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REVISITING CLIMATE NORMALS: EVIDENCE OF A REGIME SHIFT, FOREST FIRE ACTIVITY AND IMPLICATIONS FOR FOREST RESOURCES IN SOUTHWESTERN BULGARIA

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ABSTRACT

The present study aims to assess whether the transition between the climate normals 1961–1990 and 1991–2020 reflects a statistically significant change in the climatic regime in Southwestern Bulgaria and to examine the relationship between this change and the climatic conditions associated with the occurrence of forest fires. The analysis is based on temperature and precipitation data from two meteorological stations with contrasting characteristics—Sandanski (lowland) and Musala (high-mountain)—for the period 1961–2024, as well as on forest fire data from the Sandanski region for the period 2000–2025. Trend analysis methods (Mann–Kendall and Sen's slope), the De Martonne aridity index, and change-point detection methods (CUSUM and Pettitt test) were applied. The results reveal a clear and statistically significant shift in the temperature regime around 1997 at both stations. For summer temperature, an earlier transition is observed in Sandanski, around 1989. The comparison between the climate normals 1961–1990 and 1991–2020 indicates an increase in mean annual temperature of approximately 0.8°C, with the most pronounced warming occurring during summer (+1.6°C). Precipitation exhibits weaker and spatially variable changes, with no statistically significant shift detected in summer precipitation. The De Martonne index shows elevation-dependent sensitivity, with a tendency toward drier conditions observed at Musala. The analysis of forest fires indicates a strong positive relationship between summer temperature and fire activity, while precipitation and aridity show a weaker influence. The results suggest that the contemporary climate normal reflects a real change in the climatic regime, which has direct implications for wildfire risk in the region. These findings are relevant not only for wildfire risk assessment, but also for the sustainable management of forest resources and the long-term security of wood raw material supply in climate-sensitive regions.

Keywords: *climate change; climate normals; De Martonne index; wildfire risk; forest resources; sustainable forest management*

INTRODUCTION

Climate change has led to significant alterations in temperature and precipitation patterns worldwide, with particularly pronounced effects observed in Europe and the Mediterranean region [1,2]. Numerous studies have reported increasing temperatures and changes in hydroclimatic conditions, which have implications for environmental processes and natural hazards, including forest fires. These changes are often associated with shifts in the frequency and intensity of extreme events, as well as modifications in seasonal climate regimes.

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Climate normals are widely used as reference baselines for describing average climatic conditions and for assessing departures from "normal" weather and climate. According to World Meteorological Organization (WMO) recommendations, they are calculated over consecutive 30-year periods, such as 1961–1990 and 1991–2020 [3]. The period 1961–1990 is retained as a fixed reference for long-term climate change assessment, while 1991–2020 represents the most recent standard normal. However, under ongoing climate change, the interpretation of climate normals becomes less straightforward. Climate normals are calculated retrospectively but are often used to represent present or near-future conditions, which implicitly assumes stationarity of the climate system. This assumption is increasingly violated, as long-term trends alter the statistical properties of climatic variables and reduce the representativeness of traditional climate normals [4]. Recent studies further argue that in a non-stationary climate, conventional 30-year normals may not adequately reflect current climatic conditions and can introduce biases in climate monitoring and interpretation [5, 6].

In a non-stationary climate, differences between successive climate normals may reflect more than a simple update of the reference period. They may indicate a real shift in the underlying climatic regime. This distinction is important because a change in the reference normal may either represent a gradual adjustment in mean conditions or correspond to a statistically detectable structural change in the time series. Therefore, comparing climate normals alone may obscure the timing and nature of climatic transitions if the internal structure of the data is not explicitly examined.

Recent research suggests that climate change does not always manifest as gradual trends, but may involve abrupt shifts or regime changes in climatic time series. Various statistical approaches, including cumulative sum (CUSUM) analysis and change-point detection methods such as the Pettitt test, have been applied to identify such discontinuities. However, methodological limitations must be considered, as ignoring underlying trends or autocorrelation may lead to spurious identification of change points [7, 8]. At the same time, regional studies have demonstrated that such regime shifts can be detected consistently across different locations. For example, a study in Belgrade (Serbia) identified a statistically significant shift in annual temperature around 1997, highlighting the presence of coherent regional signals in Southeastern Europe [9]. Similar temperature regime shifts have also been identified elsewhere in Southeastern Europe. Radivojević et al. [10] reported statistically significant temperature regime shifts in Eastern Serbia (Sokobanja Basin), with change points detected in 1991 and

1997 depending on the homogeneity test applied. In the Dobrogea region of southeastern Romania, Maftei and Bărbulescu [11] identified coherent temperature shifts across ten meteorological stations, with most break points occurring around 1997–1998 and a marked increase in mean annual temperature after 1997. More recently, Bărbulescu and Postolache [12] reported that the majority of detected breakpoints in regional temperature series also occurred during 1997–1998. The occurrence of comparable change points in Eastern Serbia and southeastern Romania suggests that the late-1990s transition may reflect a broader regional climatic signal in Southeastern Europe rather than an isolated local phenomenon.

Additional studies in the Balkans and nearby regions also report strong warming trends accompanied by weaker and less consistent precipitation changes, supporting the notion that temperature is the dominant signal of recent climatic change [13, 14].

The practical relevance of such regime shifts is particularly evident in relation to wildfire risk. Fire activity is strongly influenced by climatic conditions, especially summer temperature, drought, and moisture availability. In the European Mediterranean region, warmer and drier summer conditions have been associated with increased fire danger, larger burned areas, and more severe fire seasons [1, 15]. Previous studies show that summer temperature and drought are key drivers of interannual fire variability, although fire regimes are also shaped by non-climatic factors such as land management, fuel availability and human ignition [1].

Southwestern Bulgaria provides a suitable case study for examining these relationships due to its Mediterranean climatic influence, pronounced seasonal variability and recurrent wildfire activity. The Sandanski station (207 m a.s.l.) represents the lowland part of the region and is characterized by warm and relatively dry summer conditions, while the Musala station (2925 m a.s.l.) represents the high-mountain environment with markedly different climatic conditions. Musala was selected as a high-altitude reference station with minimal direct anthropogenic influence, allowing the comparison of climate variability across contrasting elevation zones. The use of these two stations makes it possible to distinguish between large-scale climatic signals and local environmental variability.

In 2024, Bulgaria experienced one of the most severe wildfire seasons in recent years, with a total burned area exceeding 45,000 ha according to the European Commission Joint Research Centre [16]. This highlights the practical importance of assessing the climatic conditions associated with fire occurrence and burned area, particularly under changing climatic conditions. Despite the growing body of literature on climate normals, climate change and wildfire risk, limited attention has been paid to whether the transition between 1961–1990 and 1991–

2020 corresponds to a statistically detectable climatic regime shift at the regional scale, and whether such a shift is linked to climatic conditions associated with forest fire activity. This reveals a gap in current research, where climatic changes are often described and quantified, whereas their links to climate-related environmental impacts are less frequently examined. In the present study, this gap is addressed through the analysis of forest fire activity.

From the perspective of forest-based industries, climate-driven wildfire risk has direct implications for the availability, quality and long-term stability of wood resources. Increased fire activity may affect standing timber volume, wood quality, forest regeneration, sanitary harvesting needs and the predictability of raw material supply. Therefore, linking climate regime shifts with wildfire activity is relevant not only for environmental risk assessment, but also for forest resource planning and the sustainable development of the wood-processing sector.

The present study addresses this gap by examining long-term temperature and precipitation series from Sandanski and Musala for the period 1961–2024, together with forest fire data from the Sandanski region for 2000–2025. The objectives are: (i) to assess the differences between the 1961–1990 and 1991–2020 climate normals; (ii) to determine whether these differences correspond to statistically significant regime shifts; (iii) to compare the response of a lowland and a high-mountain station; (iv) to evaluate the relationship between contemporary climatic conditions and forest fire activity in the Sandanski region; and (v) to discuss the implications of the detected climatic changes and wildfire-related signals for forest resource management and wood raw material supply in Southwestern Bulgaria.

1 MATERIALS AND METHODS

This study is based on long-term climatic data from two meteorological stations located in Southwestern Bulgaria: Sandanski, representing a lowland environment with warm and relatively dry climatic conditions (41.57°N, 23.28°E; 207 m a.s.l.), and Musala, a high-mountain station characterized by low temperatures and distinct precipitation regimes (42.18°N, 23.59°E; 2925 m a.s.l.) (Figure 1).

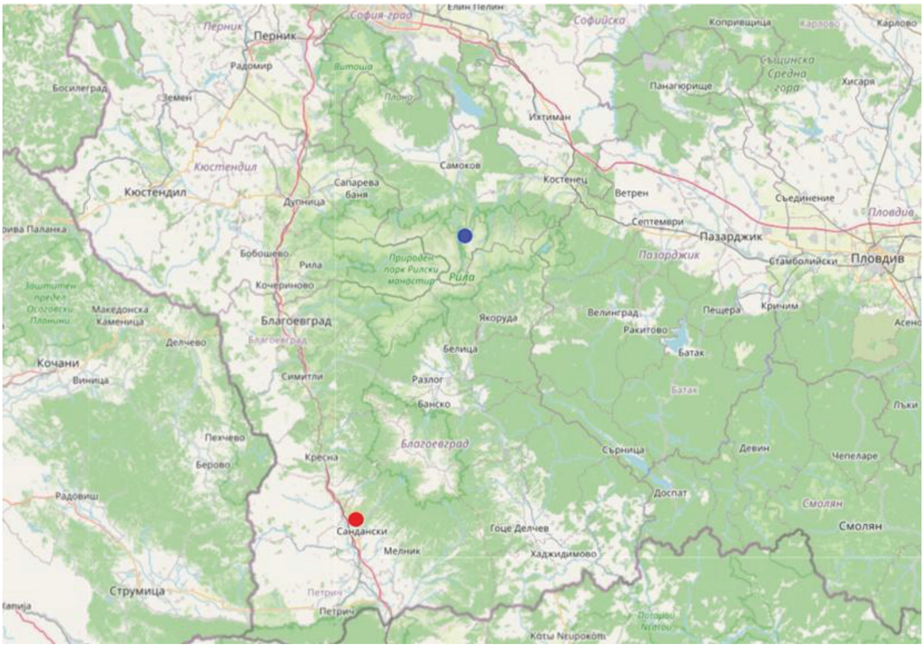


Figure 1. Location of the Sandanski (red dot) and Musala (blue dot) meteorological stations in Southwestern Bulgaria. Source: © OpenStreetMap contributors.

According to the climatic regionalization of Bulgaria by Sabev and Stanev [17], Sandanski falls within regions influenced by Mediterranean climatic conditions, whereas Musala represents a high-mountain climatic environment. The use of two stations with contrasting geographical characteristics allows distinguishing between large-scale climatic signals and local variability.

Monthly temperature and precipitation data were used for the period 1961–2024, ensuring comparability between the two stations. For Sandanski, the analysis extends to 2025 where available. Forest fire data, including the annual number of fires and burned area, were analyzed for the period 2000–2025. Seasonal (summer) and annual aggregates were calculated from the monthly data.

Climate normals were calculated for the standard 30-year periods 1961–1990 and 1991–2020, following the recommendations of the World Meteorological Organization [3]. Monthly, seasonal and annual averages were derived, and absolute differences between the two periods were computed to assess recent climatic changes. While such comparisons provide information on shifts in average conditions, they do not indicate the timing or statistical significance of possible structural changes in the time series.

To evaluate long-term tendencies, trend analysis was performed using the non-parametric Mann–Kendall test [18,19] and Sen's slope estimator [20]. These methods are widely used in climatology due to their robustness to non-normality and outliers. Prior to the application of the Mann–Kendall test, lag-1 autocorrelation was examined as a diagnostic measure, as serial correlation can affect the significance of trend detection [6].

Since gradual trends do not necessarily capture abrupt changes in the mean state, change-point analysis was applied to detect possible regime shifts in the climatic series. The cumulative sum (CUSUM) method [21] was used to identify deviations from the long-term mean, calculated as:

$$S_t = \sum_{i=1}^{t} (x_i - \overline{x}) \quad (1)$$

where x_i represents the observed value and $\overline{x}$ the mean of the series.

The CUSUM curve provides a visual indication of shifts in the mean level. To complement this, the Pettitt test [22] was applied as a non-parametric method for detecting a statistically significant single change point in the time series. The combined use of CUSUM and Pettitt allows both visual and statistical identification of potential regime shifts, which may not be fully captured by trend analysis alone [6].

Climatic conditions were further characterized using the De Martonne aridity index, defined as:

$$IDM = \frac{P}{T + 10} \quad (2)$$

where P is precipitation and T is temperature. This index integrates thermal and moisture conditions and is widely used as an indicator of climatic aridity [23]. Lower values indicate drier conditions. Annual and summer values were calculated to assess seasonal differences in moisture availability.

For seasonal analysis, the seasonal form of the De Martonne index was applied:

$$I_{(DM,S)} = (4P_S)/\left(T_{(s)} + 10\right) \quad (3)$$

where *Ps* is the total seasonal precipitation (mm) and *T(s)* is the mean seasonal temperature (°C) [24, 25]. Seasonal precipitation was calculated as the sum of precipitation for the three months included in each season, while seasonal temperature was calculated as the arithmetic mean for the same period. The multiplier 4 allows comparability between seasonal and annual index values. Lower values indicate drier climatic conditions. The seasonal form of the index has been widely applied in recent climatological studies for assessing intra-annual climate variability and hydrothermal conditions.

Seasonal averages were calculated according to standard climatological definitions: winter (December–February), spring (March–May), summer (June–August) and autumn (September–November). Winter averages were assigned to the year corresponding to January and February. Forest fire data were analyzed for the Sandanski region, focusing on two indicators: annual number of fires (occurrence) and burned area (severity). Since the fire record (2000–2025) falls entirely within the post-break climatic regime identified in the temperature series, the fire analysis was interpreted as an assessment of variability under contemporary climatic conditions rather than as a test of long-term causality.

The relationship between climatic variables and fire activity was evaluated using Spearman's rank correlation coefficient [26]. This method was selected due to the non-normal distribution and high variability of fire data, including the presence of extreme values. The analysis was conducted between fire indicators and summer climatic variables (temperature, precipitation and aridity index). The results are interpreted as statistical associations rather than causal relationships.

2 RESULTS AND DISCUSSION

2.1 Results

2.1.1 Climate normals and regime shift

The comparison between the 1961–1990 and 1991–2020 climate normals reveals a clear and consistent warming signal at both meteorological stations (Table 1). In Sandanski, mean annual temperature increased from 13.7°C to 14.5°C, corresponding to a difference of +0.8°C. At Musala, mean annual temperature increased from −3.1°C to −2.2°C, or +0.9°C. The warming signal is therefore evident both in the lowland and high-mountain environments.

Table 1. Temperature differences between climate normals and Pettitt change points.

Station	Variable	1961–1990	1991–2020	Difference	Pettitt year	p-value
Sandanski	Annual temperature	13.7°C	14.5°C	+0.8°C	1997	1.03e−07
Musala	Annual temperature	−3.1°C	−2.2°C	+0.9°C	1997	1.15e−07
Sandanski	Summer temperature	23.3°C	25.0°C	+1.7°C	1989	3.34e−09
Musala	Summer temperature	3.8°C	5.3°C	+1.5°C	1997	9.57e−09

The seasonal structure of the warming shows relatively similar increases across winter, spring and autumn, while summer exhibits a clearly stronger warming signal (Table 2). The seasonal structure of the warming further confirms the dominant role of summer temperature, which shows the largest increase, while the other seasons exhibit more moderate and comparable changes.

Table 2. Seasonal temperature differences between climate normals (1991–2020 vs 1961–1990). The strongest increases are shown in bold.

Season	Sandanski, °C	Musala, °C
Winter	+0.7	+0.7
Spring	+0.5	+0.5
Summer	**+1.7**	**+1.5**
Autumn	+0.5	+0.7

The results indicate that the temperature change between the two climate normals is not seasonally uniform, but is strongly amplified during the summer season.

This shift is clearly visible in the temperature time series (Figure 2), where a transition from predominantly lower to persistently higher temperature values can be observed after the late 1990s.

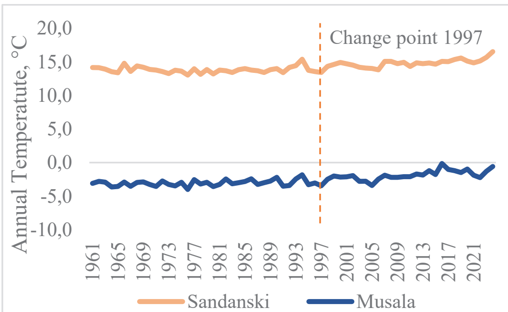
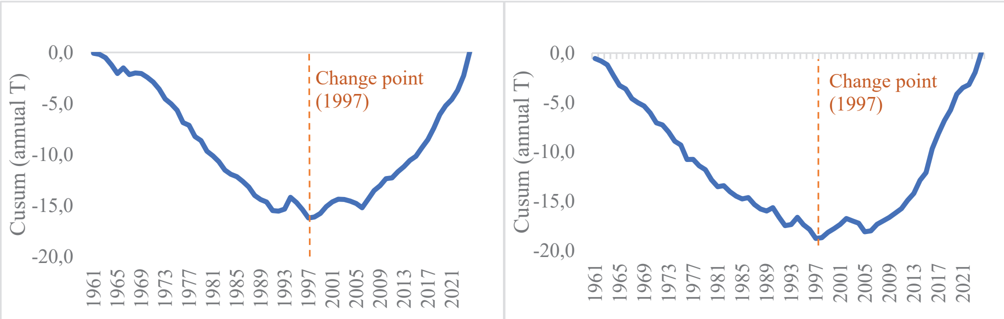


Figure 2. Annual temperature time series for Sandanski and Musala (1961–2024). The vertical dashed line indicates the change point around 1997 identified by the Pettitt test.

CUSUM analysis shows a marked change in the temperature regime at both stations. For annual temperature, the cumulative curves are dominated by negative deviations during the earlier part of the record, followed by a persistent upward phase after the late 1990s. This pattern indicates a transition from a cooler to a warmer mean state. This behavior is also reflected in the CUSUM curves (Figure 3).

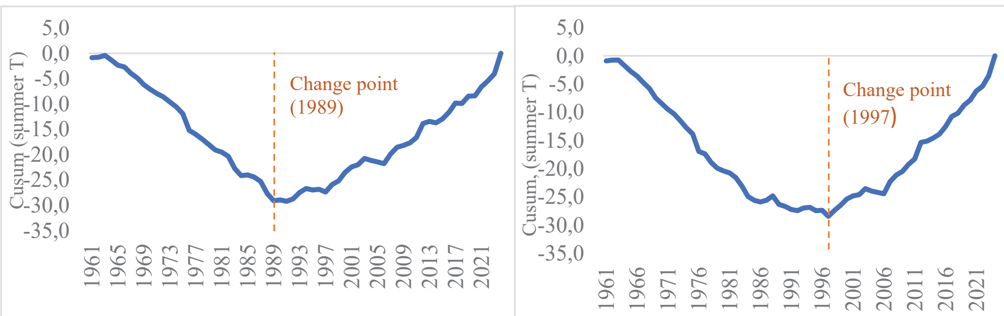


(**a**) Sandanski - Annual temperature (CUSUM) (**b**) Musala - Annual temperature (CUSUM)

Figure 3. CUSUM curves for annual temperature for Sandanski (**a**) and Musala (**b**)

The Pettitt test confirms that this transition is statistically significant. For annual temperature, the change point is detected in 1997 at both Sandanski and Musala, with very low p-values ($p < 0.001$). The agreement between the two stations indicates a synchronous shift in the annual temperature regime across contrasting elevation zones, represented by the lowland Sandanski station and the high-mountain Musala station.

For summer temperature, the timing of the shift differs between the two stations. In Sandanski, the Pettitt test identifies a change point in 1989, while at Musala the change point is detected in 1997. The earlier transition in Sandanski is evident in the summer temperature series (Figure 4).



(**a**) Sandanski - Summer temperature (CUSUM) (**b**) Musala - Summer temperature (CUSUM)

Figure 4. CUSUM curves for summer temperature for Sandanski (a) and Musala (b). Summer temperature time series showing earlier shift in Sandanski

Trend analysis further supports the warming signal. For annual temperature, the Mann–Kendall test indicates statistically significant increasing trends at both stations: Sandanski ($S = 1010$, $Z = 5.85$, $p = 5.04 \times 10^{-9}$) and Musala ($S = 1126$, $Z = 6.52$, $p = 7.13 \times 10^{-11}$). Sen's slope estimates are 0.0275°C year^{-1} for Sandanski and 0.0333°C year^{-1} for Musala, corresponding to approximately 0.28°C and 0.33°C per decade, respectively. Trend analysis indicates no statistically significant long-term trends in the De Martonne index at either station. In Sandanski, annual IDM shows a non-significant tendency ($S = 74$, $Z = 0.42$, $p = 0.672$), while summer IDM exhibits virtually no trend ($S = -4$, $Z = -0.02$, $p = 0.986$). At Musala, both annual IDM ($S = 74$, $Z = 0.42$, $p = 0.672$) and summer IDM ($S = 140$, $Z = 0.81$, $p = 0.421$) also show non-significant trends. Sen's slope values are close to zero in all cases, indicating the absence of a robust gradual change in aridity.

These results suggest that aridity changes are not expressed as a consistent long-term trend. However, Pettitt's test identifies a statistically significant change point in annual IDM at Musala, indicating that the observed change in high-mountain moisture conditions is better described as a regime shift rather than as a gradual trend.

In contrast, temperature results confirm the presence of a robust long-term warming trend, while the Pettitt test identifies the timing of the transition between climatic regimes. Overall, the temperature results show three consistent features: a clear increase between the two climate normals, a statistically significant regime shift, and a pronounced summer amplification of warming.

2.1.2 Precipitation variability

Precipitation changes between the two climate normals are weaker, less coherent and more spatially variable than temperature changes (Table 3). In Sandanski, mean annual precipitation increased slightly from 482.4 mm in 1961–1990 to 506.9 mm in 1991–2020, corresponding to an increase of +24.5 mm. Seasonal changes are modest, with the largest increase observed in autumn (+16.1 mm), while summer precipitation increased only slightly (+5.9 mm). At Musala, the pattern is different. Mean annual precipitation decreased from 927.0 mm to 831.0 mm, corresponding to a reduction of −96 mm. This decrease is mainly associated with a strong reduction in winter precipitation (−72.7 mm), whereas summer precipitation shows a slight increase (+14.6 mm).

Table 3. Precipitation changes between climate normals and Pettitt change points.

Station	Variable	Difference between normals	Pettitt year	p-value	Interpretation
Sandanski	Annual precipitation	+24.4 mm	2000	0.0436	Statistically significant
Musala	Annual precipitation	−96.4 mm	1975	0.0376	Statistically significant
Sandanski	Summer precipitation	+5.9 mm	1993	0.9248	Not significant

Musala	Summer precipitation	+14.6 mm	1984	0.3593	Not significant

CUSUM analysis indicates substantial interannual and multidecadal variability in precipitation, but without a consistent shift comparable to that observed for temperature. Pettitt's test identifies statistically significant change points in annual precipitation at both stations.

In contrast, summer precipitation does not show a statistically significant change point at either station. This is a key result, as the strongest warming is detected in summer, whereas summer precipitation does not exhibit a corresponding structural shift.

These results suggest that temperature changes represent the most pronounced component of the summer climate signal, whereas no statistically significant structural shift is detected in summer precipitation.

Trend analysis confirms the weaker and less consistent character of precipitation changes. For annual precipitation in Sandanski, the Mann–Kendall test indicates a non-significant increasing trend ($S = 194$, $Z = 1.12$, $p = 0.263$), with Sen's slope estimated at +0.91 mm $year^{-1}$. In contrast, Musala shows a non-significant decreasing trend ($S = -292$, $Z = -1.69$, $p = 0.092$), with Sen's slope estimated at −2.29 mm $year^{-1}$.

These opposite and statistically non-significant tendencies highlight the absence of a consistent precipitation signal across the two stations.

2.1.3 Changes in aridity based on the De Martonne index

The De Martonne aridity index shows contrasting behavior between Sandanski and Musala (Table 4). In Sandanski, the index remains generally stable between the two climate normals. Annual IDM increases only slightly from 20 to 21, while summer IDM remains unchanged. The largest seasonal difference is observed in autumn (+2), whereas winter shows a slight decrease (−2).

At Musala, the changes are more pronounced. Annual IDM decreases from 69 to 58, corresponding to a reduction of −11 units. The largest decrease occurs in winter (−84), while spring and autumn also show reductions (−12 and −4, respectively).

These results indicate that the decrease in annual IDM at Musala is mainly associated with changes during the cold season, particularly in winter.

Table 4. Seasonal and annual De Martonne index differences between climate normals.

Station	Variable	1961–1990	1991–2020	Difference
Sandanski	Spring IDM	18	18	0
Sandanski	Summer IDM	13	13	0

Station	Variable	1961–1990	1991–2020	Difference
Sandanski	Autumn IDM	20	22	2
Sandanski	Winter IDM	38	37	-2
Sandanski	Annual IDM	20	21	0
Musala	Spring IDM	98	86	-12
Musala	Summer IDM	37	37	0
Musala	Autumn IDM	40	36	-4
Musala	Winter IDM	243	159	-85
Musala	Annual IDM	69	58	-11

Pettitt's test confirms that no statistically significant change point is detected for either annual or summer IDM in Sandanski. At Musala, a statistically significant change point is identified only for annual IDM, with a change point in 1978 ($p = 0.0025$). In contrast, summer IDM at Musala does not show a significant change point. This indicates that the detected structural change is confined to the annual IDM series (Table 5).

Table 5. Pettitt test results for the De Martonne index.

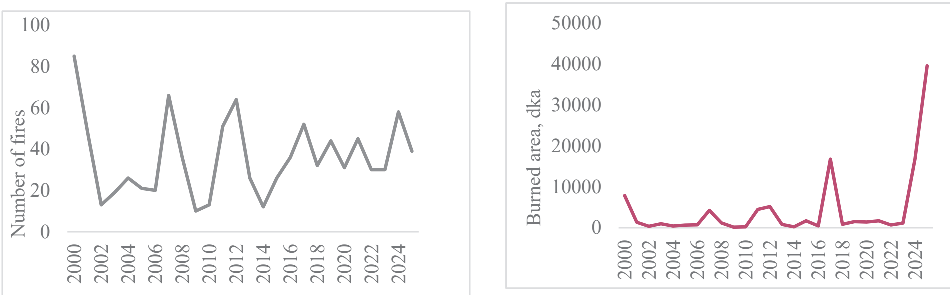
Station	Variable	Pettitt year	p-value	Interpretation
Sandanski	Annual IDM	2000	0.1823	Not significant
Sandanski	Summer IDM	2020	0.9325	Not significant
Musala	Annual IDM	1978	0.0025	Significant
Musala	Summer IDM	1965	0.6921	Not significant

Trend analysis indicates no statistically significant long-term trends in the De Martonne index at either station. In Sandanski, annual IDM shows a non-significant tendency ($S = 74$, $Z = 0.42$, $p = 0.672$), while summer IDM exhibits virtually no trend ($S = -4$, $Z = -0.02$, $p = 0.986$). At Musala, both annual IDM ($S = 74$, $Z = 0.42$, $p = 0.672$) and summer IDM ($S = 140$, $Z = 0.81$, $p = 0.421$) also show non-significant trends. Sen's slope values are close to zero in all cases, indicating the absence of a robust gradual change in aridity.

These results suggest that aridity changes are not expressed as a consistent long-term trend. However, Pettitt's test identifies a statistically significant change point in annual IDM at Musala, indicating that the observed change in high-mountain moisture conditions is better described as a regime shift rather than as a gradual trend.

2.1.4 Forest fire activity in the Sandanski region

Forest fire activity in the Sandanski region during 2000–2025 is characterized by strong interannual variability in both number of fires and burned area (Figure 5).



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

Figure 5. Time series of number of fires (**a**) and burned area (**b**) (2000–2025)

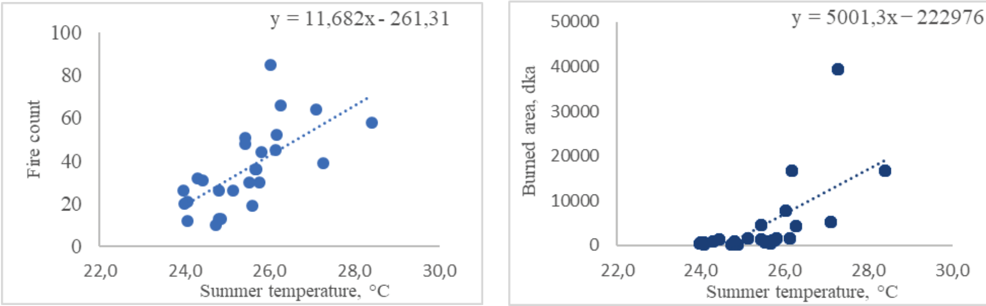
The annual number of fires ranges from 10 fires in 2009 to 85 fires in 2000. Burned area shows even stronger variability, with extreme years such as 2025 (39525 dka), 2024 (16 810 dka) and 2017 (16 746 dka) (Table 6).

Table 6. Selected extreme fire years in the Sandanski region.

Year	Number of fires	Burned area, dka
2000	85	7841
2007	66	4234
2012	64	5146
2017	52	16746
2024	58	16810
2025	39	39525

2.1.5 Climate–fire relationships

Spearman's rank correlation analysis shows clear relationships between climatic variables and fire activity (Table 7). The strength of this relationship is clearly illustrated in the scatter plots (Figure 6), which show a strong positive association between summer temperature and fire activity.



(a) **(b)**

Figure 6. Scatter plots illustrating the relationship between summer temperature and fire activity (number of fires (a) and burned area (b)). Each point represents one year. The lines indicate linear trends for visualization purposes.

Table 7. Spearman's rank correlation coefficients (ρ) between climatic variables and fire indicators (number of fires and burned area). Statistically significant correlations ($p < 0.05$) are shown in bold.

Climatic variable	Fires, ρ	p-value	Burned area, ρ	p-value
Annual temperature	**0.438**	0.034	**0.395**	0.046
Summer temperature	**0.750**	<0.001	**0.768**	<0.001
Annual precipitation	**−0.415**	0.041	−0.323	0.108
Summer precipitation	**−0.387**	0.048	**−0.482**	0.013
Annual IDM	**−0.421**	0.039	**−0.344**	0.044
Summer IDM	**−0.401**	0.044	**−0.503**	0.010

Summer temperature is strongly and positively correlated with both the number of fires ($\rho = 0.750$, $p < 0.001$) and burned area ($\rho = 0.768$, $p < 0.001$).

Annual temperature shows moderate but statistically significant correlations, particularly with burned area ($\rho = 0.395$, $p = 0.046$).

Compared with temperature, precipitation exhibits less consistent relationships with fire activity. However, summer precipitation shows statistically significant negative correlations with both fire occurrence and burned area, whereas annual precipitation is significantly related only to the number of fires and not to burned area.

The De Martonne index also shows moderate negative correlations with fire indicators, with statistically significant relationships in most cases.

These results indicate that drier conditions are associated with increased fire activity, although the strongest associations are observed for summer temperature.

2.2 Discussion

2.2.1 Climate normals and regime shift

The results demonstrate that the transition between the climate normals 1961–1990 and 1991–2020 is not merely a statistical update of reference periods, but reflects a real and statistically detectable shift in the regional temperature regime. The identification of a significant change point around 1997 in annual temperature at both Sandanski and Musala confirms that the observed differences between the two climate normals correspond to a structural change in the underlying time series rather than reflecting only a gradual long-term warming trend.

This finding is consistent with the concept that climate normals, although defined as 30-year averages, may capture different climatic states under non-stationary conditions. As noted by Arguez and Vose [4], the representativeness of climate normals decreases when the assumption of stationarity is violated. The present results provide empirical evidence that the contemporary climate normal (1991–2020) corresponds to a warmer climatic regime rather than to a simple continuation of the previous state.

The detected change point around 1997 is also consistent with findings from other regions in Southeastern Europe. For example, Čegar et al. [9] reported a similar shift in annual temperature in Belgrade, indicating that the late-1990s transition may represent a broader regional signal. This supports the interpretation that the identified regime shift is not a local anomaly but part of a larger-scale regional climatic transition.

2.2.2 Seasonal asymmetry and the role of summer temperature

A key result of the study is the pronounced seasonal differentiation of temperature change. Warming is strongest during summer, with increases of approximately +1.5 to +1.6°C observed at both stations. This seasonal amplification is particularly important because summer conditions play a dominant role in controlling moisture availability, evapotranspiration and fuel dryness.

The earlier detection of a change point in summer temperature at Sandanski (1989), compared to the annual shift around 1997, suggests that seasonal and annual temperature changes are less synchronized in the lowland station than at Musala.

This difference indicates that elevation and local climatic conditions modulate the timing of climate regime transitions.

2.2.3 Precipitation and aridity: a secondary and heterogeneous signal

In contrast to temperature, precipitation changes are weaker, less consistent and spatially heterogeneous. The absence of a statistically significant change point in summer precipitation at both stations indicates that the summer climate signal is dominated by temperature rather than by precipitation.

This result is consistent with previous studies in Southeastern Europe and other regions, which show that temperature trends tend to be more robust and spatially coherent than precipitation changes [10, 11]. The comparatively weak and inconsistent precipitation signal suggests that changes in atmospheric circulation and regional climate dynamics affect precipitation in a more complex and variable manner than temperature.

The analysis of the De Martonne index further supports this interpretation. In Sandanski, the index remains relatively stable, indicating that the increase in temperature is not accompanied by a statistically significant change in combined moisture conditions. In contrast, Musala shows a significant decrease in annual IDM, suggesting increased relative dryness at higher elevations.

However, it should be noted that the De Martonne index is derived from temperature and precipitation and does not represent an independent climatic variable. Therefore, changes in the De Martonne index should be interpreted together with the observed temperature and precipitation changes from which the index is derived.

2.2.4 Climate controls on forest fire activity

The analysis of forest fire data reveals strong statistical relationships between climatic conditions and fire activity in the Sandanski region. The most prominent result is the strong positive correlation between summer temperature and both fire occurrence ($\rho = 0.750$) and burned area ($\rho = 0.768$). These relationships indicate that warmer summer conditions are closely associated with increased fire activity.

In contrast, precipitation and the De Martonne index show weaker and predominantly negative relationships with fire activity. These results indicate that summer temperature exhibits the strongest correlation with fire activity among the climatic variables examined.

These findings are consistent with previous research in European Mediterranean region, where summer temperature and drought conditions have been identified as key drivers of fire variability [1, 12]. Turco et al. [1], for example, emphasize the importance of summer heat and drought in controlling burned area in Southern Europe.

At the same time, it is important to emphasize that the observed relationships represent statistical associations rather than causal mechanisms. Forest fire activity is influenced by a combination of climatic and non-climatic factors, including human activity, land management practices and fuel characteristics. The relatively short duration of the fire record (2000–2025) further limits the ability to establish long-term causal relationships.

It should be noted that fire occurrence and burned area are influenced not only by climatic conditions but also by a range of non-climatic factors, including fuel availability, demographic and land-use changes, fire prevention and suppression practices, and regulatory measures. Therefore, the relationships identified in this study should be interpreted as climate–fire associations rather than as a comprehensive assessment of wildfire risk.

2.2.5 Implications for climate interpretation and risk assessment

The combined results of this study highlight a coherent sequence linking climate change and fire activity: a statistically significant regime shift in temperature, a pronounced summer amplification of warming, and strong associations between summer temperature and fire activity.

This sequence suggests that the contemporary climate normal represents a new climatic regime with direct implications for environmental risk. In this context, the use of updated climate normals is not only a matter of statistical convention but reflects real changes in climatic conditions that affect processes such as wildfire occurrence.

The findings also emphasize the importance of considering seasonal signals and regime shifts when interpreting climate change impacts. Analyses based solely on long-term averages or gradual trends may overlook critical transitions that have significant consequences for environmental systems.

Overall, the study contributes to bridging the gap between climatological characterization and impact-based analysis by linking changes in climate normals to measurable environmental responses.

2.2.6 Implications for forest resources and wood raw material supply

The detected warming signal and its strong association with forest fire activity have important implications for forest resources and the forest-based sector. More frequent or more severe fire events may reduce the availability of usable timber, alter the quality of wood raw material, increase the share of damaged or degraded wood, and create additional challenges for forest management and harvesting planning. In regions where wood-processing industries depend on stable and predictable raw material supply, climate-related disturbance risks should therefore be considered as part of long-term resource planning.

Although the present study does not directly assess post-fire wood quality or industrial wood supply, the results indicate that climate-driven wildfire risk may become an increasingly relevant factor for the sustainable management of forest resources. In this context, the integration of climate analysis, wildfire risk assessment and forest-sector planning can support more resilient strategies for the use and protection of forest-based raw materials.

CONCLUSIONS

The results of this study demonstrate that the transition between the climate normals 1961–1990 and 1991–2020 reflects a real and statistically significant change in the climatic regime in Southwestern Bulgaria, rather than a simple update of reference conditions. A coherent shift in annual temperature around 1997 is detected at both Sandanski and Musala, indicating a regionally consistent transition toward warmer climatic conditions.

The warming signal shows a pronounced seasonal differentiation, with the strongest increase occurring during summer. In Sandanski, the change point in summer temperature was detected earlier (1989) than the corresponding annual change point, whereas Musala exhibited a more synchronized timing of annual and seasonal temperature changes. In contrast, precipitation changes were less consistent than temperature changes, and no statistically significant shift was detected in summer precipitation.

The analysis of forest fire activity shows that summer temperature exhibits the strongest association with both fire occurrence and burned area.

Strong positive correlations indicate that warmer summer conditions are closely linked to increased fire activity, while precipitation and aridity play a secondary role.

Taken together, the results reveal a consistent sequence linking climate change and wildfire activity: a statistically detectable regime shift, a pronounced summer warming signal, and a strong relationship between summer temperature and fire occurrence and burned area.

This highlights the importance of considering both regime shifts and seasonal dynamics when interpreting climate change impacts.

The study further suggests that contemporary climate normals represent not only updated climatic references but also substantially altered climatic conditions with direct implications for wildfire occurrence, burned area and wildfire risk assessment.

More broadly, the integration of climatological analysis with impact-oriented indicators provides a useful framework for evaluating climate-related environmental hazards under ongoing climatic change. Nevertheless, fire occurrence and burned area are influenced by both climatic and non-climatic factors, and the relationships identified in this study should therefore be interpreted within this broader context.

From an applied perspective, the results also underline the relevance of climate-related wildfire risk for forest resource management and wood raw material supply. The observed warming regime and its association with fire activity suggest that adaptation strategies in forestry should consider not only ecological risks, but also the long-term stability, quality and availability of forest-based raw materials for the wood-processing sector.

AUTHOR CONTRIBUTIONS

Conceptualization, A.G.; methodology, A.G.; software, A.G.; validation, A.G.; formal analysis, A.G.; investigation, A.G.; resources, A.G.; data curation, A.G.; writing—original draft preparation, A.G.; writing—review and editing, A.G.; visualization, A.G. The author has read and agreed to the published version of the manuscript.

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The author used digital language-editing tools during manuscript preparation. The author reviewed and approved the final version of the manuscript.

CONFLICTS OF INTEREST

The author declares no conflicts of interest.

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