structure of the relationship between heat resources and moisture resources determines the level of humidification (natural or anthropogenic); therefore, the indicator of humidification of the territory for any intra-annual period of the average year is the ratio:

$$\beta \mathrm{kx} = \frac{\mathrm{KX}}{\mathrm{Zm}} \quad (4)$$

The boundary of the optimal ratio of heat and moisture is spatially expressed by the isoline of a single value of the coefficient of moisture, zero deficiency of moisture, and soil moisture (in fractions of the lowest moisture capacity) equal to unity. This boundary is the upper limit of optimal moisture for most crops [10,11].

External users can obtain raw meteorological data from the national meteorological services of Kazakhstan and Russia or via the repository and can rerun all analyses [12–14]. The methodology provides a robust framework for assessing climatological trends and their drivers.

3. Results

Air temperature and precipitation in the modern period have increased compared to the basic, but the intensity of temperature growth is greater, leading to aridization, that is, to a growing moisture deficit and a decreasing moisture coefficient. **Figure 1** presents air temperature indicators averaged over 30 years for the basic and modern periods.

Compared to the basic period, in the modern period there is a trend of increasing temperature of the vegetation period by 0.2–0.7°C at all studied meteorological stations.

For agriculture, the climatic conditions during the vegetation period are significant. The months from May to August were considered as the vegetation period [15,16].

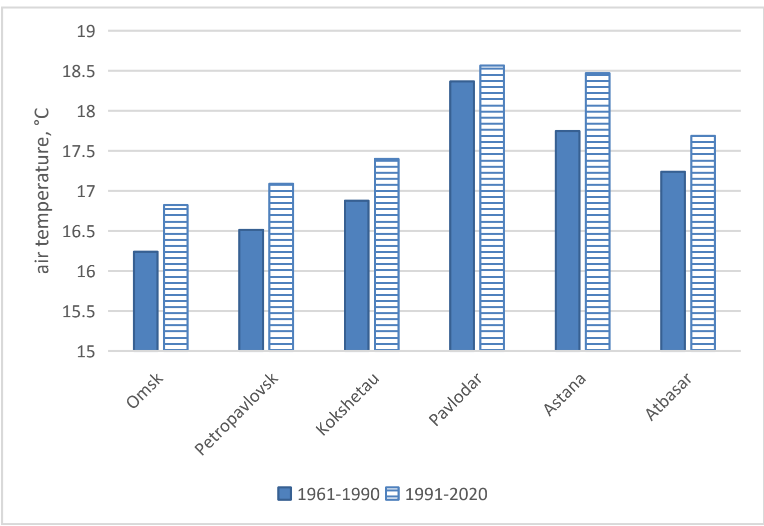

Figure 1. Air temperature of the vegetation period (may-august) for the basic (1961–1990) and modern periods (1991–2020) with averaged data for 30 years.

To facilitate comparative analysis, the entire study period of 60 years was divided into two periods of 30 years: the basic period — from 1961 to 1990, and the modern period — from 1991 to 2020.

The duration of the calculation period was chosen in accordance with the requirements of climatic studies, where to determine average long-term norms, data of a minimum of 30 years (3 solar cycles of 11 years) are necessary.

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Figure 2 presents the amounts of annual precipitation for the base and modern periods. In the modern period, there is a slight increase in precipitation of 1–2 mm at the studied meteorological stations, except for Kokshetau, where precipitation levels remained unchanged.

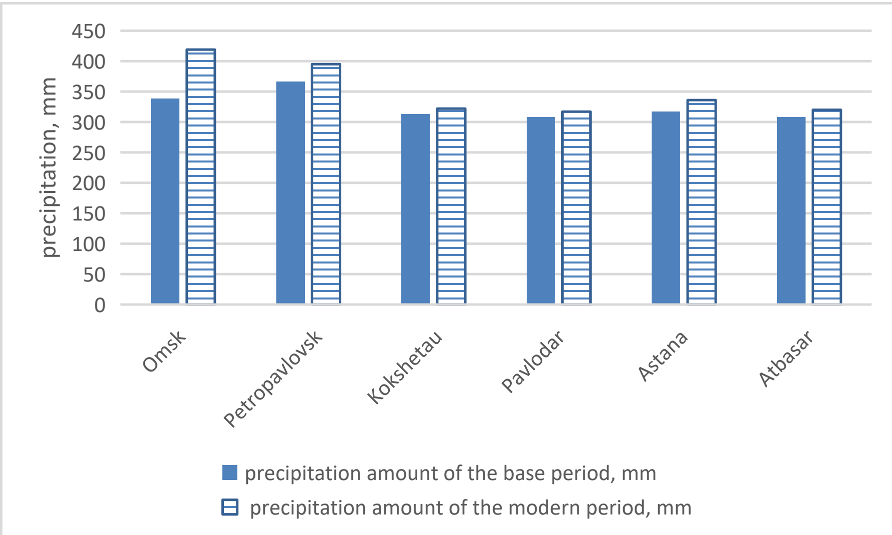

Figure 2. Annual precipitation sums for the basic (1961–1990) and modern periods (1991–2020) with averaged data for 30 years.

In this work, moisture deficits for the territory of Northern Kazakhstan and adjacent territories of Western Siberia over 60 years, during the vegetation period, have been calculated. **Table 1** provides a comparative characteristic of average air temperature and moisture deficit for the basic and modern periods. Moisture deficit is the difference between atmospheric precipitation and the water equivalent of heat and energy resources (ΔKX=KX−Zm). It has been revealed that moisture deficit values increase depending on the growth of air temperature during the vegetation period [17,18]. The correlation coefficient for this dependence was 0.97.

Table 1. Dependence of moisture deficit on air temperature during the vegetation period (may–august) for the basic (1961–1990) and modern periods (1991–2020) (averaged data for 30 years).

Weather Stations	Air Temperature,°C		ΔKX, mm		Weather Stations	Air Temperature,°C		ΔKX, mm	
	1961–1990	1991–2020	1961–1990	1991–2020		1961–1990	1991–2020	1961–1990	1991–2020
Ishim	15.5	16.2	−300	−325	Shchuchinsk	15.8	16.3	−315	−356
Makushino	16.3	16.9	−334	−391	Ruzaevka	17.2	17.6	−413	−426
Isilkul	16.3	16.8	−351	−387	Pavlodar	18.4	18.6	−466	−476
Blagoveshchenka	16.8	17.2	−381	−403	Yesil	18.1	18.4	−476	−485
Poltavka	17.0	17.4	−384	−411	Atbasar	17.2	17.7	−436	−454
Irtyshsk	17.7	18.3	−440	−466	Ereymentau	17.0	17.2	−392	−421

Correlation coefficient R = 0.97.

Table 2 presents statistical characteristics of the sum of precipitation during the vegetation period at meteorological stations of Northern Kazakhstan and adjacent territories of Western Siberia for two periods. Precipitation is unevenly distributed in different years.

Table 2. Statistical characteristics of the sum of precipitation during the vegetation period (May–August) at meteorological stations of Northern Kazakhstan and adjacent territories of Western Siberia for the basic (1961–1990) and modern periods (1991–2020), in mm.

Weather Stations	Average for the Period	Minimum	Maximum	Standard Deviation	Coefficient of Variation
			1961-1990		
Omsk	203	80	320	53	0.26
Petropavlovsk	184	100	283	50	0.27
Kokshetau	181	84	384	64	0.35
Pavlodar	149	103	276	39	0.26
Astana	157	79	295	57	0.36
Atbasar	140	48	255	45	0.32
			1991-2020		
Omsk	207	112	402	71	0.34
Petropavlovsk	193	99	335	56	0.29
Kokshetau	180	80	313	64	0.35
Pavlodar	157	74	261	51	0.33
Astana	161	68	254	47	0.29
Atbasar	148	39	282	58	0.39

In the contemporary period, compared to the baseline, observed trends in air temperature are characterized as follows:

1. A trend of increasing mean annual temperature and temperature during the vegetative season is noted across all examined meteorological stations.

- The increase in air temperature is more pronounced in the steppe zone than in the foreststeppe zone, while precipitation changes are more significant in the forest-steppe zone than in the steppe zone.
- In the forest-steppe zone, the mean warming rate is 0.30–0.33 °C per decade; in the steppe zone, it ranges from 0.20 to 0.43 °C per decade.
- During the vegetative season, temperature increases range from 0.2 to 0.7 °C.

2. A slight increase in annual precipitation totals is observed at all meteorological stations under study, primarily due to elevated precipitation during the cold season.

- In the forest-steppe zone: an average rise of approximately 10 mm per decade; in the steppe zone: 3–8 mm per decade.
- During the growing season, precipitation has increased by 1–2 mm across most sites, except in Kokshetau, where no significant change is noted—likely attributable to the barrier effect of the terrain.
- A reduction in precipitation has been identified in late summer and early autumn.

3. The increase in moisture deficit values is primarily driven by rising air temperature.

- In the regions of the Omsk and Petropavlovsk meteorological stations, the mean annual temperature has increased with an average warming rate of 0.3–0.33 °C per decade. Precipitation has increased by approximately 10 mm per decade, mainly during the winter and spring–summer seasons; however, reduced precipitation is observed at the beginning of autumn.
- In the regions of the Kokshetau and Astana stations, the mean annual temperature shows an increase at a rate of 0.4–0.43 °C per decade.
- In the areas of the Pavlodar and Atbasar stations, the mean annual temperature is rising at a rate of 0.2–0.23 °C per decade.
- In the Pavlodar and Astana areas, precipitation has increased by an average of 6–8 mm per decade, predominantly in the winter–spring period and the first half of summer, while a decline is noted in late summer and autumn.
- In the regions of the Kokshetau and Atbasar stations, a slight increase in precipitation of about 3–4 mm per decade is recorded, mainly in the spring–summer season, while a reduction in precipitation is observed in autumn.

The regression model of multifactorial correlation-regression analysis of yield (biological productivity) showed that the decrease in the ratio of thermal to water elements and the increase in moisture deficit in the modern period compared to the basic period lead to a decrease in yield of the studied territory from 2 to 7%. At the same time, fewer changes are observed in the northern part than in the southern and eastern parts of the studied territory.

Numerous agroclimatological projections emphasize both the beneficial and adverse impacts of climatic variability– particularly warming– on crop productivity. Over recent decades, rising temperatures have exerted a marked influence on cereal cultivation and grain yields throughout the steppe zone [19–22]. The most extensive grain-sown areas are located four northern regions of Kazakhstan. In **Table 3**, regression statistics are presented to evaluate yield U (c/ha) in relation to meteorological elements: air temperature and precipitation during the growing period.

Table 3. Regression statistics for assessing yield U (c/ha) in relation to meteorological elements.

Weather Stations	R	R^2	Normalized R-squared	Standard Error	The Regression Equation
Ruzaevka (North Kazakhstan region)	0.51	0.26	0.17	2.52	U = 30.52 − 1.08Tveg + 0.01Xveg
Kostanay (Kostanay region)	0.66	0.43	0.37	2.24	U = 45.58 − 1.82Tveg − 0.005Xveg
Yesil (Akmola region)	0.80	0.64	0.60	1.50	U = 27.11 − 1.09Tveg + 0.02Xveg
Irtysh (Pavlodar region)	0.71	0.51	0.46	2.08	U = 33.94 − 1.60Tveg + 0.02Xveg

The regression equations identified through calculation can be used to determine yield for retrospective analysis in the absence of actual data.

The strength of the combined effect of meteorological factors on yield (multiple correlation coefficient R) is greatest in the Akmola region (Yesil, R = 0.80). The obtained dependencies explain between 26% and 64% of the variance (variability) of yield under the influence of the considered indicators.

The outcomes of the regression analysis were evaluated by means of Fisher's F-test (**Tables 4** and **5**). Because the computed F-value (15.7) exceeds the critical value (4.41), the regression model can be deemed statistically significant, indicating that its parameter estimates are reliable.

Table 4. Analysis of Variance.

	df is the Number of Degrees of Freedom	SS is the Sum of Squares	MS is the Average Value	F is the Fisher Criterion
Regression	2	71.070	35.535	15.716
Remains	18	40.699	2.261	
Total	20	111.769		

Table 5. Results of Regression Statistics.

	Coefficients	Standard Error	T-statistics	*P*-Value
Y-intersection	27.11	7.68	3.53	0.002
Variable X 1	−1.09	0.39	-2.82	0.011
Variable X 2	0.02	0.01	3.01	0.007

The standard error quantifies the extent to which a given test statistic is expected to fluctuate across repeated samples. It is obtained from the standard deviation of that statistic's sampling distribution. Put simply, the standard deviation itself measures the degree of dispersion or spread within a dataset.

The statistical significance of the model parameters (regression coefficients) was evaluated using Student's t-test. We tested the null hypothesis H_0 that each parameter equals zero ($a = b_i = 0$), obtaining t-values of $t_a = 3.5$, $t\_b_1 = –2.8$, and $t\_b_2 = 3.01$. At the 5% significance level with 18 degrees of freedom (n – k), the critical t-value is 2.1. Because all calculated t-statistics exceed this threshold (3.5 > 2.1; 2.8 > 2.1; 3.01 > 2.1), we reject H_0 and conclude that the coefficients are statistically significant.

The accuracy of the regression model is assessed using the mean error of approximation (**Table 6**).

Table 6. Results of checking the significance of the regression equation using the mean error of approximation.

Years	Actual Yield, U(y)	Estimated Yield, y(x)	Discrepancy, y-y(x)	(y-y(x))/y*100
1999	13.3	11.9	1.4	10.5
2000	7.9	10.9	−3	−38.6
2001	11.2	11.4	−0.2	−1.6
2002	9.1	11.02	−1.9	−21.1
2003	9.1	11.4	−2.3	−25
2004	7.1	7.8	−0.7	−9.2
2005	8.5	10	−1.5	−17.9
2006	9.6	10.2	−0.6	−5.8
2007	11.6	10.5	1.1	9.5
2008	7.5	7.9	−0.5	−6
2009	11.2	10	1.2	10.4
2010	5.2	6.5	−1.3	−25.1
2011	15.6	14.4	1.2	7.7
2012	7	6.8	0.2	3.4
2013	10.4	10.7	−0.3	−3.2
2014	11	8.9	2.1	19.2
2015	10.8	9.4	1.4	13
2016	11.6	12	−0.4	−3.8
2017	11.2	9.1	2.1	18.3
2018	11.7	11.3	0.4	3.1
2019	9.5	10.3	−0.8	−8.4

Note: $A=\frac{1}{n}*\sum\left(\frac{y-y(x)}{y}\right)*100\% = \frac{-70.64}{21} = 3.4\%$.

Since the permissible limit for the mean approximation error does not exceed 8–10%, the regression model we employed—exhibiting a 3.4% error—demonstrates a high degree of accuracy.

4. Discussion

Grain yield (spring wheat) is strongly influenced by site moisture. To assess this effect, we examined the moisture coefficient (β_{kx}), defined following V.S. Mezentsev as the ratio of heat resources (Zm) to moisture resources (KX) for any intra-annual period (5) [10]:

$$\beta_{KX} = \frac{KX}{Z_m} \quad (5)$$

Using multifactorial correlation-regression analysis (**Tables 7, 8** and **9**), we quantified the impacts of β_{kx} and the moisture deficit (ΔK_x) on yield. The multiple correlation coefficient (R = 0.77) indicates a strong relationship between yield and these two explanatory variables. The overall regression equation's significance was confirmed via Fisher's F-test: since the computed F-value (12.8) exceeds the critical value (4.41), the model is statistically reliable. The multiple correlation coefficient (R = 0.77) indicates a strong relationship between yield and these two explanatory variables. A high correlation coefficient (for example, R = 0.77) indicates that the whole model explains the dependent variable well. It may be that the model as a whole is significant, but individual variables are not. The reason for this is multicollinearity. The two independent variables are strongly correlated with each other. The Variance Inflation Factor (VIF), which measures the degree of multicollinearity, increases when variables are highly interrelated; VIF > 5 or >10 indicates multicollinearity. If a variable is strongly correlated with another, then the VIF becomes large. In this model, the variables are strongly correlated with each other, i.e. Multiple R-squared- $R^2 = 0.91$. It was calculated:

$$VIF = \frac{1}{(1-0.91)} = \frac{1}{(0.09)} = 11$$

In our case, VIF >10 indicates multicollinearity. As a result, the variable becomes insignificant, even if in reality it is important.

Finally, yield projections for grain crops in the Akmola region—derived from these regression equations over the period 1999–2019—were compared against observed values. The correlation between predicted and actual yields (R = 0.77) is statistically significant.

Table 7. Regression statistics for estimating the yield U (c/ha) depending on the parameters of heat and moisture supply.

Weather Stations	R	R^2	Normalized R-squared	Standard Error	The Regression Equation
Yesil (Akmola region)	0.77	0.59	0.54	1.60	$U = 27.76 - 6.48\beta_x + 0.03_{\Delta}KX$

Table 8. Analysis of Variance.

	df is the Number of Degrees of Freedom	SS is the Sum of Squares	MS is the Average Value	F is the Fisher Criterion
Regression	2	65.699	32.85	12.834
Remains	18	46.070	2.559	
Total	20	111.769		

Table 9. Statistical Analysis.

	Coefficients	Standard Error	T-statistics	*P*-Value
Y-intersection	27.76	11.69	2.38	0.03
Variable X 1	−6.48	13.48	−0.48	0.64
Variable X 2	0.03	0.02	1.91	0.07

The analysis of the obtained regression equations for Northern Kazakhstan showed the greatest contribution to the variance of the yield of the average summer air temperature [23–25].

From the graph in **Figure 3** and the regression equations, it is clear that there is a fairly close inverse relationship with a correlation coefficient of R = −0.84 between unproductive years with high temperatures in the growing season and droughts and productive years with lower temperatures and, consequently, a more optimal balance of heat and moisture.

Based on regression equations of the dependence of grain crop yield on heat and moisture supply parameters, average yield indicators for two periods were calculated (**Table 10**), and changes over 30 years expressed in percentage terms were determined.

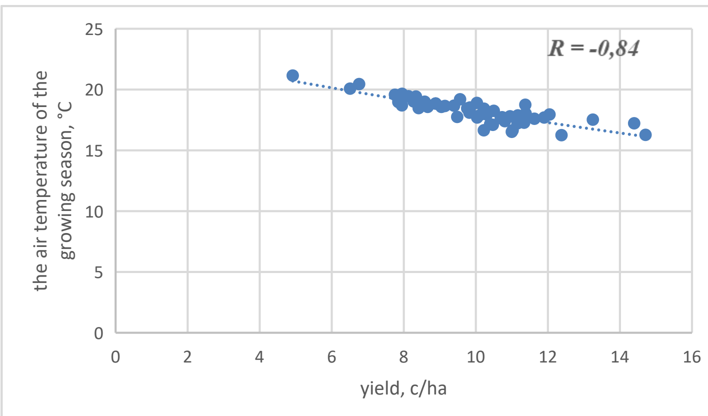

Figure 3. The dependence of yield on the average air temperature of the growing season.

According to the results of calculations, a decrease in the moisture coefficient and an increase in moisture deficit in the current period lead to a reduction of the average long-term yield (i.e., the norm) for the studied territory by 2 to 7%. If the norm changes by 2–7%, this is already a trend that needs to be noted.

At the same time, in the northern part, fewer changes are observed than in the southern and eastern parts of the studied territory. For example, in the area of the Irtyshsk weather station in the Pavlodar region, grain crop yield over the past 30 years decreased by 7%, while in the Akmola region, in the area of the Ruzaevka weather station, it decreased by 2%.

The yield of grain crops in Northern Kazakhstan is influenced by the moisture indicator and its deficit by 15 to 59%.

Table 10. Regression statistics of the dependence of grain crop yield in Northern Kazakhstan on thermal and water elements and moisture deficit.

Weather Stations	R	R^2	Normalized R-squared	Standard Error	The Regression Equation	Yield, c/ha		
						1961–1990	1991–2020	Changes Over 30 years, %
Irtyshak	0.59	0.34	0.28	2.35	U = 16.21 + 3.81βx + 0.02ΔKX	8.5	7.9	−7
Ruzaevka	0.39	0.15	0.06	2.62	U = 23.25-4.59βx + 0.02ΔKX	13.6	13.3	−2
Pavlodar	0.56	0.31	0.24	2.40	U = 25.37 − 8.41βx + 0.03ΔKX	9.3	8.9	−4
Yesil	0.77	0.59	0.54	1.60	U = 27.76 − 6.48β_x + 0.03ΔKX	12.0	11.7	−2.5

As a result of calculations performed using the method of hydro-climatic calculations, complex indicators of thermal and water balances of the studied territory were determined and presented in **Table 11**.

These indicators were calculated for the vegetation period using sums of air temperatures above 0°C and sums of precipitation.

According to their averaged values, compared to the basic period, in the current period there is:

- an increase in the indicators of heat and energy resources of evaporation and an increase in moisture shortages – at all weather stations;
- reduction of the humidification coefficient – at most weather stations, with the exception of Ruzaevka, Pavlodar, Yesil and Atbasar.
- reduction of precipitation at 5 weather stations: Makushino, Isilkula, Poltava, Shchuchinsk, Yerementau.
- increased precipitation at 6 weather stations: Ishim, Irtysh, Ruzaevka, Pavlodar, Yesila, Atbasar;
- constant precipitation – at the Blagoveshchenka weather station.

An increase in the heat and energy resources of evaporation combined with a decrease or unchanged precipitation leads to a shortage of humidification of the territory.

Table 11. Elements of thermal and water balances, averaged according to the data of the period 1961-2020 for the growing season (May-August).

Weather Stations	KX, мм		Zm, мм		ΔKX, мм		βx (fractions of units)	
	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020
Ishim	227	235	527	559	−300	−325	0.44	0.42
Makushino	221	192	555	583	−334	−391	0.41	0.33
Isilkul	203	193	554	580	−351	−387	0.37	0.34
Blagoveshchenka	189	189	570	591	−381	−403	0.34	0.32
Poltavka	195	187	576	598	−384	−411	0.34	0.32
Irtyshsk	157	162	596	628	−440	−466	0.27	0.26
Shchuchinsk	222	207	538	563	−315	−356	0.42	0.37
Ruzaevka	168	179	581	605	−413	−426	0.29	0.30
Pavlodar	156	164	622	641	−466	−476	0.25	0.26
Yesil	137	151	613	636	−476	−485	0.23	0.24
Atbasar	146	154	582	608	−436	−454	0.25	0.26
Ereymentau	190	183	581	604	−392	−421	0.33	0.31

5. Conclusions

As a result of the conducted research, the following was established:

1. The spatial and temporal variability of the temperature regime over the modern period (1991–2020) compared with the base period (1961–1990) is characterized by an increase in the average annual temperature and the temperature of the growing season at all the studied meteorological stations. At weather stations in the forest-steppe zone, this increase was 0.3–0.33°C per decade, and in the steppe zone, it was 0.2–0.43°C per decade. There is a

slight increase in annual precipitation, mainly due to colder months, as well as a decrease in late summer and the first half of autumn.

2. Over the past 30 years (1991–2020), five out of ten surveyed weather stations have seen reduced precipitation during the growing season and an increase in the humidification deficit of the territory, while the remaining weather stations have seen a slight increase or unchanged precipitation. The invariance of precipitation with an increase in air temperature can lead to aridization of the territory. The structure of long-term fluctuations of atmospheric precipitation in the studied area is heterogeneous. In the modern period, the boundaries of arid zones in the study area have shifted to the northward.

3. A decrease in the ratio of thermal and water elements and an increase in moisture deficiency in the modern period compared to the base period lead to a decrease in yields. At the same time, there are fewer changes in the northern part than in the southern and eastern parts of the study area. The yield of grain crops in Northern Kazakhstan is 15-59%, dependent on the moisture content and its deficiency.

4. Increased aridization is more influenced by an increase in the frequency of droughts during the growing season. Territorial aridization leads to a decrease in yields.

5. The analysis of climatic data for the period from 1961 to 2020 makes it possible to identify changes in the occurrence of meteorological phenomena in the studied area. Changes in temperature and humidity can have severely negative consequences for agriculture, which is one of the most weather-dependent sectors of the economy.

6. Forecasting of climatic features, anomalies, extreme events, and subsequent adaptation to them is a priority task for the steppe zone in the conditions of Northern Kazakhstan. The study of the nature of changes in humidification and the territorial spread of droughts and desertification in Northern Kazakhstan in the modern period of increasing global warming under the influence of anthropogenic factors can be noted as a prospective direction for further research. For a more detailed study of the influence of atmospheric humidity, which is the main limiting factor in the cultivation of grain crops in forest-steppe and steppe zones, it is necessary to continue work on expanding the meteorological database to improve the quality of regression models.

Author Contributions

Conceptualization, A.A.K. and G.M.Z.; methodology, A.A.K.; software, G.M.Z.; validation, A.A.K., G.N.C. and G.M.Z.; formal analysis, G.M.Z.; investigation, A.A.K.; resources, G.N.C.; data curation, G.M.Z.; writing—original draft preparation, A.A.K.; writing—review and editing, A.A.K.; visualization, G.N.C.; supervision, G.M.Z.; project administration, A.A.K.; funding acquisition, G.M.Z.. All authors have read and agreed to the published version of the manuscript.

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The relevant data supporting the obtained results can be found here: http://meteo.ru/data/; https://meteo.kazhydromet.kz/database_meteo/; https://meteoinfo.ru/climatcities

Conflict of Interest

The authors declare no conflict of interest.

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