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An Assessment of the Present Trends in Temperature and Precipitation Extremes in Kazakhstan

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Abstract: The article presents the results of a study on the assessment of modern space–time trends of extreme values of air temperature and precipitation in 42 meteorological stations throughout Kazakhstan for the period from 1971 to 2020. Spatial and temporal analysis of the distribution of specialized climatic indices was recommended by the WMO climatology commission and an assessment of their trends was carried out. Spatial heterogeneity was revealed in terms of the degree of manifestation of changes and trends. Temperature indices are shown to confirm the overall warming trend. The division of the territory of Kazakhstan by the degree of manifestation of climate change into the southwestern and northeastern half was revealed. Extreme trends are most pronounced in the southwestern half, where a significant trend has been identified both for an increase in extremely high daytime and extremely low night temperatures. The calculated trends in temperature indices are generally significant, but the significance is mainly not ubiquitous; the trends are significant only in certain parts of Kazakhstan. WSDI and CSDI trends were found to confirm a widespread increase in the overall duration of heat waves and a reduction in the overall duration of cold waves. No significant extreme effects were found in the sediments. It is confirmed that Kazakhstan has weak, statistically insignificant, positive and negative trends in the maximum duration of the non-traveling period. Precipitation index trends, unlike temperature ones, are statistically insignificant in most of the country.

Keywords: temperature extremes; precipitation extremes; spatial distribution; temporal trends; climate change; Kazakhstan

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Citation: Salnikov, V.; Talanov, Y.; Polyakova, S.; Assylbekova, A.; Kauazov, A.; Bultekov, N.; Musralinova, G.; Kissebayev, D.; Beldeubayev, Y. An Assessment of the Present Trends in Temperature and Precipitation Extremes in Kazakhstan. *Climate* **2023**, *11*, 33. https://doi.org/10.3390/cli11020033

Academic Editor: Nir Y. Krakauer

Received: 9 December 2022
Revised: 9 January 2023
Accepted: 14 January 2023
Published: 23 January 2023

1. Introduction

According to the WMO [1], the last decade of the 21st century was the warmest decade on record. So, for example, 2016, 2019, and 2020 are among the three warmest years. The average global temperature in 2020 was approximately 14.9 °C, 1.2 (±0.1) °C above pre-industrial (1850–1900) levels [1,2] Although the study and understanding of the main patterns of global and regional climate change are very important, the most significant applied significance is their consequences in the form of extreme meteorological events, such as heat and cold waves, heavy rains and snowfalls, hail, storms, squalls, etc. This can cause or exacerbate other dangerous events, such as droughts, floods, landslides, wildfires, and avalanches. These processes increase the risks of adverse impacts on different areas of human life and the country's economy [3]. The most vulnerable areas include agriculture, water resources, biodiversity, social infrastructure, etc. [4–6].

According to modern research [7], over the past 50 years, there have been more than 11,000 natural disasters caused by climate change, which have killed more than 500,000 people and led to huge destruction, and economic damage amounted to about USD 3.6 trillion. Extreme weather events accounted for 56% of deaths and 75% of economic losses [8].

As climate change continues to threaten human lives, ecosystems, and economies, risk information and early warning systems are increasingly seen as key factors in reducing these impacts.

The issue of mitigation measures for extreme weather events is recognized as one of the priorities, and research on climate extremes is one of the key areas of activity of the World Meteorological Organization [8].

Kazakhstan occupies a vast area in the center of the Eurasian mainland with various climatic zones, from very hot and dry desert zones in the south to very cold steppe and forest zones in the north, which contributes to an increase in the frequency and intensity of dangerous hydrometeorological phenomena [9].

The above data show that in Kazakhstan, climate change and warming are clearly expressed, and given this, it is of considerable practical interest to study the increase in the repeatability of weather anomalies.

Currently, a lot of studies have been published that analyzed various aspects of the impact of climate change on various sectors in Kazakhstan, in particular on water resources, mudflows, glaciers, snow cover, dust storms, and the agricultural sector, which show that the recurrence of these phenomena has increased over the past decade [10–23]. Such publication activity indicates that the study of extreme natural events is a rather urgent task for Kazakhstan, the solution of which is a key factor in the process of creating an early warning system, adapting, and the reduction in vulnerability.

However, despite a significant number of works on the impact of extreme weather manifestations on the economy, ecology, and other spheres of the country's life, there are practically no studies on a detailed analysis of the spatial and temporal features of extreme meteorological events in Kazakhstan.

The purpose of this study is to assess climate change throughout Kazakhstan, in terms of its extreme manifestations, based on the study of modern space–time trends in extreme values of air temperature and precipitation.

The results are presented as follows. Section 1 describes the dataset and methodology, Section 2 analyzes the spatial and temporal characteristics of extreme temperatures, Section 3 discusses the main results and conclusions of this study, and Section 4 provides the main conclusions.

2. Data and Methods

2.1. Data

As initial data, the average daily values of air temperature and daily sums of atmospheric precipitation, as well as their extremes at 270 meteorological stations throughout Kazakhstan, provided by the National Hydrometeorological Service "Kazhydromet", were used. The time range of data for the analysis was a half-century period from 1971 to 2020. In order to obtain correct and reliable results, all initial data were critically analyzed for row length and absence of omissions. Initially, data from those stations where missing values did not exceed 5% of the length of the main sample were selected. In the selected data, the omissions were restored by long-term (for the period 1981–2010) average daily values for a specific day. In the selected data, the omissions were restored by long-term (for the period 1981–2010) average daily values for a specific day. In order to assess the impact of climate change, it is necessary to identify a statistically significant trend in the shift of meteorological indicators prior to statistical analysis, by identifying differences between them to obtain statistically reliable conclusions. Further, the initial series were tested for homogeneity using Student's and Fisher's criteria and meeting all the necessary confidence criteria.

As a result, 42 weather stations were selected from 270 meteorological stations fully meeting the criteria (Figure 1).

Figure 1. The administrative division and the distribution of 42 meteorological stations in Kazakhstan.

The analysis shows that the stations as a whole are relatively evenly distributed over the territory in question. Only in the southern and central parts of the Aktobe region are they relatively rare.

As part of the study of the spatial distribution of extremity indices, the territory of Kazakhstan is conditionally divided into 5 large zones (Table 1).

Table 1. Main zones of territorial division of Kazakhstan.

Zones	Region
Northern Kazakhstan (I)	North Kazakhstan, Pavlodar, Kostanay, Akmola
Western Kazakhstan (II)	Mangystau, Aktobe, Atyrau, western Kazakhstan
Central Kazakhstan (III)	Karaganda
East Kazakhstan (IV)	East Kazakhstan, Almaty
South Kazakhstan (V)	Kyzylorda, the south Kazakhstan region, Zhambyl, Turkestan

This zoning was carried out considering the physical and geographical features of the regions, and circulation conditions for the formation of extreme meteorological phenomena and can be used for their early warning in the future

2.2. Methods

To monitor extreme values of climatic parameters, the most significant for specific sectors of the economy and social sphere, a set of specialized climatic indices recommended by the WMO climatology commission [24] was used. To calculate them, the software product ClimPACT2 (https://climpact-sci.org/assets/climpact2-user-guide.pdf; accessed on 27 September 2022) was used, which allows for analyzing extreme climate events using weather or climate data, including an assessment of change and intensity. The used indices make it possible to conduct a comprehensive analysis of the air and precipitation temperature regime, and to identify and analyze the features of their extremes. The use of this approach makes it possible to compare the results of the analysis of precipitation extremes and temperatures at the global and regional levels [25–30].

Trends in the air temperature and precipitation regime over the multi-year period were estimated by linear trends, the significance of which was determined through the determination coefficient.

Linear trends in temperature index time series were calculated using the standard least squares method, and statistical significance was evaluated using the Mann–Kendall non-parametric test [23,31] modified by effective sample size [32] at a significance level of 0.05.

Contour maps require a regular pattern of node points. In the Gridding study, the values of the interpolation function at regular network points were calculated from the values of station observation data. As a result, a regular array of values of Z-coordinates of nodal points was formed along an irregular array (X, Y, Z) -coordinate of the original points. For these purposes, the geostatistical method of building a network (Kriging method) was used.

In 2015, the World Meteorological Congress decided to "standardize meteorological, hydrological, climatic, space meteorological and other information related to hazardous phenomena and environmental risks and develop identifiers to catalog meteorological, hydrological and climatic extreme events" [33].

There are five criteria used as indicators:

- Compliance: Each key indicator must be a clear and understandable indicator of global climate change and meet the broad needs of different users.
- Representativeness: Collectively, indicators should provide a representative picture of climate change-related changes in the Earth's system.
- Consistency: Each indicator must be calculated using an internationally agreed method.
- Timeliness: Each indicator must be calculated regularly.
- The adequacy of the data available for the indicator must be reasonably sound, reliable, and valid.

All climate indices were used to assess whether extremities were conditionally divided into four categories (Table 2) [10,34,35]:

- Indexes based on thresholds.
- Indices based on absolute values.
- Percentile-based indices.
- Indices based on event duration.

Table 2. Temperature and precipitation indexes with their definitions and units used in this study.

ID	Index Name	Definitions	Units	Number of Stations	Sectors of Economics
		Indexes based on thresholds			
FD	Number of frost days	Annual count of days when *TN* (daily minimum temperature) < 0 °C.	days	42	Health, agriculture and food security, and disaster risk reduction
SU	Number of summer days	Annual count of days when *TX* (daily maximum temperature) > 25 °C.	days	42	Health and disaster risk reduction
ID	Number of icy days	Annual count of days when *TX* (daily maximum temperature) < 0 °C.	days	42	Agriculture and food security, and disaster risk reduction

Table 2. *Cont.*

ID	Index Name	Definitions	Units	Number of Stations	Sectors of Economics
R10mm	Annual count of days when PRCP $\geq$ 10mm	Let RR_{ij} be the daily precipitation amount on day i in period j. Count the number of days where $RR_{ij} \geq 10$ mm.	days	42	Agriculture and food security
R20mm	Annual count of days when PRCP $\geq$ 20 mm	Let RR_{ij} be the daily precipitation amount on day i in period j. Count the number of days where $RR_{ij} \geq 20$ mm.	days	42	Agriculture and food security
		Indices based on absolute values			
TXx	Monthly maximum value of daily maximum temperature	Let TX_x be the daily maximum temperatures in month k in period j.	°C	42	Agriculture and food security, energy, and disaster risk reduction
TNn	Monthly minimum value of daily minimum temperature	Let TN_n be the daily minimum temperatures in month k in period j.	°C	42	Agriculture and food security, and energy
		Percentile-based indices			
TX10p	Percentage of days when TX < 10th percentile	Let TX_{ij} be the daily maximum temperature on day i in period j and let $TX_{in}10$ be the calendar day 10th percentile centered on a 5-day window for the base period 1981–2010.	days	42	Energy
TN10p	Percentage of days when TN < 10th percentile	Let TN_{ij} be the daily minimum temperature on day i in period j and let $TN_{in}10$ be the calendar day 10th percentile centered on a 5-day window for the base period 1981–2010.	days	42	Energy
TX90p	Percentage of days when TX > 90th percentile	Let TX_{ij} be the daily maximum temperature on day i in period j and let $TX_{in}90$ be the calendar day 90th percentile centered on a 5-day window for the base period 1981–2010.	days	42	Energy
TN90p	Percentage of days when TN > 90th percentile	Let TN_{ij} be the daily minimum temperature on day i in period j and let $TN_{in}90$ be the calendar day 90th percentile centered on a 5-day window for the base period 1981–2010.	days	42	Energy
R99p	Annual total PRCP when RR > 99th percentile	Let RR_{wj} be the daily precipitation amount on a wet day w ($RR \geq 1.0$ mm) in period i and let $RR_{wn}99$ be the 99th percentile of precipitation on wet days in the 1981–2010 period.	days	42	Agriculture and food security, and disaster risk reduction

Table 2. *Cont.*

ID	Index Name	Definitions	Units	Number of Stations	Sectors of Economics
		Indices based on the duration of the phenomenon			
WSDI	Warm spell duration index: annual count of days with at least 6 consecutive days when *TX* > 90th percentile	Let TX_{ij} be the daily maximum temperature on day *i* in period *j* and let $TX_{in}90$ be the calendar day 90th percentile centered on a 5-day window for the base period 1981–2010.	days	42	Health, agriculture and food security, water resources and food security, and disaster risk reduction
CSDI	Cold spell duration index: annual count of days with at least 6 consecutive days when *TN* < 10th percentile	Let TN_{ij} be the daily maximum temperature on day *i* in period *j* and let $TN_{in}10$ be the calendar day 10th percentile centered on a 5-day window for the base period 1981–2010.	days	42	Health, agriculture and food security, water resources and food security, and disaster risk reduction
DTR	Daily temperature range	Let TX_{ij} and TN_{ij} be the daily maximum and minimum temperature respectively on day *i* in period *j*.	days	42	Agriculture and food security
CDD	Maximum length of dry spell: maximum number of consecutive days with RR < 1mm	Let RR_{ij} be the daily precipitation amount on day *i* in period *j*. Count the largest number of consecutive days where $RR_{ij} < 1$ mm.	days	42	Health, agriculture and food security, and disaster risk reduction
CWD	Maximum length of wet spell: maximum number of consecutive days with RR ≥ 1 mm	Let RR_{ij} be the daily precipitation amount on day *i* in period *j*. Count the largest number of consecutive days where $RR_{ij} \geq 1$ mm.	days	42	Agriculture and food security, and disaster risk reduction
PRCPTOT	Annual total precipitation on wet days	Let RR_{ij} be the daily pre if *i* represents the number of days in *j*.	mm	42	Agriculture and food security, and water resources and food security

Indicators have several advantages since they are expressed in quantitative form, are objective, and show changes over time. Changing the frequency and/or intensity of extreme meteorological and climate events as a result of climate change and variability is one of the most important impacts of climate change [33,36].

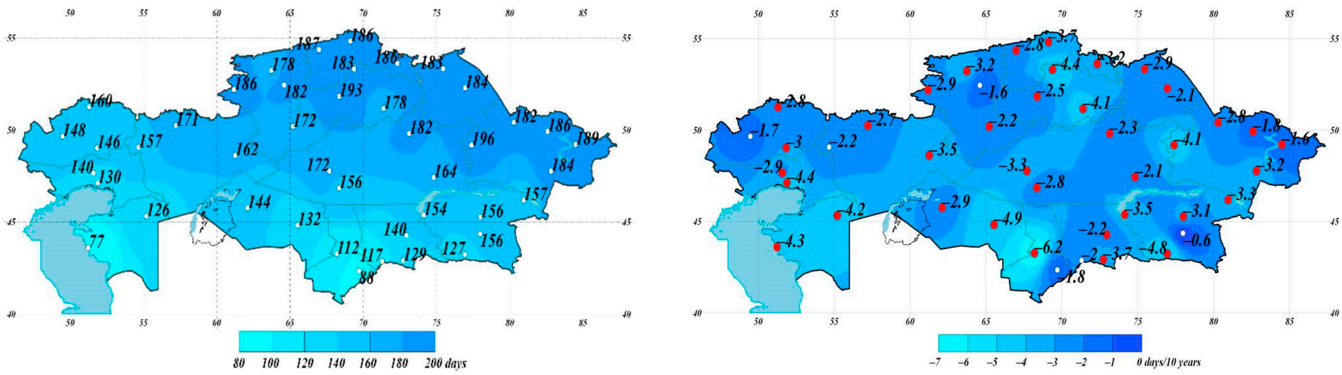
3. Results and Discussion

3.1. Spatial and Temporal Variations in the Threshold Indices of Air Temperature

To obtain a complete picture of the change in the air temperature field the analysis used climatic indices characterizing extreme values. The most significant and useful ones for use in specific sectors of the economy and social sphere were mentioned above.

One such index is the FD index, which characterizes the number of days with a minimum daily temperature of < 0 °C.

Analysis of its spatial distribution (Figure 2) shows that negative temperatures are observed everywhere in Kazakhstan during the cold half of the year. The average FD values for the territory of Kazakhstan are 140–170 days. A characteristic feature of the distribution of this index is mainly the latitudinal nature of the distribution, disturbed by the influence of the Caspian Sea. It is noteworthy that parts of the north and northeast of Kazakhstan had high FD values. In this zone, values range from 182 to 196 days with separate zones of the largest values in the area of MS Kainar and MS Atbasar, 196 and 193 days, respectively (Figure 2). At the same time, the lowest FD value is noted in the opposite part of Kazakhstan, in the southern and southwestern parts (Fort Shevchenko MS-77 days and Shymkent MS-88 days). This distribution of FD gives us reason to assume that the territory of Kazakhstan can be conditionally divided into two equal parts along a diagonal line from northwest to southeast.



(**a**) (**b**)

Figure 2. Spatial distribution of the number of days with minimum daily temperature < 0 °C (FD) (**a**) and trends of this parameter (**b**) for the period 1971–2020.

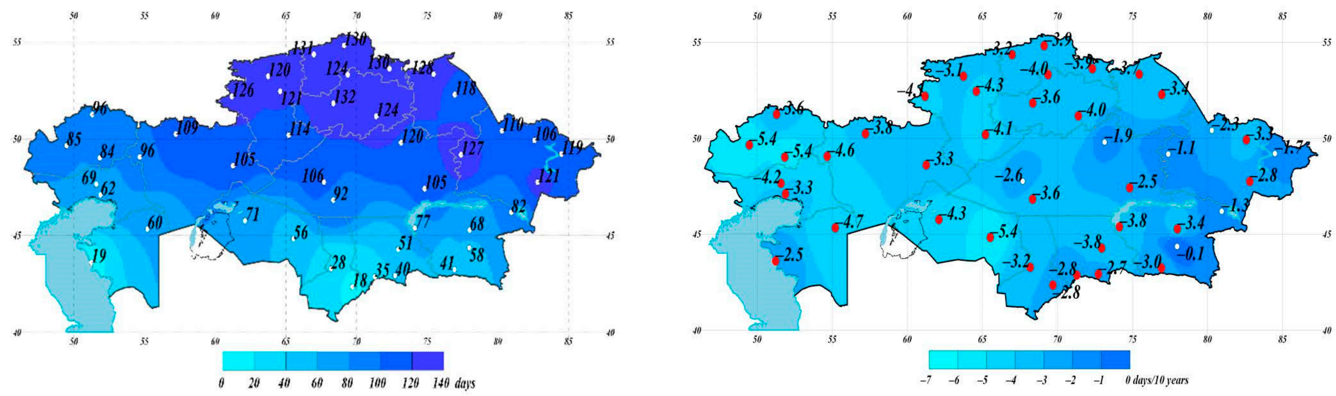
Of great interest is the assessment of the latest FD trends. The analysis of significant trends in the change of the FD parameter over time demonstrates a pronounced tendency for a widespread decrease in the number of days with a minimum daily temperature < 0 °C, which is 2–6 days over 10 years. The spatial distribution of trends is also not unambiguous and has no latitudinal distribution as originally expected. In general, the reduction in the number of FDs is more pronounced in the southern, warmer part, which is explained by a large number of border days (with temperatures slightly below or close to zero degrees). The southern meteorological stations Turkestan and Shymkent, at which the maximum and close to the minimum values are noted, respectively, draw attention to themselves. At the same time, these stations are not far from each other and are neighboring; therefore, such strong differences in trends raise questions. However, with detailed data validation and comparison with other results, there were no significant grounds for culling. In the future, on some maps, data on Turkestan also stands out from the rest.

In general, the observed reduction in FD is quite consistent with both global trends and the results of domestic researchers [13,37]. For example, the results obtained are consistent with a reduction in spring snowmelt and an earlier snowfall that directly depends on temperature. The analysis shows that in general, in the territory of Kazakhstan, the total duration of cold waves is being reduced everywhere.

An important characteristic required for a comprehensive analysis of current climate change trends in Kazakhstan is an index characterizing the number of days of daily temperature highs below zero degrees (ID) (Figure 3). Its values for the territory in question range from 8 to 132 days.

The minimum values of the index are observed in the southwest, south, and southeast of the country. The maximum number of days was noted in the northern and northeastern regions of Kazakhstan.

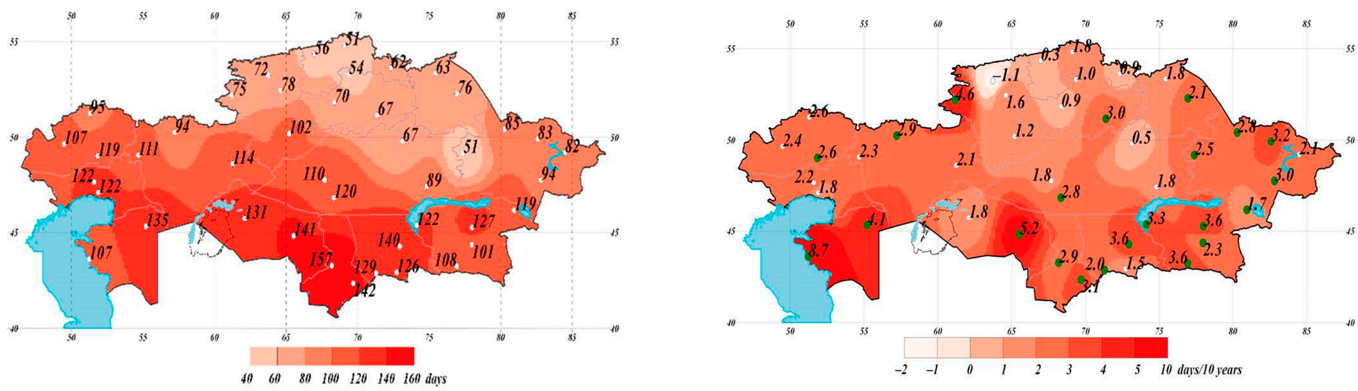
An analysis of the ID index trend shows its significance, with a tendency to decrease the values of this parameter by 2–5 days throughout Kazakhstan. In the west, north, and south of the republic, the number of days with daytime frosts is reduced; that is, when the daily maximum air temperature is below 0 °C.



(**a**) (**b**)

Figure 3. The spatial distribution of the index is the number of days of daily temperature maxima below zero degrees (ID) (**a**) and trends (**b**) of this parameter for the period 1971–2020.

The number of days with a maximum daily temperature of < 25 °C (SU) is characteristic of the warm season and has the opposite distribution to FD (Figure 4). The SU change range is 51–76 days in northern Kazakhstan and 134–157 days in southwestern and southern Kazakhstan. In the latitudinal zone from 49° to 52° N, average SU values are observed and are 103–122 days. The maps also show latitudinal zonality disturbed by the influence of the Caspian Sea.



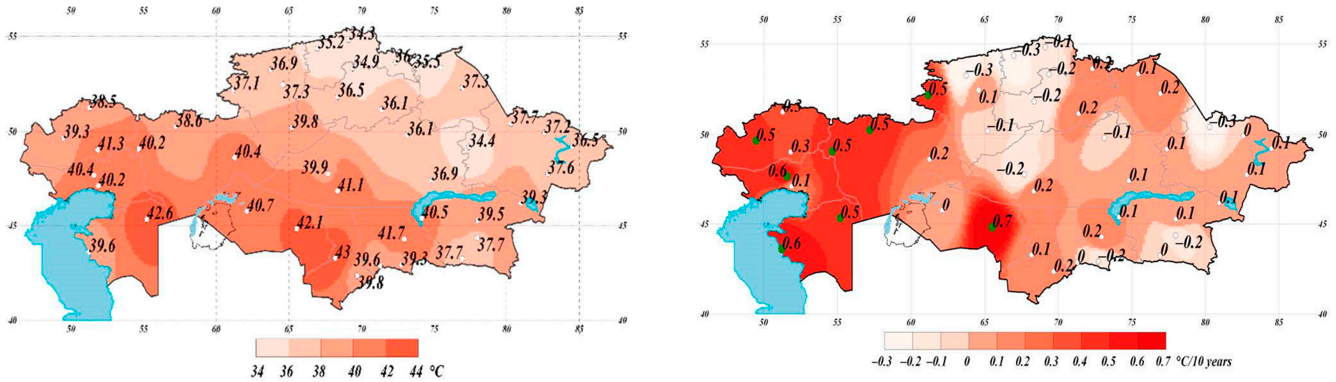
(**a**) (**b**)

Figure 4. Spatial distribution of the index characterizing the number of days with maximum daily temperature < 25 °C (SU) (**a**) and trends (**b**) of this parameter for the period 1971–2020.

Changes in SU over time tend to rise across the board. At the same time, the observed trends are statistically significant. The most significant positive trends are observed in the territory of southern Kazakhstan, as well as in the south of western Kazakhstan, and range from 3 to 9 days in 10 years.

The largest monthly values of maximum daily air temperatures (TXx) in Kazakhstan range from 34–36 °C in northern Kazakhstan to 40–44 °C for the southern regions of western and southern Kazakhstan (Figure 5).

In general, the trend of TXx index repeatability increase prevails; however, insignificant and non-significant negative trends are observed in the northeastern and northern zones of Kazakhstan. Significant positive trends are observed only in western Kazakhstan and amount to 0.4–0.7 °C/10 years.



(**a**) (**b**)

Figure 5. Spatial distribution of the index characterizing maximum monthly values of maximum daily air temperatures (TXx) (**a**) and trends (**b**) of this parameter for the period 1971–2020.

The lowest monthly values of minimum daily air temperatures (TNn) in the territory of Kazakhstan are observed in the north and east of Kazakhstan (minus 35 °C-minus 38.8 °C) (Figure 6).

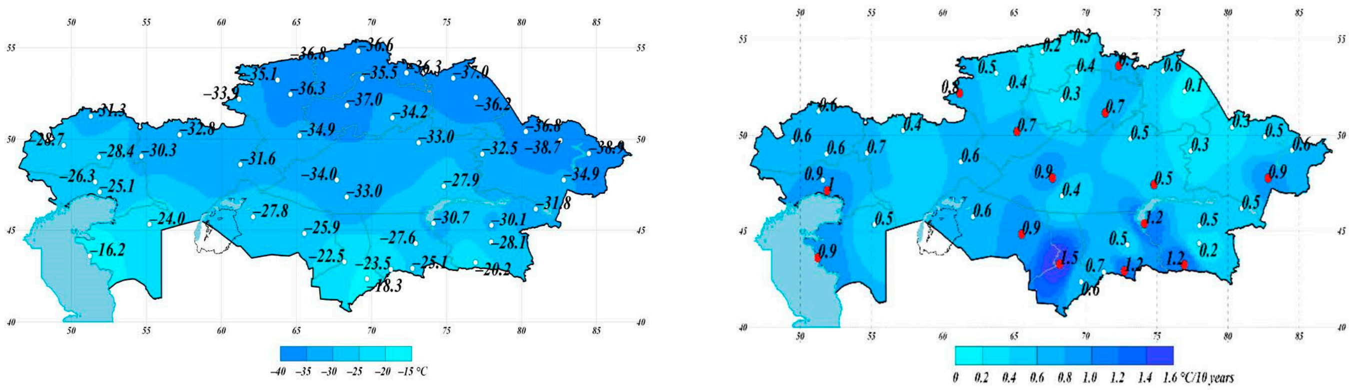


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Figure 6. Spatial distribution of the index characterizing minimum monthly values of minimum daily air temperatures (TNn) (**a**) and trends (**b**) of this parameter for the period 1971–2020.

The largest monthly values of the minimum daily air temperatures (TNn) are observed in the south and southwest, which confirms our assumption of conditional division into two equal parts along the diagonal line from northwest to southeast.

For western Kazakhstan, TNn values range from minus 31.4 °C in Uralsk to minus 16.4 °C Fort Shevchenko. In south Kazakhstan, values vary from minus 18 °C to 28 °C. This is most likely due to the fact that these areas, with mild unstable winters, are characterized by a significant amplitude of temperature fluctuations.

The territory of Kazakhstan is generally characterized by a positive TNn trend, but significant trends are observed only in central and southern Kazakhstan, and noticeable positive trends are observed off the coast of the Caspian Sea and in the southeastern part of Kazakhstan. Additionally, an abnormal value is distinguished at the Turkestan meteorological station, with the maximum value that we paid attention to earlier.

The share of extremely hot warm days (TX90p) expressed in percent, in general, does not increase evenly across the territory of Kazakhstan from east to west (Figure 7). The largest positive values of the TX90p trend are noted in western, central, and southern Kazakhstan (1.5–2.9%/10 years). In the territory of northern and eastern Kazakhstan, the values increase to 0.7%/10 years. In the spatial distribution of warm nights (TN90p), no definite patterns showed. The share of warm nights is spotty; the highest values of TN90p are noted in Mangistau, Kyzylorda, Turkestan, and southern Almaty regions and makeup 2.2–2.8%/10 years. In the rest of Kazakhstan, the trend changes slightly from 0.7 to 1.5%/10 years.

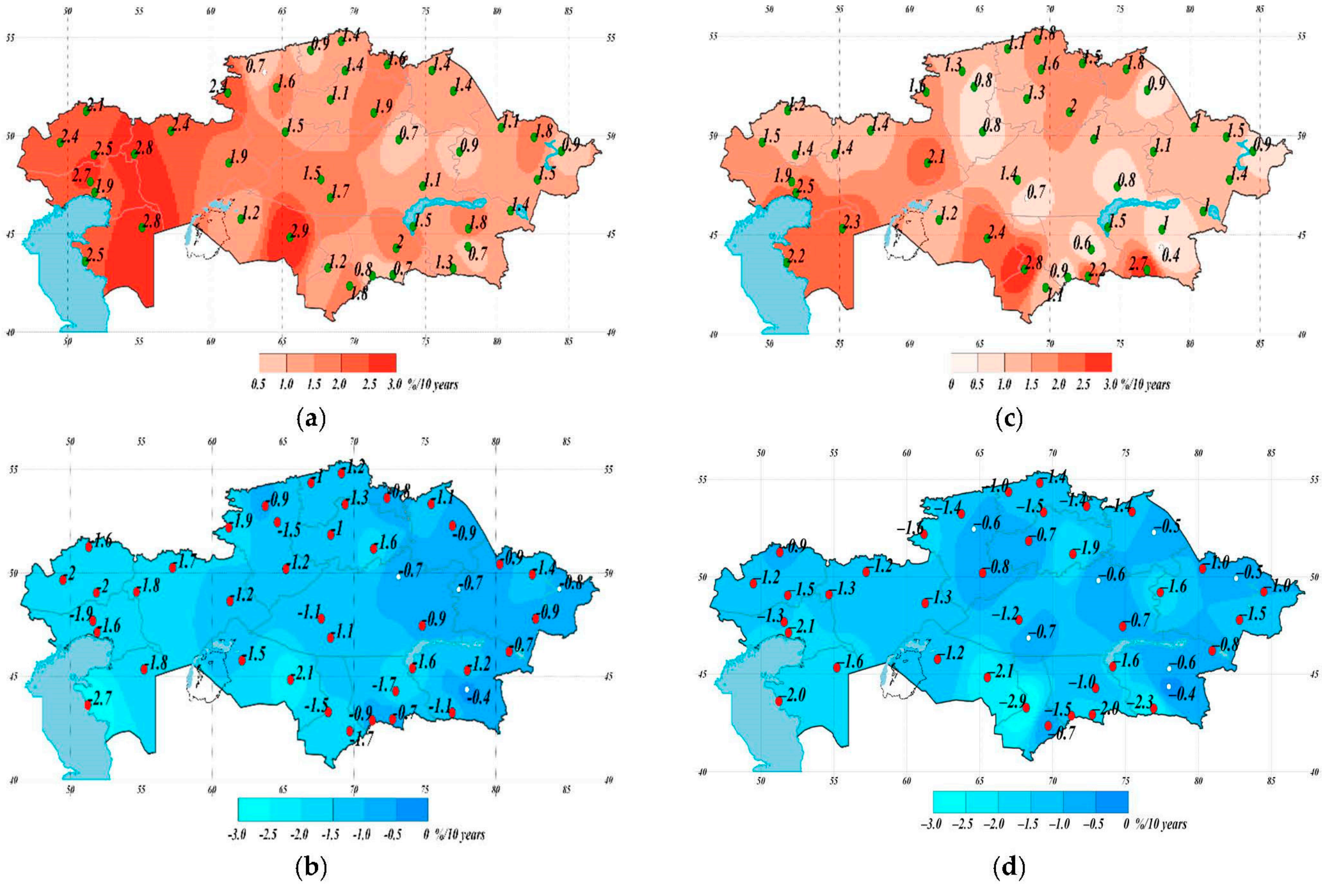
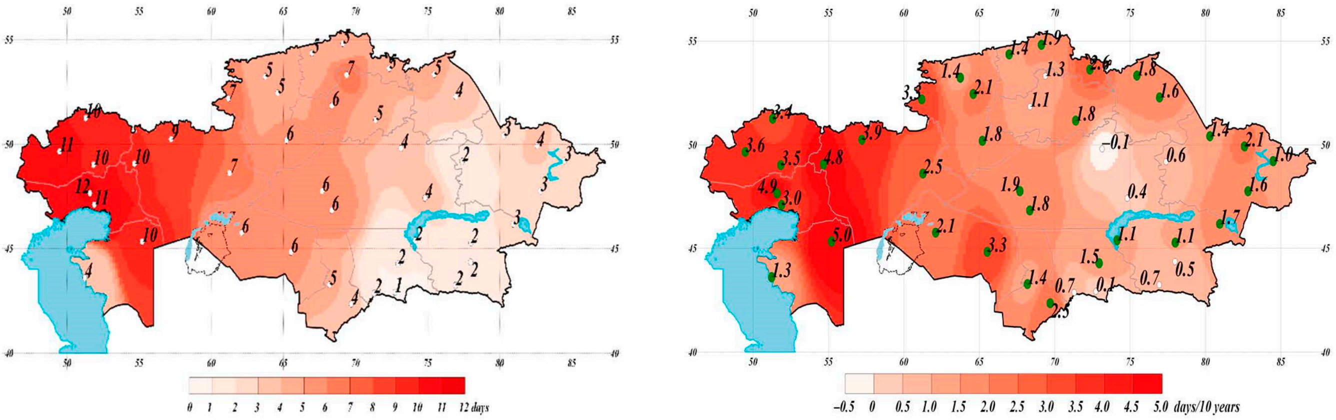


Figure 7. Spatial distribution of indices characterizing the proportion of extremely hot days TX90p (**a**) and warm nights TN90p (**b**), the proportion of non-hot days TX10p (**c**), extremely cold nights TN10p (**d**), and trends of these parameters for the period 1971–2020.

The proportion of non-hot days (TX10p) and extremely cold nights (TN10p) shows generally opposite TX90p trends, decreasing from west to east of the Republic. The largest values are noted in western Kazakhstan (minus 1.7-minus 2.7%/10 years), the smallest in the southeast and east of the study area (0.4–0.9%/10 years).

For the entire territory of Kazakhstan, there are characteristics and significant trends. The opposite nature of the trends logically fits into the expected climate changes and confirms the significance and reliability of the study's results.

At the same time, a more detailed comparison of maps of trends in TX90p and TN10p demonstrates the legality of the conditional division of the territory of Kazakhstan into the southwestern and northeastern half characterized by varying degrees of climate change (Figure 8). So, in the southwestern half, there is a significant trend both for an increase in extremely high daytime and extremely low night temperatures, and in the northeastern part, this trend is less pronounced both for extremely high daytime and extremely low night temperatures.



(**a**) (**b**)

Figure 8. The spatial distribution of the index characterizing the distribution of the duration of heat waves (WSDI) (**a**) and trends (**b**) of this parameter for the period 1971–2020.

Thus, a number of indices demonstrate a tendency to increase temperature. In this regard, it is of interest to consider additional indices characterizing heat and cold waves, the duration of the rainless period and etc., which is more obvious to assess the fact of temperature increase and the current trend.

The heat wave duration distribution (WSDI) shows a clear pronounced increase from east to west of Kazakhstan (Figure 8).

The heat wave duration index (WSDI) increased from the east of the center to the west of Kazakhstan. In the east of the republic, the value of the duration of the heat wave was 4–5 days. In the center of the republic from south to north, there is also an increase in the spread of days with waves of heat. In the southeast of Kazakhstan, the days with heat waves amounted to 2–5 days.

In the west of the republic, the duration of heat waves reached 9–11 days. In southeastern Kazakhstan, the number of days with heat waves was 1–2. The distribution of trends in heat waves also shows their large values in the west of Kazakhstan up to 5 days/10 years, and to a lesser extent trends appear in the south and centers-up to 3 days/10 years. In the southeast and eastern part of the republic, the lowest values are noted.

The WSDI index has significant trends throughout the republic and varies from 2 to 5 days.

Meanwhile, the cold wave duration distribution (CSDI) does not show such a clear distribution pattern and is spottier with individual separate zones (Figure 9). Interestingly, high values are noted in south and southwest of Kazakhstan (with a maximum in Turkestan). Although, in these territories, one should expect lower values since, in general, warming is recorded in these territories. However, given that this index is considered an indicator of extremity, it is legitimate to conclude that the southern regions of the country are more extreme. Overall, the CSDI index values range from 3–9 days.

At the same time, almost all trend values have negative values and show a decrease in the number of cold waves; only in the east of the republic are there insignificant positive trend values (0.2–0.7). In the west and south, the cold waves are expected to be fewer. Cold wave distribution trends are significant in most of the republic.

The found trends of the WSDI and CSDI are supported by data [38] which show that there is a ubiquitous increase in the total duration of heat waves and a reduction in the total duration of cold waves.

The daily temperature amplitude index (the average difference between the daily maximum and the daily minimum) (DTR) has the largest values in the mountainous regions of southern and southeastern Kazakhstan; the index values vary between 11–14 °C, and the minimum is in Aktau, which is explained by the smoothing effect of the Caspian Sea (Figure 10).

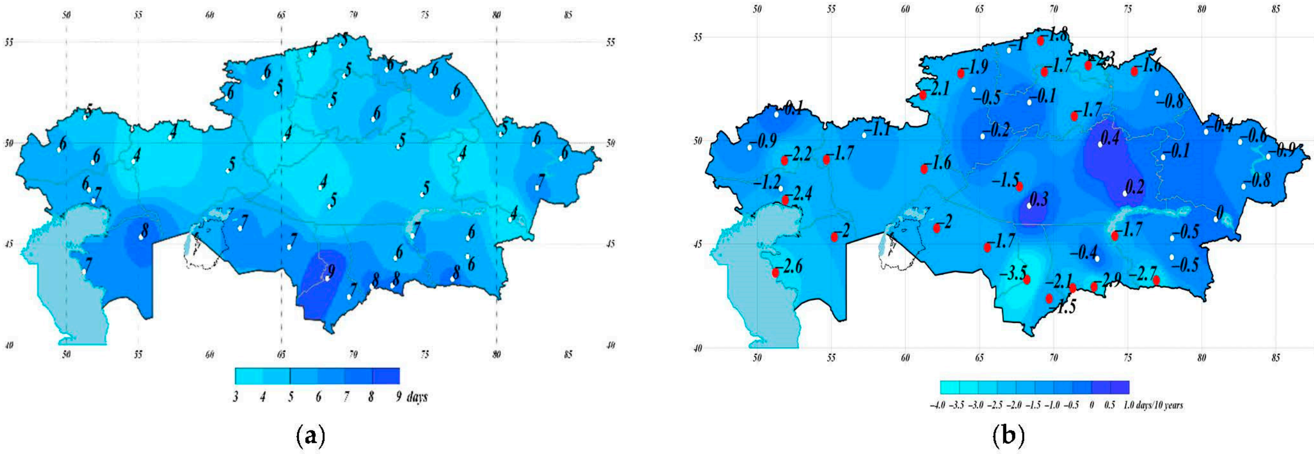


Figure 9. Spatial distribution of the index characterizing the distribution of cold wave duration (CSDI) (**a**) and trends (**b**) of this parameter for the period 1971–2020.

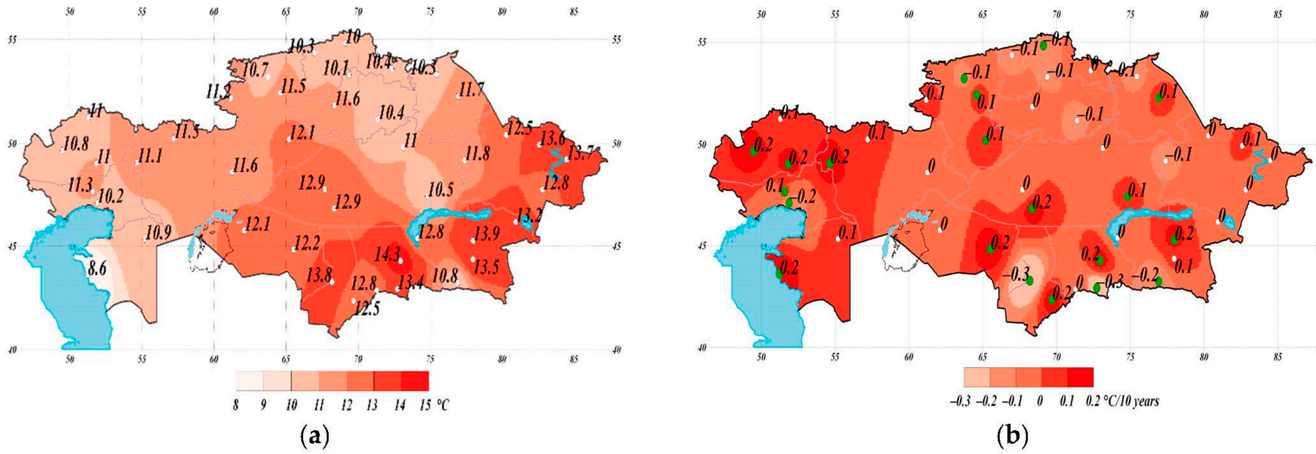


Figure 10. Spatial distribution of the daily temperature amplitude index (DTR) (**a**) and trends (**b**) of this parameter for the period 1971–2020.

Low values are observed in the territory of western, northern, and a small part of central Kazakhstan and are subject to the influence of Lake Balkhash (10–11 °C).

The trends of this index are not significant but statistically relevantin most of the territory of the republic and have positive significance in the west, southwest, and certain regions of the southeast, but negative values were observed in most of north and central Kazakhstan, and mountainous regions and the foothill regions south and southeast of the republic. High positive trend values correspond to the maximum index values.

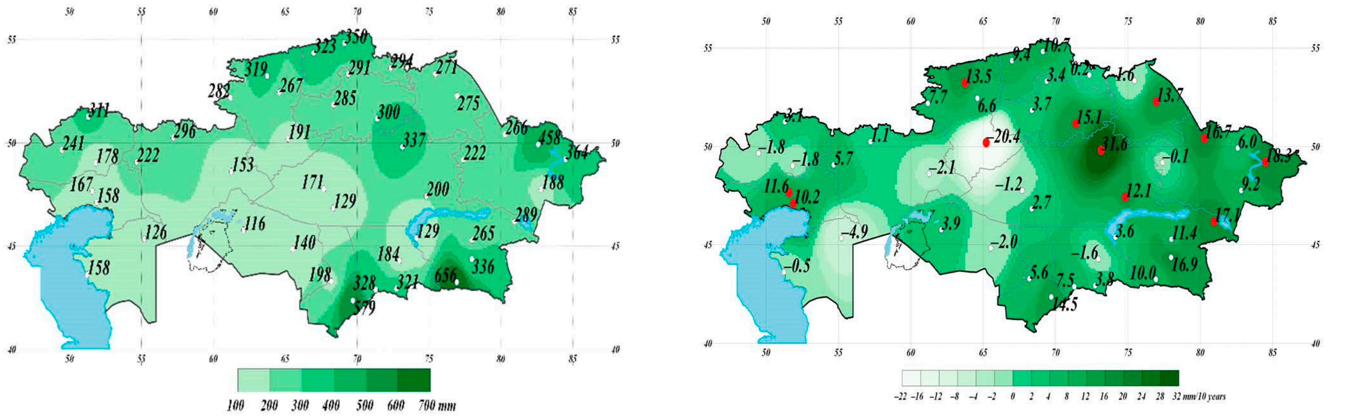
The obtained results on temperature changes are quite consistent with the data of the National Hydrometeorological Service [39], according to which, on average, in the territory of Kazakhstan for the period 1971–2020, an increase in the average annual air temperature is 0.31 ºC/10 years. For the period 1971–2020, there is a steady increase in the number of days with temperatures above 35 °C and nights with temperatures above 20 °C, which is especially noticeable in the south, southwest, and west of the republic; there is a steady increase in the number of days everywhere with an average daily temperature above 10 °C.

Along with air temperature, an important element of the climate is precipitation; the distribution and trends of which must be examined for a more complete assessment of the climate. The trends of extremes in precipitation are discussed below.

3.2. Spatial and Temporal Variations in the Threshold Indices of Precipitation Extremes

The distribution of precipitation over the study area and the trend of changes in total annual and extreme precipitation are also considered using the specialized indices mentioned above.

The total annual rainfall is the Annual Rainfall Total Index (PRCPTOT). PRCPTOT values increase from west to east of the republic, with separate maxima corresponding to the mountainous and foothill regions of the republic (477–660 mm) and minima (111–294 mm) in the area of Lake Balkhash, as well as desert and semi-desert regions of the south and west of the republic (Figure 11).



(a) (b)

Figure 11. Spatial distribution of the index characterizing the annual precipitation sum index (PRCPTOT) (**a**) and trends (**b**) of this parameter for the period 1971–2020.

The trends of this index are insignificant in most of the republic. The trends of this index are positive and significant only in the northeast and east of the republic, as well as the Caspian lowland, ranging from 10.2 to 31.6 mm over 10 years. At the same time, according to the National Hydrometeorological Service [Annual Bulletin, 2020], in the period 1971–2020, Kazakhstan tends to increase the annual amount of atmospheric precipitation by 4.3 mm/10 years. Thus, the results of this study confirm the general trend toward an increase of precipitation in Kazakhstan.

A significant amount of extreme precipitation (R99p) is observed in the mountainous regions of the south, southeast, and northeast, as well as in the northern part of Kazakhstan, showing latitudinal relief dependence (repeating, in general, the contours of annual precipitation) disturbed by the anomaly in the Pavlodar region (Figure 12). Values ranged from 31 to 41 mm. The maximum value of 41 mm was noted in Almaty, located in the mountainous region, with the greatest precipitation, and on the anomalous territory in the Pavlodar region where, in general, precipitation is half as much. The lowest precipitation values are observed in Kyzylorda, the south of Mangistau, as well as in the center of the Zhambyl region. The amount of precipitation ranged from 7 to 9.1 mm.

These results differ somewhat from the data of the National Hydrometeorological Service of the Republic of Kazakhstan, according to which in most of Kazakhstan there is a decrease in the maximum daily rainfall in the year; the share of extreme precipitation in the annual amount of precipitation varies, mainly slightly.

An increase in extreme precipitation trends is noted in Shymkent, the northeast, and in the east of the Karaganda region, northern Kazakhstan, where the trend values reached values from 2 to 7.8 mm/10 years.

A decrease in the trend is noted in a large part of the territory of western Kazakhstan, the Kyzylorda region, and in the center of the Karaganda region, where the value changed from −0.3 to −1.6. A decrease was also noted in the Pavlodar region.

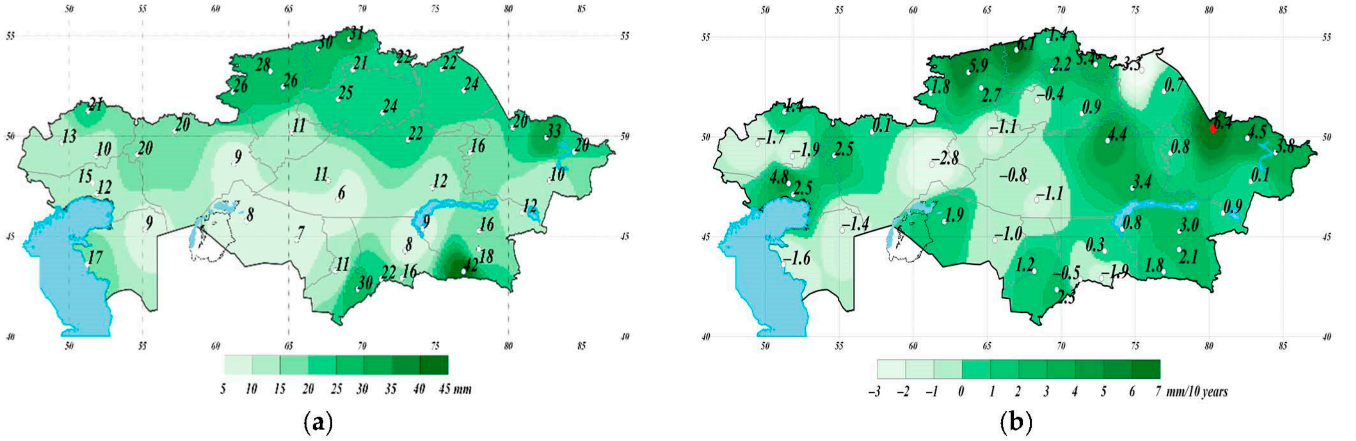


Figure 12. Spatial distribution of the index characterizing the amount of extreme precipitation (R99p) (**a**) and trends (**b**) of this parameter for the period 1971–2020.

Distributions of precipitation amount to more than 10 and 20 mm per day and are characterized, respectively, by indices R10mm and R20mm (Figure 13).

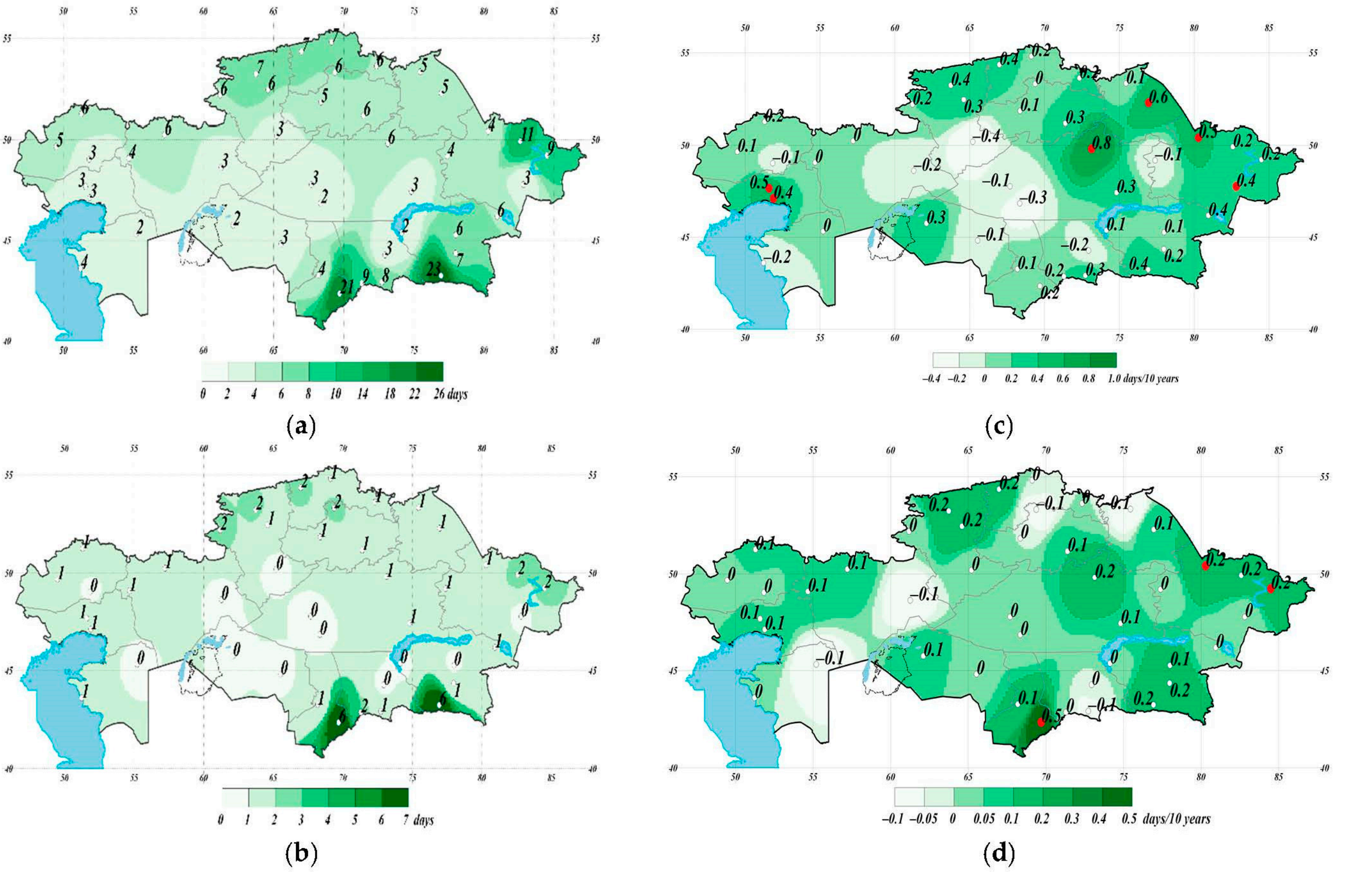


Figure 13. Spatial distribution of indices characterizing the distribution of precipitation amounts more than 10 and 20 mm per day R10mm (**a**), R20mm (**c**), and the heir trends (**b**,**d**) of these parameters for the period 1971–2020.

In Kazakhstan, it varies from 3 to 5 days, with minimum values of 2 days in desert and semi-desert areas, and maximum values of more than 8 days in mountainous and the foothill areas of the south and southeast of the country. There are also separate zones with the largest number of days with precipitation amounts of more than 10 mm (up to 22 days) in the northeast, east, and southeast of the republic. The highest value is noted in Almaty for 23 days.

A similar pattern is observed for the R20mm index, but the maximum number of days with daily rainfall of more than 20 mm does not exceed 6 days. For the larger territory of the republic, there are from 1 to 2 days with daily rainfall of more than 20 mm, except for central Kazakhstan, where precipitation of more than 20 mm does not fall. There are no significant trends for R10mm and R20mm everywhere.

It is also of interest, along with precipitation, to consider the opposite index of the dry (non-traveling) period duration (Figure 14).

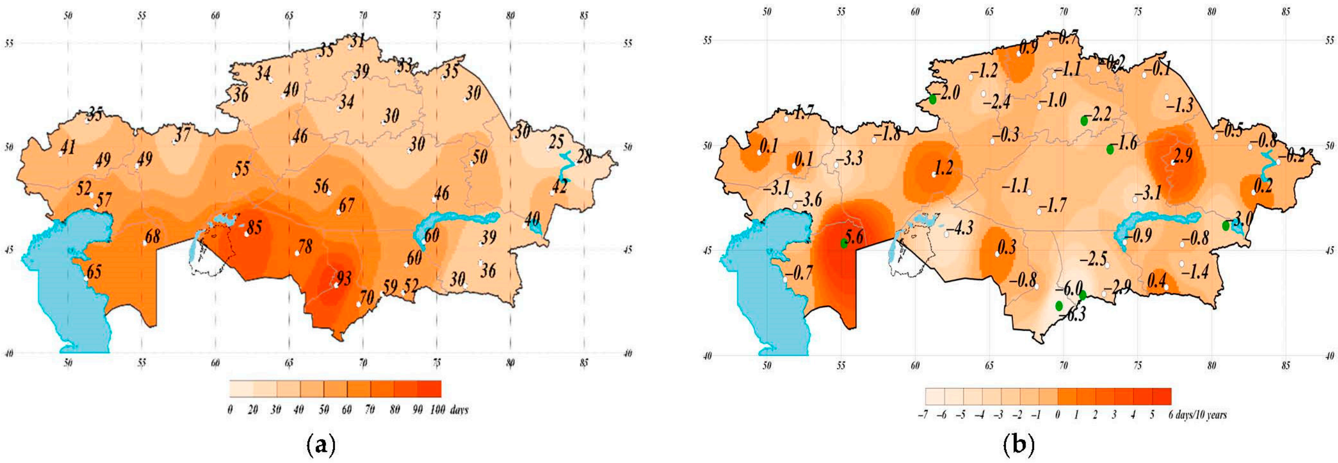


Figure 14. Spatial distribution (**a**) and trend (**b**) of the dry period duration (CDD) index for the period 1971–2020.

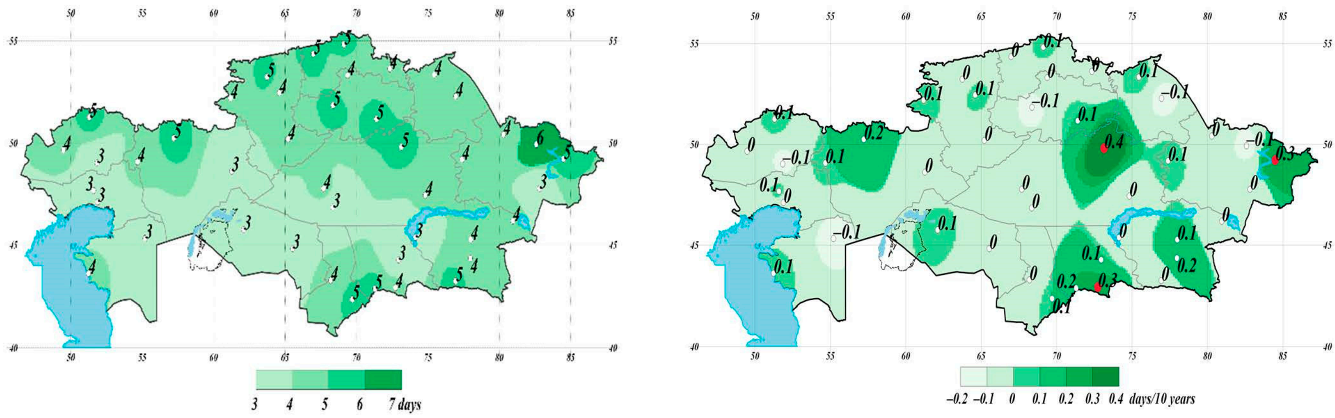
The Maximum Dry Period Duration Index (CDD) shows the expected latitudinal distribution increasing from north to south, disturbed by the influence of non-homogeneity of the terrain and especially the mountainous territories of southeast Kazakhstan, ranging from 25–35 in mountainous regions to 70–93 days in the south. High values of 74–93 days are observed in the territory of Kyzylorda, Turkestan, and in the extreme south of Mangystau regions. The maximum value falls in the south (Turkestan).

The trends of this index are insignificant in a large territory of the republic and are mainly negative, but only in some areas. There are positive trends which changed from 0.2 to 5.6 days over 10 years.

The results are consistent with the data that there are weak, statistically insignificant, positive and negative trends in the maximum duration of the non-traveling period.

The index of the maximum annual number of consecutive days with rain more than 1 mm (CWD) increases from southwest to north, in the northeast of the republic, with a separate focus on the minimum in the area of Lake Balkhash, and the focus on the maximum in the area of Aktobe region. Index values range from 3–6 days (Figure 15). The smallest index values of 3 days are observed in the west and south of Kazakhstan, with a separate focus on the area of Lake Balkhash. The largest values of 5–6 days are observed in the northern regions, mountains, and foothill regions of the south, southeast, and east of the republic, as well as a separate maximum in the of Aktobe. Trends in this index are insignificant in most of the territory.

According to the distribution of the index of the maximum annual number of consecutive days with rain more than 1 mm (CWD), in a large part of the republic, the average number of precipitation days is about 4 days. The minimum value is recorded in the desert and semi-desert regions of Kazakhstan. The maximum is observed in the mountainous and foothill regions of the east and certain regions of the north. Trends in this index are also insignificant in most of the territory.



(**a**) (**b**)

Figure 15. Spatial distribution of the index characterizing the maximum dry period duration (CWD) (**a**) and trends (**b**) of this parameter for the period 1971–2020.

4. Conclusions

This paper presents the results of the study on the assessment of modern space–time trends of extreme values of air temperature and precipitation.

A large amount of initial information on 270 meteorological stations for half a century has been processed. A critical and preliminary analysis of the data was carried out and the data recovery procedure was based on the results, of which the most complete and correct data were selected for 42 meteorological stations throughout Kazakhstan.

A complex of specialized climatic indices recommended by the WMO climatology commission and the ClimPACT2 software product was used to comprehensively analyze the air and precipitation temperature regimes to identify their features and extremes.

A generalization and conditional division of climatic indices recommended by the WMO climatology commission into four categories was carried out: indices based on threshold values, indices based on absolute values, indices based on percentiles, and indices based on the duration of the phenomenon. A spatial–temporal analysis of the distribution of indices and an assessment of their trends demonstrating the heterogeneity of changes and trends were carried out.

In particular, the FD index, which characterizes the number of days with a minimum daily temperature < 0 °C, shows a pronounced trend toward a widespread decrease of 2–6 days over 10 years, while the decrease in the number of FD is more pronounced in the southern, warmer part of the country. The ID index, as expected, shows a tendency to decrease by 2–5 days, also throughout Kazakhstan. The opposite SU index in terms of value tends to have statistically significant growth. The most significant positive trends are observed in the territory of southern Kazakhstan, as well as in the south of western Kazakhstan, and range from 3 to 9 days in 10 years. Similar trends in opposite indices confirm the overall warming trend.

The analysis of trends in the index characterizing the maximum monthly values of maximum daily air temperatures (TXx) demonstrates that, in general, the tendency to increase the repeatability of the TXx index prevails; however, in the northeastern and northern zones of Kazakhstan, there are insignificant and not significant negative trends. Significant positive trends are observed only in western Kazakhstan and amount to 0.4–0.7 °C/10 years.

The minimum daily air temperatures (TNn) generally have a positive trend, but significant trends are observed only in central and south Kazakhstan, and noticeable positive trends are observed off the coast of the Caspian Sea and in the southeastern part of Kazakhstan.

The share of extremely hot warm days (TX90p) and warm nights (TN90p) does not increase evenly throughout Kazakhstan. The largest positive values of the TX90p trend are noted in western, central, and south Kazakhstan (1.4–2.7%/10 years); in the territory of northern and eastern Kazakhstan, the values decrease to 0.4–0.9%/10 years. The share of warm nights is spotty and accounts for 2.4–2.6%/10 years. In the rest of Kazakhstan, the trend changes slightly from 0.7 to 1.5%/10 years. The proportion of non-hot cold days (TX10p) and extremely cold nights (TN10p) decreases from the southwest to the northeast of the country. Significant trends are characteristic of the entire territory of Kazakhstan.

Comparison of trends in TX90p and TN10p on the map made it possible to identify the division of the territory of Kazakhstan by the degree of manifestation of climate change in the southwestern and northeastern half. In the southwestern half, there is a significant trend both for an increase in extremely high daytime and extremely low nighttime temperatures, and in the northeastern part, this trend is less pronounced both for extremely high daytime and extremely low nighttime temperatures. The distribution of the duration of heat waves (WSDI) shows a pronounced and significant trend toward an increase from east to west in Kazakhstan. At the same time, the distribution of the cold wave duration (CSDI) does not show such clear consistency and is spottier. The found trends of the WSDI and CSDI confirm the fact of a widespread increase in the total duration of heat waves and a reduction in the total duration of cold waves.

Trends in indices of the annual amount of precipitation turned out to be statistically insignificant in most of the republic. The spatial distribution of the index characterizing the amount of extreme precipitation (R99p) shows spots. An increase in extreme precipitation trends is noted in Shymkent, the northeast, and east of the Karaganda region, northern Kazakhstan, where the trend values reached values from 2 to 7.8 mm/10 years.

A decrease in the trend is noted in a large part of the territory of western Kazakhstan, the Kyzylorda region, and in the center of the Karaganda region, where the value changed from −0.3 to −1.6. Additionally, a decrease was noted in the Pavlodar region. At the same time, trends for R10mm and R20mm are not significant everywhere.

The results of the analysis confirmed the data that in Kazakhstan there are weak, statistically insignificant, positive and negative trends in the maximum duration of the non-traveling period. The trends of the index of the maximum dry period duration (CDD) are mainly negative. Only in some areas is there a positive trend that varies from 0.2 to 5.6 days over 10 years, while are insignificant in a large territory of the republic.

In general, the results of the study made it possible to significantly supplement and clarify the information provided by the National Hydrometeorological Service in the annual climate monitoring bulletin (https://meteo.kazhydromet.kz/database_meteo/; accessed on 17 January 2023).

According to the results of the analysis of the climatic series of the average daily air temperature, maximum and minimum temperatures, and the amount of daily precipitation at 42 meteorological stations throughout Kazakhstan during the half-century period 1971–2020, revealed not only the fact of significant climatic changes but also their spatial heterogeneity in terms of manifestation. The results show the persistence of uncertainty in some key trends of climate change and the relevance of further research for maximum adaptation to the climate challenges of the current century.

Author Contributions: Conceptualization, V.S., S.P. and A.K.; methodology, V.S., S.P. and A.K.; formal analysis, V.S., Y.T., A.K., A.A., G.M. and D.K.; investigation, V.S., S.P., A.A., N.B. and A.K.; data curation, Y.B. and D.K.; writing—original draft preparation, S.P., G.M. and D.K.; writing—review and editing, V.S., A.K. and S.P.; visualization, Y.B. and A.A.; supervision, V.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: https://meteo.kazhydromet.kz/database_meteo/, accessed on 7 December 2022.

Conflicts of Interest: The authors declare no conflict of interest.

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