https://doi.org/10.33864/2309-4494.2026.n1.30-42

SPACE-TIME INDICATIONS OF CLIMATE ARIDIZATION IN BELARUS

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Abstract. This study investigates how climate aridization has unfolded across Belarus. We analysed trends in air temperature, precipitation, potential evapotranspiration (PET), climatic water balance, and key moisture indices from 1950 to 2023, using data from 36 weather stations. Our analysis shows that aridization isn't mainly due to less precipitation. Instead, it's driven by warmer temperatures and an increased atmospheric evaporative demand in the warm season. The climatic water balance in the warm season is worsening due to higher PET, even though total rainfall has slightly increased. Analyses using the Aridity Index (AI), Standardized Precipitation Index (SPI), and Standardized Precipitation Evapotranspiration Index (SPEI) all point to a clear, growing moisture deficit over the last 20–30 years. Looking ahead, projections through 2035 and 2050 suggest this trend will continue: warm-season water availability is expected to decline further.

Keywords: climate aridization; Belarus; climate change; potential evapotranspiration (PET); climatic water balance; Aridity Index (AI); SPI; SPEI.

1. Introduction

In recent decades, aridification has been recognized as one of the key manifestations of contemporary climate change, as it reflects not only potential reductions in precipitation but also a deeper shift in regional water availability driven by rising air temperatures, increased atmospheric evaporative demand, and changes in soil moisture and landscape water balance. The IPCC report emphasizes that aridity can be assessed using various groups of indicators—from the ratio of precipitation to evaporation to characteristics of surface and groundwater, as well as soil moisture [1]. Contemporary global studies also show that increasing aridity in many regions is more often linked not to absolute declines in precipitation, but to a faster rise in potential evapotranspiration and temperature-driven "atmospheric demand" for water [2, 3].

This is why no single, universal indicator of aridification exists in the literature. In global and regional climate studies, the most commonly used metric remains the UNEP aridity index: AI = P/PET, where P is precipitation and PET is potential evapotranspiration. This approach forms the basis of major international aridity databases, allowing consistent comparisons of regions by climatic dryness. Yet AI alone fails to capture the full temporal pattern of aridity—particularly in transitional zones where annual precipitation may not drop sharply, but the warm season still becomes significantly more water-deficient. For this reason, recent research increasingly defines aridification as a combination of changes in temperature, PET, climatic water balance (WB), and the frequency of dry episodes.

Among drought indicators, the Standardized Precipitation Index (SPI) is most widely used. The WMO even recommends it as the go-to tool for tracking meteorological drought. But SPI looks only at precipitation, ignoring rising evaporation, which matters a lot in today's warming climate [4].

To fill that gap, researchers developed the Standardized Precipitation Evapotranspiration Index (SPEI), which builds on the climatic water balance (P − PET). As shown in [5], SPEI picks up on global warming because it factors in how higher temperatures increase the atmosphere's demand for water. That's why SPEI has become one of the most reliable indices for measuring aridification in regions where rising temperatures are now a key driver of drying – on their own, apart from changes in rainfall.

Aridification is becoming an increasingly urgent issue for Belarus. The region has traditionally been classified as having adequate – and in many areas, even excess – moisture. But recent research by Belarusian scientists shows that, amid overall warming, the seasonal pattern of water availability is shifting dramatically. Study [6] outlines the spatiotemporal trends of climate change in Belarus, while study [7] directly connects signs of aridification to declining effective precipitation and ecosystem responses. This means that for Belarus, aridification is not simply a matter of general drying – but rather a gradual intensification of water deficit during the warm season, a worsening balance between precipitation and evaporation, and a shifting of traditional moisture boundaries.

Thus, in Belarus, detecting signs of aridization shouldn't rely just on total rainfall amounts – it's far more meaningful to track a suite of indicators that reflect rising temperatures, increased potential evaporation, a deteriorating water balance, and more frequent dry anomalies. This approach is especially critical for long-term spatiotemporal analyses, as it helps determine how synchronously aridization processes are unfolding across different regions, where they are most pronounced, and which components of the climate system are driving the current water deficit.

2. Methods and Materials

The goal of this study is to identify the space-time patterns of climate aridization in Belarus over the period from 1950 to 2023, using data from 36 meteorological stations. We looked at changes in air temperature, precipitation, potential evapotranspiration, the climatic water balance, and standardized moisture indices to assess changes in dryness conditions.

Both annual and seasonal metrics were examined. Within-year variability was analysed not only by calendar seasons (spring, summer, autumn, winter) but also by two extended half-year periods - warm and cold – given that the warm season is when rising temperatures most strongly intensify atmospheric evaporative demand and exacerbate water deficits.

To better understand how these changes unfolded over time, we split the period into two key phases: the “pre-warming” era (1950 – 1988) and the “warming era” (1989 – 2023).

For additional climatic context and comparison, we also reference the standard 30-year climatological normals: 1961–1990 and 1991–2020.

3. Results and Discussions

Analysis of data from 36 meteorological stations across Belarus reveals a consistent warming trend between the reference periods 1950 – 1988 and 1989 – 2023. The mean annual air temperature increased by 1.61°C, while the warm season experienced a slightly lower rise of 1.16°C. At the same time, annual precipitation increased by 47.9 mm, with a mere 13.1 mm of that increase occurring during the warm season (Table 1). This suggests that while temperatures have risen sharply, precipitation has changed far more modestly.

The long-term trend in annual temperature across Belarus from 1950 to 2023 is 0.36°C per decade. But during the modern warming phase (1989 – 2023), the warming rate in the warm season accelerated to 0.50°C per decade. Importantly, this warming trend is statistically significant at all 36 stations, confirming that the observed climate shift is not localized or stochastic, but rather a regionally coherent and persistent phenomenon.

Table 1. Mean climate values across representative periods

Indicator	1950-1988	1989-2023	Absolute change	Change, %
Annual temperature, °C	5.79	7.39	1.61	27.8

Annual precipitation, mm	608.1	655.9	47.9	7.9
Annual PET, mm	577.8	614.1	36.2	6.3
Annual P−PET, mm	30.3	41.9	11.6	38.4
Annual AI	1.06	1.07	0.02	1.5
Warm-season temperature, °C	13.49	14.65	1.16	8.6
Warm-season precipitation, mm	373.9	387.0	13.1	3.5
Warm-season PET, mm	541.5	567.3	25.8	4.8
Warm-season P−PET, mm	-167.6	-180.3	-12.7	7.6
Warm-season AI	0.69	0.68	-0.01	-1.2

Figures 1 and 2 depict the temporal trends in air temperature and precipitation over the period 1950 – 2023. The most robust and persistent indicator of climatic aridization in Belarus is the marked and sustained increase in temperature. However, rising temperatures alone do not automatically imply drying. To demonstrate true aridization, it is essential to show that atmospheric evaporative demand and the water balance are deteriorating at a faster rate than precipitation increases.

Figure 1. Annual mean temperature in 1950 – 2023.

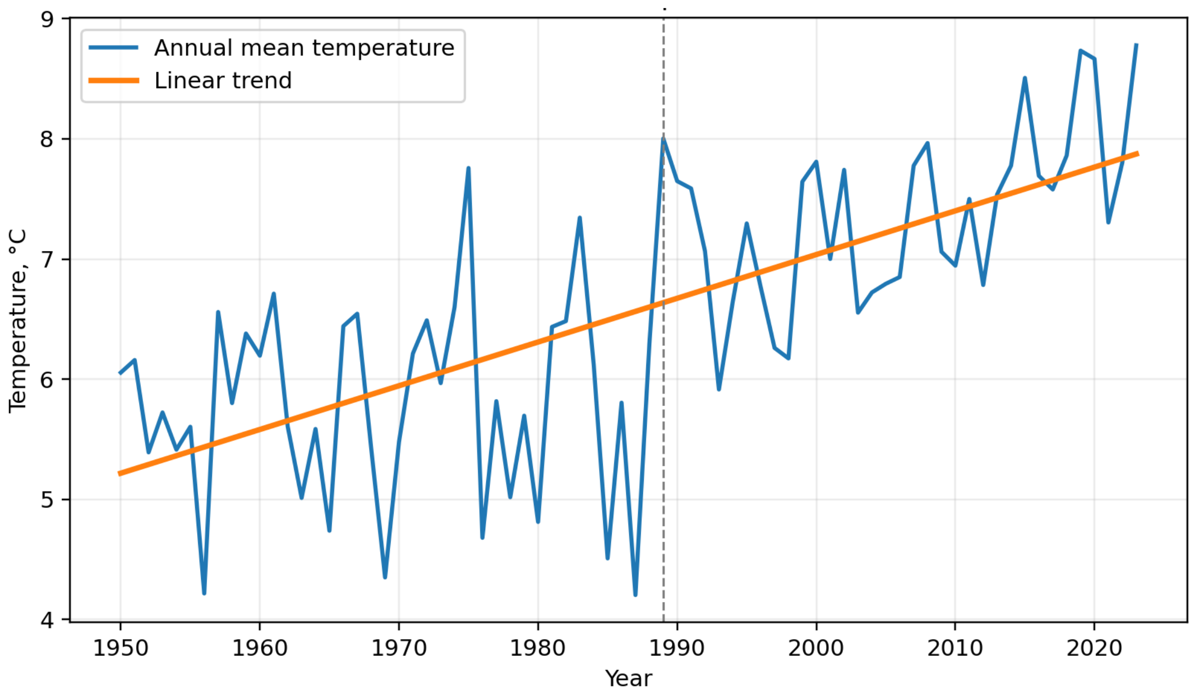
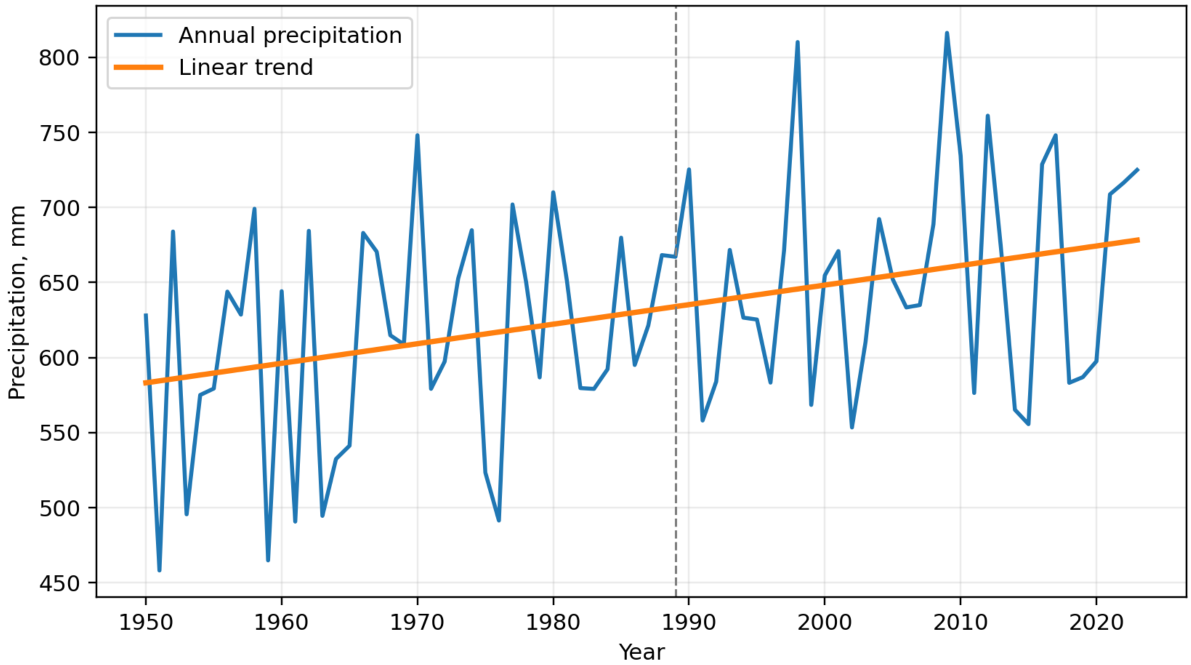


Figure 2. Annual precipitation in 1950 – 2023.



Thornthwaite-based PET estimates reveal a widespread and consistent increase in atmospheric evaporative demand across the study region. Between the periods 1950 – 1988 and 1989 – 2023, annual PET rose by an average of 36.2 mm, while warm-season PET increased by 25.8 mm. Concurrently, the warm-season water balance deteriorated by 12.7 mm, and the warm-season aridity index decreased by 0.009.

Between 1989 and 2023, the long-term trend in potential evapotranspiration (PET) during the warm season averaged 11.3 mm per decade across Belarus, while the corresponding warm-season water balance declined at a rate of –15.5 mm per decade. A statistically significant increase in PET was observed at all 36 monitoring stations, whereas a significant deterioration in water balance occurred at only five. This pattern indicates that aridification in Belarus is driven primarily by a rapid rise in PET – linked to warming

Figures 3 and 4 illustrate the temporal trends in precipitation, PET, and the climatic water balance during the warm season.

Figure 5 presents the intra-annual distribution of mean monthly air temperatures and total precipitation for two periods: 1950 – 1988 and 1989 – 2023. A significant increase in air temperature is evident during winter and in July – August. Notably, precipitation has also increased during winter months, as well as in July and October.

Table 2 summarizes the key climatic indicators for three 30-year reference periods (1961 – 1990, 1991 – 2020, and the most recent decade) aligned with the standard climatological normals used by the World Meteorological Organization.

Figure 3. Warm-season precipitation and PET (April - September)

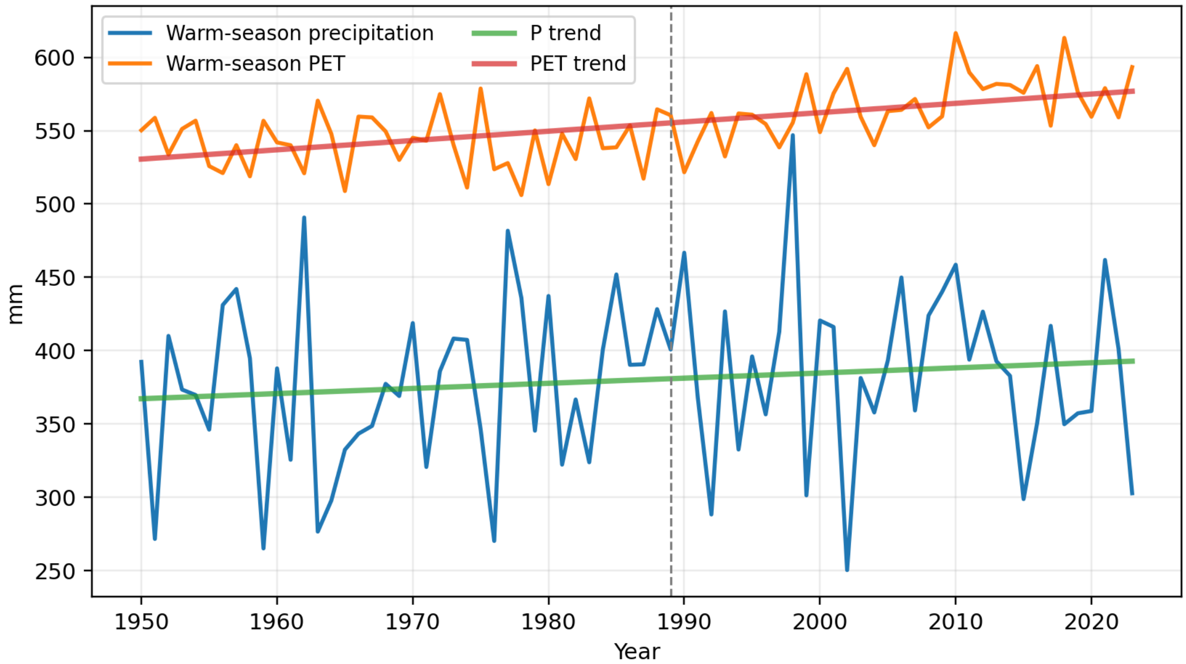


Figure 4. Warm-season water balance (April - September)

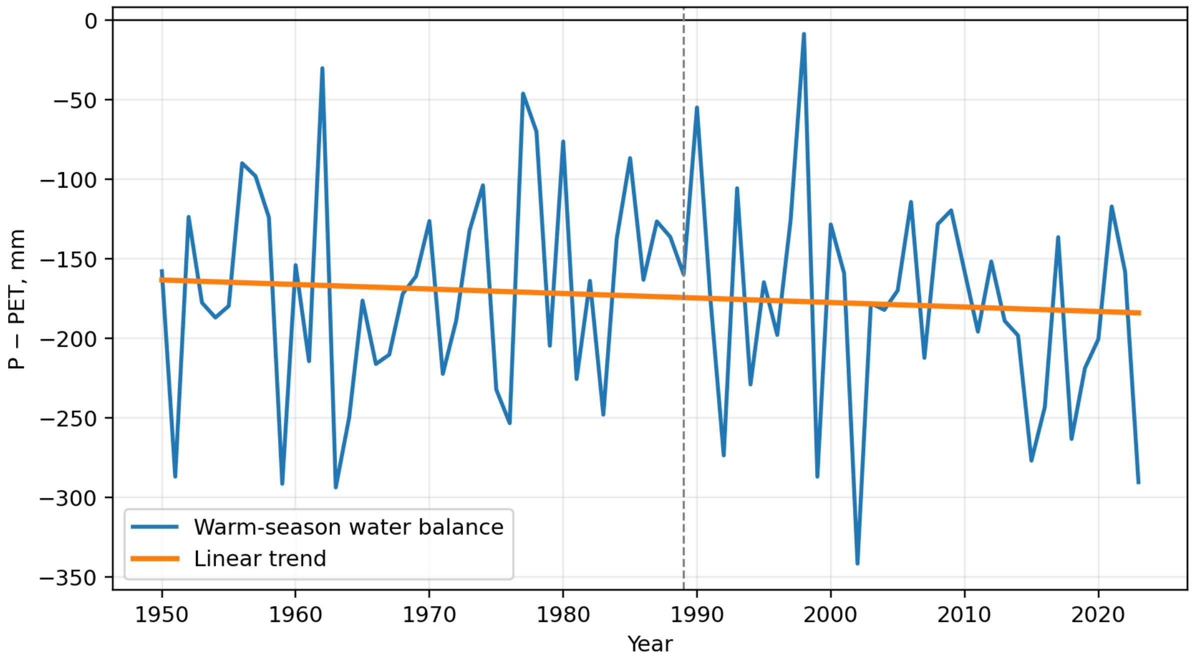


Figure 5. Monthly mean air temperature and precipitation in 1950 – 1988 and 1989 – 2023.

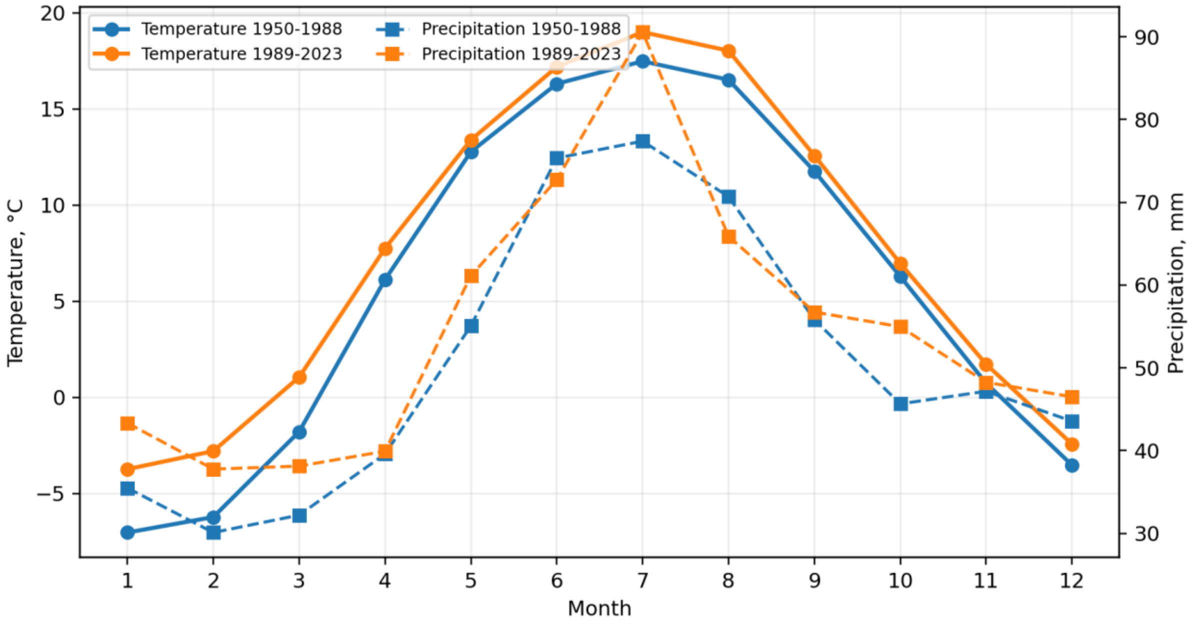


Table 2. Climate normals and contemporary trends in mean conditions across 36 weather stations

Period	Annual temperature, °C	Annual precipitation, mm	Annual PET, mm	Annual P−PET, mm	Annual AI	Warm-season temperature, °C	Warm-season precipitation, mm	Warm-season PET, mm	Warm-season P−PET, mm	Warm-season AI
1961 - 1990	5.93	620.2	580.8	39.5	1.07	13.51	378.8	541.5	-162.7	0.70
1991 - 2020	7.31	647.2	613.4	33.8	1.06	14.67	383.7	568.1	-184.4	0.68

2011 - 2023	7.89	655.7	629.8	25.8	1.00	15.19	376.5	579.6	-203.0	0.65

Based on these findings, a critical insight emerges: climate aridization in Belarus is not primarily characterized by a simple decline in annual precipitation, but rather by a growing moisture deficit during the warm season – driven by a faster rate of increase in potential evapotranspiration (PET) relative to precipitation. Even when annual precipitation rises slightly, the warm period becomes increasingly water-deficient.

Spatial analysis reveals that annual warming extends across the entire territory of Belarus; however, the response in terms of moisture availability is not uniform. In the north-eastern, central, and parts of the south-eastern regions of Belarus, there is a notable combination of significant temperature increases, marked growth in PET, and the most pronounced deterioration of the warm-season water balance. Conversely, in the western and southwestern regions, aridification is also evident, but in certain areas, this effect is partially mitigated by greater interannual variability in precipitation. The results for individual weather stations are presented in Table 3.

Table 3. Changes in key indicators at representative weather stations

Station	**ΔT warm, °C**	**ΔP warm, mm**	**ΔPET warm, mm**	**ΔWB warm, mm**	**ΔAI warm**
Brest	1.31	12.4	29.6	-17.2	-0.01
Minsk	1.30	23.5	29.2	-5.7	0.00
Gomel	1.45	28.2	34.4	-6.1	0.01
Vitebsk	1.52	22.6	34.6	-12.0	-0.00
Pinsk	1.49	29.8	34.0	-4.2	0.02
Orsha	1.15	-0.1	25.6	-25.7	-0.03

At representative weather stations, it is evident that an increase in temperatures during the warm season by 1 to 1.5 °C is often not accompanied by a proportional rise in precipitation. Consequently, even at stations experiencing neutral or slightly positive changes in warm-season precipitation, the rise in PET results in a decline in the water balance. This supports the notion that aridification in Belarus is emerging as a comprehensive thermodynamic balance process.

The comparison between the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) is crucial for differentiating the precipitation signal from the temperature-evaporation signal. While SPI primarily captures anomalies in precipitation, SPEI incorporates both precipitation and potential evapotranspiration through the P − PET calculation. As a result, SPEI is more responsive to aridification in the context of climate warming (Figure 6).

Analysis of the selected weather stations indicates that periods of significant negative SPEI values are predominantly concentrated in recent decades, particularly in the central and eastern regions of Belarus. Notably, interannual variability remains high, which is characteristic of areas undergoing transitional moisture conditions. Overall, the index analysis confirms that the climatic signal of aridification is more pronounced in the balance indicators and SPEI than in precipitation alone.

Table 4 presents the trends in the changes of the examined characteristics.

Figure 6. Changes in SPEI-12 at certain stations in September

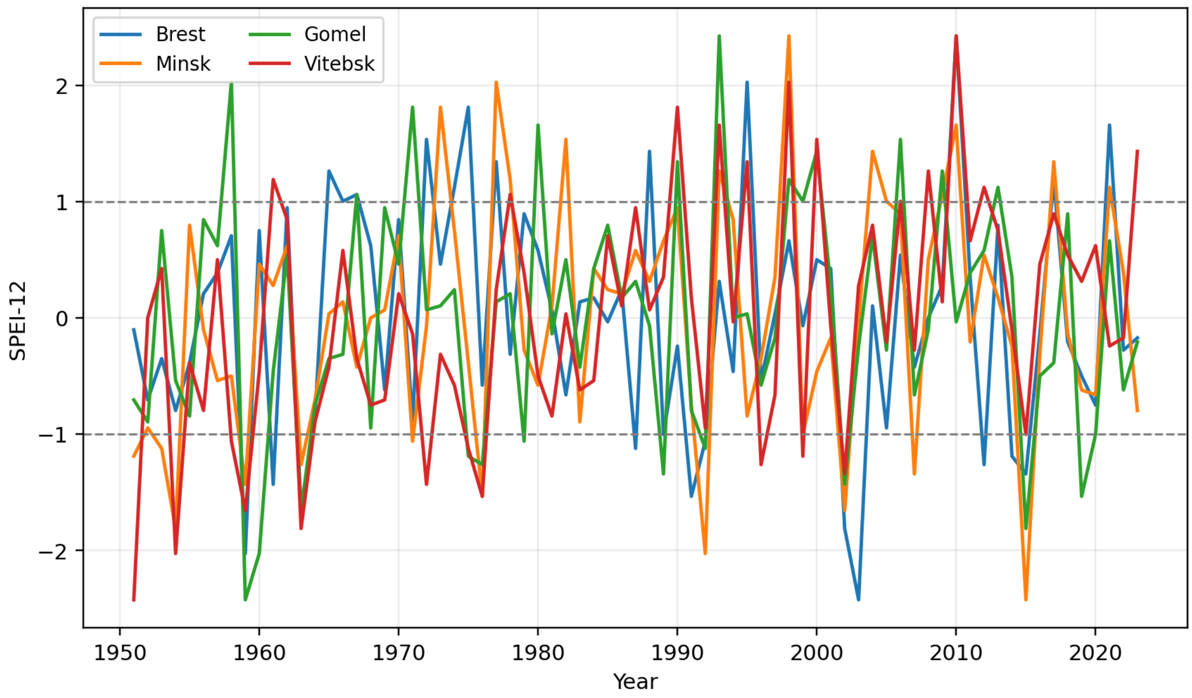


Table 4. Trends in changes of key indicators based on mean values for Belarus (per 10 years)

Indicator	Trend 1950-2023	Trend 1989-2023
T annual, °C	0.36	0.36
P annual, mm	13.0	10.3
PET annual, mm	8.7	13.4

WB annual, mm	4.3	-3.1
AI annual	0.007	-0.006
T warm, °C	0.28	0.50
P warm, mm	3.5	-4.2
PET warm, mm	6.3	11.3
WB warm, mm	-2.8	-15.5
AI warm	-0.002	-0.021

A statistical projection based on observed trends from 1989 to 2023 suggests a continued intensification of aridification during the warm season in Belarus. By 2035, the mean warm-season temperature is projected to reach 16.09°C, with PET rising to 600.1 mm and the warm-season water balance declining to –225.4 mm. By 2050, these values are expected to increase further to 16.83°C, 617.1 mm, and 248.7 mm, respectively (Table 5).

Under the projected climate scenario, the warm-season aridity index is expected to decline from current levels of approximately 0.65 to 0.62 by 2035 and to 0.59 by 2050, signalling a transition toward a dry subhumid climate classification for Belarus. Crucially, while potential evapotranspiration continues to rise steadily, warm-season precipitation totals are not projected to increase – and may even decline slightly – across the country. Consequently, the primary driver of increasing aridity is the ongoing thermal intensification of atmospheric evaporative demand.

Table 5. Projected mean values for Belarus for the years 2035 and 2050.

Indicator	2035	2050
T annual, °C	8.43	8.97
P annual, mm	685.7	701.1
PET annual, mm	652.8	672.8
WB annual, mm	32.94	28.32
AI annual	1.050	1.040
T warm, °C	16.09	16.83
P warm, mm	374.7	368.3
PET warm, mm	600.1	617.1
WB warm, mm	-225.4	-248.7
AI warm	0.620	0.590

Table 6 identifies the monitoring stations that exhibit the most robust and consistent signals of aridification over the projection periods.

Table 6. Stations with the strongest projected aridification trends

Station	AI warm 2035	AI warm 2050	WB warm 2035, mm	WB warm 2050, mm	T warm 2050, °C	PET warm 2050, mm	Composite score
Senno	0.572	0.508	-255.4	-296.7	16.72	621.9	1.099
Lepel	0.470	0.359	-310.9	-378.6	16.23	612.2	1.065
Vitebsk	0.625	0.579	-223.6	-254.1	16.70	623.5	0.832
Zhlobin	0.560	0.520	-273.6	-304.2	17.83	642.6	0.722
Gomel	0.558	0.516	-277.4	-308.9	18.44	658.5	0.679
Marina Gorka	0.633	0.625	-221.8	-232.7	17.03	621.0	0.648
Lida	0.606	0.562	-233.2	-262.3	16.75	613.2	0.506
Pinsk	0.601	0.581	-247.3	-266.1	18.10	641.6	0.500
Volozhin	0.648	0.616	-208.0	-230.2	16.51	609.9	0.494
Orsha	0.601	0.547	-233.9	-269.3	16.54	614.0	0.456

By mid-century, the strongest projected signals of aridification are evident at the stations of Senno, Lepel, Vitebsk, Zhlobin, Gomel, and Marina Gorka. These sites exhibit a converging pattern of marked temperature increases, accelerated rises in potential evapotranspiration (PET), substantially negative warm-season water balances, and consistently low projected Aridity Index (AI) values.

Conclusion

The analysis indicates that contemporary aridization in Belarus is predominantly driven by shifts in the water balance, with temperature rise serving as the dominant forcing factor. Between 1950 and 2023, sustained increases in air temperature have been observed across the entire country, yet concurrent increases in precipitation have been insufficient to offset the pronounced rise in potential evapotranspiration, particularly during the warm season.

The comparison of the periods 1950 – 1988 and 1989 – 2023 reveals that the annual mean temperature across 36 meteorological stations in Belarus increased by 1.61 °C, with the warm-season temperature rising by 1.16 °C. Although annual precipitation increased by 47.9 mm, the corresponding increase during the warm season was modest at just 13.1 mm. Meanwhile, potential evapotranspiration (PET) during the warm season rose by 25.8 mm, leading to a net decline in the climatic water balance of 12.7 mm.

The most robust indicators for detecting climatic aridization are potential evapotranspiration (PET), the precipitation–PET deficit (P−PET), the Aridity Index (AI), and the Standardized Precipitation Evapotranspiration Index (SPEI), as these metrics integrate both precipitation dynamics and temperature-driven increases in atmospheric evaporative demand. Spatially, the most significant declines in warm-season moisture availability are observed across north-eastern, central, and south-eastern Belarus.

Projections under future climate scenarios indicate a continued and accelerating trend toward aridization by mid-century. By 2050, warm-season temperatures are expected to reach 16.83 °C, PET to increase to 617.1 mm, and the climatic water balance to deteriorate to −248.7 mm. The warm-season Aridity Index is projected to fall to 0.59, indicating a transition from humid to subhumid climatic conditions.

These findings highlight the imperative for sustained, multi-indicator monitoring of aridization trends in Belarus and the urgent need to incorporate these projections into adaptive strategies for agriculture, land reclamation, and water resources management.

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