

Article

Long-Term Changes in Temperature Extremes Based on Climate Indices in Different Physical-Geographical Conditions of Georgia, 1961–2020

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Abstract

We studied long-term changes in temperature extremes in Georgia against the backdrop of ongoing global warming within 1961–2020. Using observational data from 20 meteorological stations from different physical-geographic regions of the country, we analyzed the main climate temperature indices recommended by the WMO and the Expert Team on Climate Change Detection and Indices (ETCCDI). Indices characterizing extremely cold and warm conditions (ice days, frost days, summer days, and tropical nights); growing season length; as well as indices of absolute extremes and percentile temperature characteristics were considered. The results show that along the Black Sea coast and the Kolkheti Lowland, changes in temperature indices are less pronounced due to the moderating influence of the sea and humid landscapes; however, a significant increase in the number of tropical nights is observed. In areas with a more continental climate (Eastern Georgia, the South Georgian Highlands, and the mid-mountain zone of the Greater Caucasus), a general decrease in the number of ice days and frost days was observed, along with a simultaneous increase in the number of hot summer days, tropical nights, and growing season length. Tropical nights and percentile temperature indices were found to be the most sensitive to global warming. Overall, the results indicate widespread long-term tendencies consistent with regional manifestations of global warming, characterized by decreases in cold extremes and an expansion of warm indices. However, the statistical robustness and explanatory power of these trends vary substantially across physical-geographical regions and specific indices. Many significant shifts exhibit low coefficients of determination ($R^2 < 0.1$), indicating that although long-term warming trajectories are real, local topography and intense interannual natural variability remain the primary drivers of annual temperature fluctuations in Georgia.

Academic Editor: Dae Il Jeong

Received: 22 May 2026

Revised: 30 June 2026

Accepted: 2 July 2026

Published: 8 July 2026

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Keywords: ETCCDI index; climate change; temperature; trend; Georgia

1. Introduction

In the late 20th and early 21st centuries, not only has there been a rise in surface air temperature in various regions of the world, but also an increase in the frequency and intensity of air temperature extremes [1–4]. This, in turn, has significant negative impacts on ecosystems and society [5–7]. Therefore, when studying climate change, it is important to study not only the average temperature but also extreme values at a global or regional level [8].

The World Meteorological Organization Commission for Climatology (CCI), World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDI) defined 27 core climate extreme indices [9,10].

The list of all core ETCCDI indices is given at http://etccdi.pacificclimate.org/list_27_indices.shtml (accessed on 4 March 2026).

These indices, based on daily temperature and precipitation values, have become a widely used method for detecting and monitoring climate change [1–15].

There is a large body of literature devoted to the study of extreme temperatures, which examines their long-term fluctuations across different regions of the globe; for example, Tesfaye et al. (2025) [16] investigated the spatiotemporal variability and trends of extreme temperatures in southeastern Oromia, Ethiopia. Ozurturk (2023) [17] determined extreme temperatures in future climate scenarios in Central Asia; Shiromani Priyanthika Jayanthika Jayawardena et al. (2018) [18] examined trends in extreme temperature indices in Sri Lanka, Li et al. (2022) [19] performed a comparative analysis of changes in extreme temperatures since 1960 in China and Greece. Dong et al. (2023), Ayalew et al. (2025), and Soltani et al. (2016) [20–22] studied the spatiotemporal characteristics of extreme temperatures in Xinjiang, northern Ethiopia, Iran, and India; Shenoy et al. (2022) and Powell et al. (2015) [23,24] studied trends in rare extreme temperature events over the United States. Similar studies were conducted for Europe and the Mediterranean [25], and various regions of Russia [26,27], including southern Siberia [15], etc.

Studies based on ETCCDI indices were also conducted for Georgia [28,29].

In these studies, the trends of extreme daily temperatures in Georgia in 1971–2010, and the temperature indices of climate change—extreme temperatures, frosty, cold, and hot days, tropical nights, and indices based on percentiles of distribution—were investigated in 1961–2010.

These studies show that between 1971 and 2010, Georgia was more strongly affected by warm temperature extremes than by cold extremes. The impacts were especially noticeable in nighttime temperature indices, while cold extremes based on daytime indices showed weaker trends. Furthermore, in 1960–2010, the frequency of summer days, warm days, and warm nights, as well as the duration of warm spells, increased significantly across Georgia. In contrast, cold extremes exhibited only moderate warming trends.

While foundational work by Keggenhoff et al. [28,29] established important baseline warming signals for the region up to 2010, the present study advances beyond a basic temporal expansion. This work represents a major structural and geographical evolution in three distinct ways. First, we expand the observation network to a highly robust, homogenized dataset of 20 meteorological stations, correcting the spatial underrepresentation of previous studies which relied on fewer observation points. Second, we transition away from broad regional groupings to implement a refined classification based on highly granular physical-geographical and altitudinal conditions. This allows for a deeper examination of how distinct topographies—from the humid subtropical Black

Sea coast to the arid continental lowlands and alpine ranges—modulate climate drivers. Finally, by integrating the highly volatile 2011–2020 decade and introducing additional metrics like the Growing Season Length (GSL), this study captures non-linear accelerations and demonstrates that percentile-based indices operate with much higher decadal sensitivity than absolute extreme metrics in complex mountainous terrain.

The Caucasus region remains relatively understudied compared to other parts of Europe in terms of climate extremes. Therefore, this study contributes to improving the understanding of regional manifestations of global warming in a climatically complex mountainous region by analyzing long-term variations in the temperature regime of Georgia using temperature-based climate indices for the period 1961–2020.

Scientific Significance

This study provides a comprehensive assessment of long-term changes in temperature extremes in Georgia based on standardized ETCCDI climate indices and high-resolution daily observations from 20 meteorological stations covering the period 1961–2020. The scientific significance of the study lies in its contribution to filling a regional knowledge gap, as the Caucasus remains relatively understudied in terms of climate extremes compared to other parts of Europe and Asia.

By analyzing multiple categories of temperature indices, including absolute, threshold-based, and percentile-based metrics, the study offers a robust evaluation of climate variability across diverse physical-geographical regions, ranging from humid coastal lowlands to continental and mountainous environments. The results reveal clear spatial heterogeneity in warming trends and demonstrate that continental and high-altitude regions are more sensitive to changes in temperature extremes.

Importantly, the study identifies tropical nights and percentile-based indices as the most sensitive indicators of ongoing climate change, highlighting their value for climate monitoring and impact assessment. The use of homogenized long-term observational datasets enhances the reliability of detected trends and strengthens the scientific basis for regional climate analysis.

Overall, the findings contribute to a better understanding of how global warming manifests in complex mountainous regions and provide valuable insights for climate risk assessment, environmental management, and the development of adaptation strategies in sectors such as agriculture, water resources, and public health.

2. Materials and Methods

2.1. Study Area

Georgia is a country in the Caucasus region on the Black Sea coast between 41–44° N latitude and 40–47° E longitude, and covers an area of approximately 69,700 km². It is bordered by Russia to the north, Azerbaijan to the southeast, and Armenia and Turkey to the south (Figure 1). Georgia's topography is highly diverse. The Greater Caucasus Range in the north of the country, with altitudes ranging from about 1500 to 5000 m, acts as a major climatic barrier, shielding Georgia's territory from Arctic high-pressure systems originating in Central Asia during winter. The Lesser Caucasus Range in the south of the country reaches elevations of up to 3500 m.

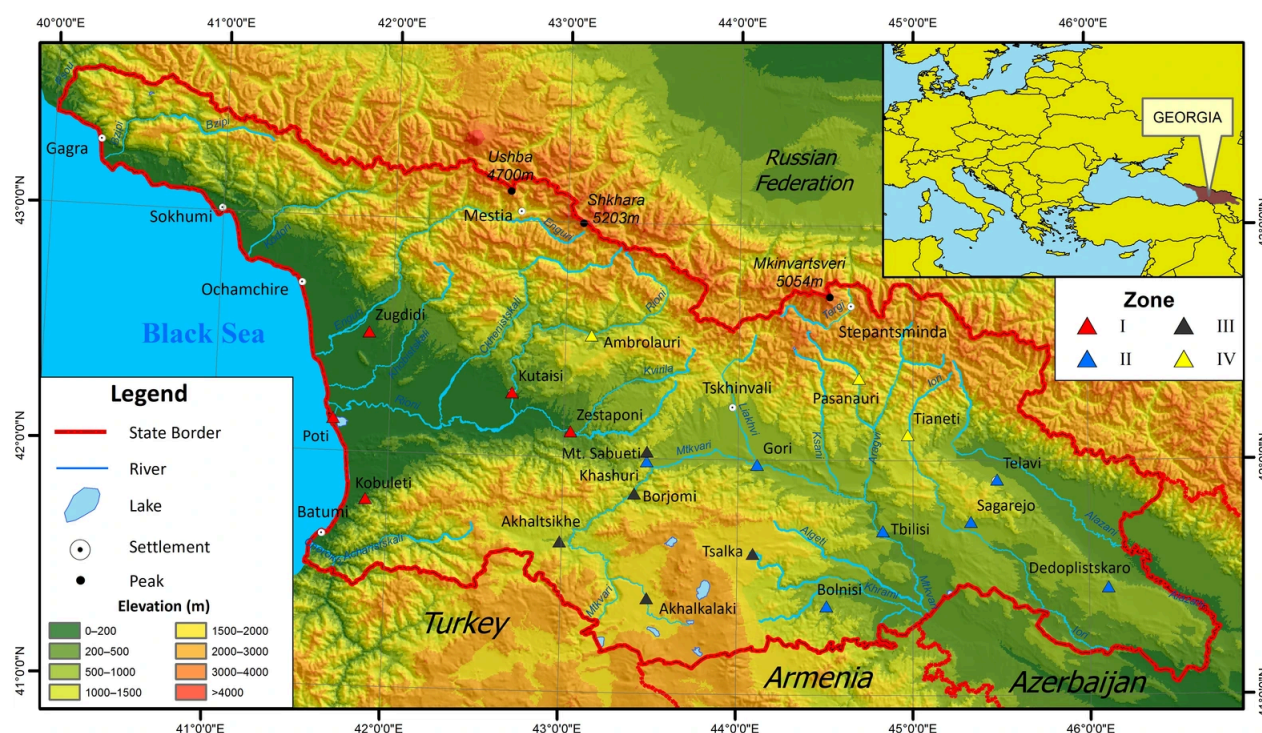


Figure 1. Location of meteorological stations according to different physical-geographical regions (I, II, III, IV) of Georgia. I—Black Sea coast and Kolkheti Lowland; II—Eastern Georgia; III—South Georgian Highlands and Likhi Range; IV—Mid-Mountain zone of the Greater Caucasus.

The Surami Mountain Range, with a maximum elevation of approximately 1000 m, connects the Greater and Lesser Caucasus and divides the country into two physical-geographical areas: western Georgia and eastern Georgia. Western Georgia, characterized by humid subtropical climatic conditions, generally experiences mild winters and warm summers, with mean annual temperatures of 13–15 °C and high annual precipitation values ranging from 1200 to 2400 mm. In contrast, eastern Georgia has a transition from humid to dry subtropical climatic conditions, characterized by lower annual precipitation (about 500–600 mm in the lowlands) and mean annual temperatures between 10 and 13 °C. In mountainous regions, mean annual temperatures range from −5 to 10 °C, while precipitation varies between 800 and 1400 mm [28].

2.2. Data, Quality Control, and Homogeneity Testing

Meteorological observations in Georgia are conducted under the guidance of the National Environmental Agency (<https://nea.gov.ge/En> (accessed on 4 March 2026)). This study is based on observations from 20 meteorological stations in Georgia for the period 1961–2020 (Figure 1 and Table 1), in particular, the daily mean, maximum, and minimum temperatures. These stations perform long-term observations using standard meteorological instrumentation, recording temperature every 3 h and precipitation twice daily. In recent years, automatic meteorological stations have also been installed on some of them. The NEA utilizes data from these stations for climate analysis and sends the information to the World Meteorological Organization (WMO).

Table 1. Location of meteorological stations used in this study.

Region	Weather Station	Lat, N	Long. E	Alt, a.s.l., Meter
I—Black Sea coast and Kolkheti Lowland	Kobuleti	41.80	41.88	7
	Poti	42.14	41.68	3
	Kutaisi	42.27	42.70	114
	Zugdidi	42.51	41.87	117
	Zestaponi	42.11	43.04	167
II—Eastern Georgia	Tbilisi	41.70	44.83	403
	Telavi	41.92	45.48	568
	Gori	41.98	44.11	588
	Dedoplistskaro	41.46	46.11	800
	Sagarejo	41.74	45.33	802
	Khashuri	41.99	43.60	690
	Bolnisi	41.38	44.51	534
III—South Georgian Highlands and Likhi Range	Akhalkalaki	41.40	43.49	1716
	Akhaltzikhe	41.64	42.99	982
	Borjomi	41.85	43.41	789
	Tsalka	41.60	44.09	1457
	Mt. Sabueti	42.03	43.48	1242
IV—Mid-Mountain zone of the Greater Caucasus	Ambrolauri	42.52	43.15	544
	Pasanauri	42.35	44.69	1070
	Tianeti	42.11	44.97	1099

We grouped the meteorological stations according to the following physical-geographical regions:

I—Black Sea coast and Kolkheti lowland, which is characterized by a humid subtropical climate, mild winter, warm summer, landscapes: sea, mountains near the coast, subtropical forests, plains, swamps, river floodplains.

II—Eastern Georgia's climate is drier, continental; hot summers, cold winters. Landscapes: plains and intermontane basins, steppes and semi-deserts, mountain slopes.

III—South Georgian Highlands and Likhi Range climate is moderate continental, with relatively dry, cold winters. Landscapes: high plateaus, mountain meadows, steppe areas, volcanic forms, mid-mountain ridges, dense forests, and passes.

IV—Middle Mountain zone of the Greater Caucasus climate: varies greatly by altitude—low slopes: humid subtropical; middle and upper zones: moderately cold and cold, snowy winters. Landscapes: high mountains with sharp peaks, glaciers, alpine meadows, mountain forests, gorges, and rivers.

The dataset was sourced directly from the National Environmental Agency of Georgia (<https://nea.gov.ge/En>). A detailed quality control (QC) procedure was applied before analysis to ensure the integrity and physical realism of the time series. This step is essential to filter out non-physical values and potential measurement or transcription errors that could artificially distort the calculated trends in climate extremes. The following specific checks were systematically applied to all daily variables, consistent with the standard procedures recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI): 1. Non-Physical Temperature Limits: Daily temperature values were checked for extremes outside of physically plausible ranges. 2. Internal Consistency Check: The relationship between the two temperature variables was verified, flagging

any instance where the daily maximum temperature was less than the daily minimum temperature. 3. Date and Data Type Integrity: The time series were checked for all values corresponding to an impossible date (e.g., February 30th, 32nd of any month) and for the presence of non-numeric entries in the data fields. A preliminary assessment of data completeness was performed. Stations were to be excluded if more than 20% of the data over the entire period of record was missing [30]. However, all 20 selected stations were found to possess sufficient viable data; thus, no stations were dropped based on this criterion.

Non-climatic factors, such as station relocation, changes in instrumentation, or alterations in the local environment, can introduce artificial shifts (inhomogeneities) into the time series [31].

To ensure that observed trends are purely climate-driven, all-time series were tested and adjusted for homogeneity [32].

Data homogeneity testing, detection, and adjustment of inhomogeneous time series have been carried out using the RHtestsV4 software package

etccdi.pacificclimate.org/software.shtml (accessed on 4 March 2026). This package employs the Penalized Maximal *t*-test to detect undocumented mean shifts. Due to the unavailability of detailed metadata concerning station histories (such as exact dates of instrument changes or relocations), the analysis relied on absolute testing (i.e., the case “without a reference series”). The tests rely solely on statistical properties of the series itself to detect shifts. The statistical significance level for breakpoint detection was set to $\alpha = 0.05$ (corresponding to a 95% confidence level), using the default settings of the RHtests packages. Any shifts found to be statistically significant were designated as breakpoints. The final step involved using the respective RHtests software to apply mean-shift and variance-shift adjustments or mean-shift/ratio adjustments to the series segments, effectively homogenizing the data and producing the best-estimated climate series for the calculation of extreme indices [33,34].

2.3. Extreme Air Temperature Indices and Analytical Methods

Table 2 lists the 11 extreme air temperature indices used for this study with index names, definitions, and units.

Table 2. ETCCDI temperature indices used for this study (TX—daily maximum air temperature, TN—daily minimum air temperature, TM—daily mean air temperature).

Acronym	Index Name	Definition	Units
FD	Frost days	Annual count when TN (daily minimum temperature) $< 0\text{ }^{\circ}\text{C}$	days
SU	Summer days	Annual count when TX (daily maximum temperature) $> 25\text{ }^{\circ}\text{C}$	days
ID	Icing days	Annual count when TX (daily maximum temperature) $< 0\text{ }^{\circ}\text{C}$	days
TR	Tropical nights	Annual count when TN (daily minimum temperature) $> 20\text{ }^{\circ}\text{C}$	days
TX _x	Max TX (the hottest day)	Monthly maximum value of daily maximum temperature	$^{\circ}\text{C}$
TN _x	Max TN (the hottest night)	Monthly maximum value of daily minimum temperature	$^{\circ}\text{C}$
TX _n	Min TX (coldest day)	Monthly minimum value of daily maximum temperature	$^{\circ}\text{C}$

Acronym	Index Name	Definition	Units
TNn	Min TN (coldest night)	Monthly minimum value of the daily minimum temperature	°C
TN10p	Cool nights	Percentage of days when TN < 10th percentile of 1961–1990	days
TX90p	Warm days	Percentage of days when TX > 90th percentile of 1961–1990	days
GSL	Growing season length	Annual (1 January to 31 December in Northern Hemisphere (NH), 1 July to 30 June in Southern Hemisphere (SH)) count between first span of at least 6 days with daily mean temperature TG > 5 °C and first span after 1 July (1 January in SH) of 6 days with TG < 5 °C.	days

Index calculations were performed using RClimDex (Version 2.15.2 etccdi.pacificclimate.org/software.shtml, accessed on 4 March 2026)) based on daily maximum and minimum temperature data, and were subject to strict data completeness requirements. An annual index value was classified as incomplete if more than 15 daily observations were missing within a year. Monthly values were not calculated when three or more days were missing, and annual values were only derived when all twelve months were available. Percentile-based indices were calculated only when at least 70% of the data within the reference period were present. Additional standard criteria recommended by the Expert Team on Climate Change Detection and Indices were applied in accordance with <https://etccdi.pacificclimate.org/ClimDex/climindex-v1-3-users-guide.pdf> (accessed on 4 March 2026)..

While some temperature indices, such as TX_x, TN_x, TXn, TNn (Table 2) are initially identified as maximum or minimum values on a monthly scale according to standard ETCCDI criteria, their long-term behavior is evaluated here using annual time series. For each year in the 1961–2020 baseline, the absolute highest or lowest daily value recorded across all 12 months was extracted. Consequently, the resulting trend calculations reflect long-term multi-decadal shifts in absolute annual temperature extremes rather than isolated intra-annual monthly variability.

The statistical parameters, including mean, minimum, maximum, and standard deviation (SD), were calculated for the 11 extreme temperature indices used in this study. Statistical significance of differences between mean values for different averaging periods was evaluated using Student's *t*-test [35].

$$t_e = \frac{|M_1 - M_2|}{\sqrt{\frac{\sigma_1^2}{N_1} + \frac{\sigma_2^2}{N_2}}}$$

where M_1 is the arithmetic mean of the first sample; M_2 is the arithmetic mean of the second sample; σ_1 is the standard deviation of the first sample; σ_2 is the standard deviation of the second sample; N_1 is the size of the first sample; N_2 is the size of the second sample. If the calculated value of the criterion exceeds the corresponding value of the Student's table, the discrepancy between the means is considered significant at a certain significance level; otherwise, the discrepancy is random.

The trend in long-term changes in climate indices was assessed using the *p*-value for a Type I error when rejecting the null hypothesis (significance level). The null hypothesis was that the long-term change in temperature indices (trend) for the period 1961–2020 is

random. Accordingly, the alternative hypothesis, excluding the null hypothesis, implied the validity of changes in these characteristics over time (trend significance). If the p -value is small (less than or equal to 0.05), the null hypothesis is rejected, and the trend is considered significant [36].

In addition to classical linear regression, particular attention was given to the limitations associated with trend detection in climatic time series. Since temperature indices often exhibit serial autocorrelation, which can inflate the statistical significance of trends, the robustness of the results was evaluated by considering the potential influence of temporal dependence. Therefore, the interpretation of statistical significance was complemented by an assessment of effect size and the coefficient of determination (R^2), allowing for a more comprehensive evaluation of the explanatory power of detected trends. Trends characterized by low R^2 values were treated with caution and interpreted as weak or unstable, even when statistically significant at conventional confidence levels.

No pre-whitening procedure was applied before trend estimation. Consequently, the potential influence of serial autocorrelation on significance estimates cannot be completely excluded. To reduce the risk of overinterpreting weak trends, statistical significance was considered together with trend magnitude and explanatory power (R^2). Therefore, the interpretation of the results was based not only on significance levels but also on the overall consistency, magnitude, and spatial coherence of the detected trends.

Before trend analysis, all temperature series underwent quality control and homogeneity assessment using the RHtestsV4 package. This procedure minimizes the influence of non-climatic discontinuities related to station relocations, instrumentation changes, observational practice modifications, and other artificial shifts in observational records.

3. Results

The study focuses on 11 extreme air temperature indices derived from daily maximum and minimum temperatures recorded at 20 meteorological stations of Georgia. To track how climate extremes are shifting in Georgia, we examined a 60-year period from 1961 to 2020. We specifically split this timeframe into two equal, 30-year blocks—1961–1990 and 1991–2020—to align with official World Meteorological Organization (WMO) standards. This setup lets us compare the WMO's Historical Standard Reference Period (1961–1990), which acts as our baseline for long-term climate change, directly against the modern Climatological Standard Normal (1991–2020). By using two identical, consecutive 30-year windows, we ensure the data stays completely balanced and consistent, avoiding the mathematical biases or skewed trends that happen when you throw uneven or incomplete multi-year periods into the mix.

Table 3 compares some extreme air temperature indices for two 30-year periods, averaged for different physical-geographic regions of Georgia.

Table 3. Some extreme air temperature indices for different periods (a—1961–1990; b—1991–2020) in different physical-geographic regions: I—Black Sea coast and Kolkheti Lowland; II—Eastern Georgia; III—South Georgian Highlands and Likhi Range; IV—Mid-Mountain zone of the Greater Caucasus).

Region	Indices	Average		Maximum		Minimum		Standard Deviation	
		a	b	a	b	a	b	a	b
I	ID	0.2	0.1	5	3	0	0	0.6	0.3
	FD	14	13	63	42	0	0	8	7
	SU	140 *	136 *	176	175	75	82	12	12
	TR	46 *	55 *	94	99	3	14	11	12
	GSL	353	351	366	366	280	280	15	18
II	ID	6 *	4 *	34	28	0	0	6	5
	FD	75 *	67 *	129	123	7	10	17	16
	SU	101 *	111 *	134	149	34	71	12	11
	TR	12 *	22 *	58	73	0	0	7	10
	GSL	288	288	363	365	221	233	29	26
III	ID	25	25	74	95	0	0	10	12
	FD	131	129	170	190	57	64	14	14
	SU	65	68	147	158	0	1	10	13
	TR	0.2 *	0.6 *	6	8	0	0	0.4	0.7
	GSL	241	239	347	345	178	183	22	20
IV	ID	14 *	12 *	44	48	0	0	8	9
	FD	106 *	100 *	154	153	17	22	14	12
	SU	66 *	81 *	127	150	17	26	13	15
	TR	4	5	27	39	0	0	2	3
	GSL	256	259	363	352	192	208	25	19

Note : Statistically significant values are shown in bold and with *.

Table 3 shows that along the Black Sea coast and the Kolkheti Lowland, in humid subtropical climate conditions, no significant changes in climate indices were observed over two thirty-year periods (1961–1990 and 1991–2020). The exception was Tropical nights and Summer days. The former increased significantly, while the latter decreased slightly, possibly due to the stabilizing influence of the Black Sea and humid landscapes. Tropical nights in the second period increased by 9 units compared to the first, which is approximately 20% of the average number of tropical nights for the first period. This change is statistically significant with an inference reliability of 0.99. The number of hot days decreased by 4 days on average across the region, and even by 10 days in some locations (Poti, Zestaponi), which, when compared to the average values, can be considered statistically significant at a level of 0.95. In other regions with a more continental climate, the changes are more noticeable. In the second period (1991–2020), compared with the first period (1961–1990), the number of frost days (FD) and Ice days (ID) generally decreased, while the number of summer days, tropical nights, and growing season length (GSL) generally increased, which can be attributed to ongoing global warming. For example, in eastern Georgia, the number of frost days in the second period decreased by 8 days compared with the first, which is more than 10% of the average number of frost days in the first period. This change is statistically significant with an infer-

ence reliability of 0.99. Meanwhile, in Dedoplistskaro, the number of frost days (FD) increased by 5 units. The number of tropical nights (TR) in the second period increased on average almost twofold compared to the first, and in Tbilisi by 19 nights, ranging from 19 to 38. The number of summer days (SU) increased by an average of 10 units. These changes are also statistically significant with an inference reliability of 0.99. A decrease in the number of ice days (ID) by 2 days is statistically significant at the 0.95 level. This table also shows that on the Black Sea coast, in the Kolkheti Lowland, and in the plains of eastern Georgia, the growing season length (GSL) can last an entire year.

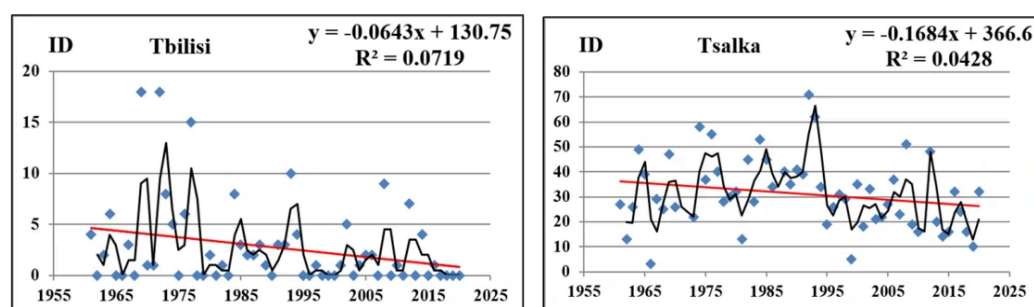
In the South Georgian Highlands, climate changes are less significant. The number of frost days (FD) in the second period decreased by only 2 days compared to the first, while the number of summer days (SU) increased by 3 days (significant only at the 0.9 level), although changes are significant in some areas. For example, in Akhaltsikhe, the number of frost days (FD) in the second period decreased by 10 units compared to the first, while in Tsalka the number of summer days (SU) increased by 12 units. Meanwhile, in some locations, such as Akhalkalaki, the opposite pattern is observed: an increase in the number of frost days (FD) and a decrease in the number of summer days (SU). Here, tropical nights are rare, but their slight decrease can be estimated with an inference reliability of 0.98.

In the mid-mountain zone of the Greater Caucasus, there is a slight decrease in the number of ice days (ID), and the number of frost days (FD), and an increase in the number of summer days (SU), tropical nights (TR), and growing season length (GSL). According to the table, the number of ID is 10–12, and in the high-mountain zone of the Greater Caucasus, it reaches 210. A decrease in the number of ID by 2 days is statistically significant at the 0.95 level. A decrease in the number of FD and an increase in the number of SU are statistically significant with an inference reliability of 0.99. Tropical nights are observed only in Ambrolauri.

A more detailed look at the long-term trends in some extreme air temperature indices can be found in the graphs (Figure 2).

All trends presented on Figure 2 are statistically significant except for the trends of ice days (ID) in Tsalka, length of the growing season (GSL) in Pasanauri, and summer days (SU) in Kobuleti.

Ice days (ID) on the Black Sea coast and the Kolkheti Lowland, as well as on the Imeretian highlands, in the conditions of a wet subtropical climate with a mild winter, are a rare phenomenon, and in the rest of the regions, there is a regular tendency of their decrease. The rate of reduction of the number of ID on the plains of Eastern Georgia (Tbilisi) is 0.6 days, and on the Southern Georgian highlands (Tsalka)—1.7 days per decade, although judging by the coefficient of determination (R^2), the contribution of the trend to the total variability of the number of frosty days is insignificant and amounts to only 4–7%.



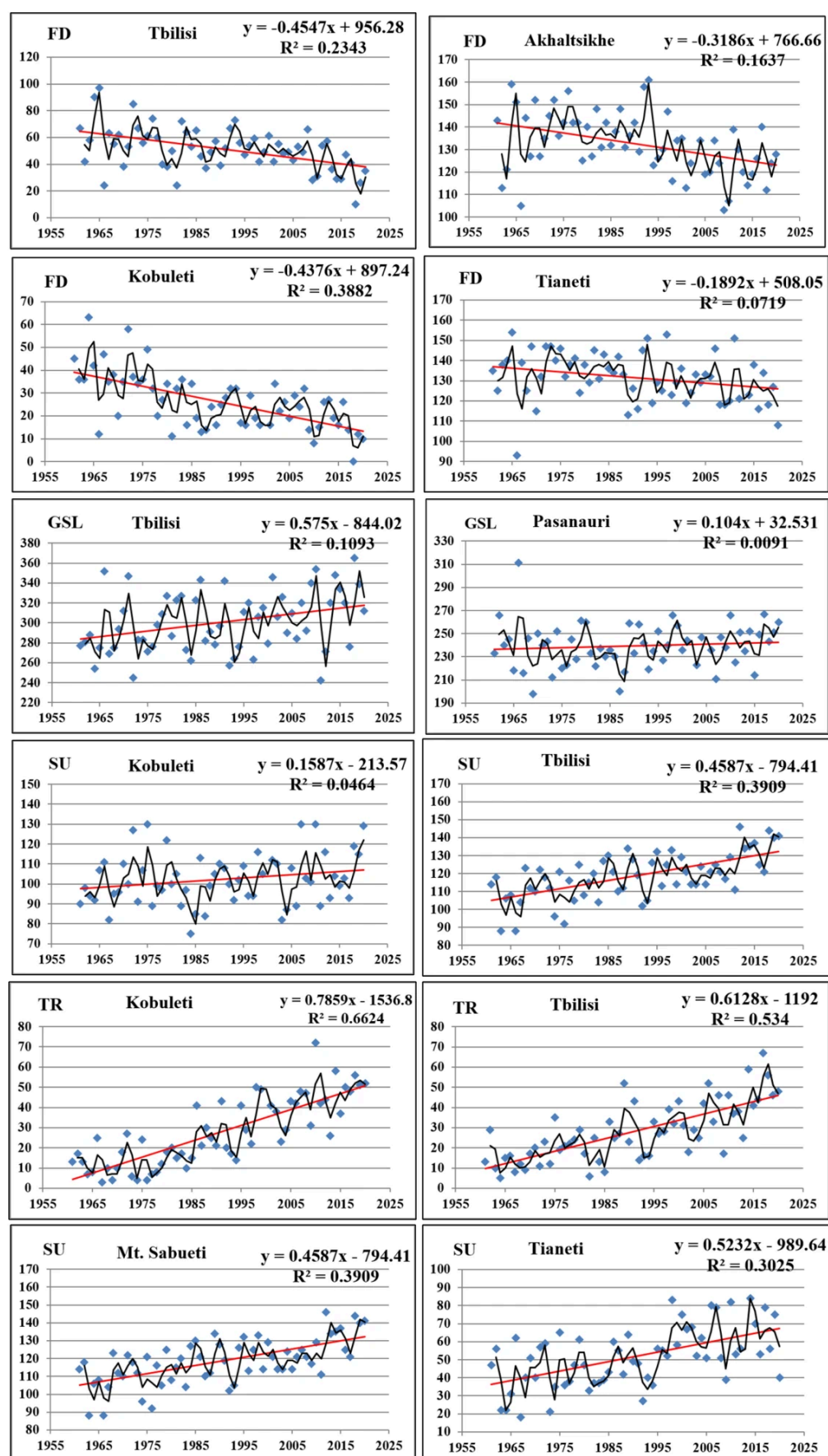


Figure 2. Long-term trends in some extreme air temperature indices, corresponding to linear regression equations, and the coefficient of determination (R^2).

The number of FD in the conditions of global warming is decreasing everywhere, which indicates an increase in night temperatures. The speed of reduction of the number of frost days (FD) in the significant territory of Georgia is approximately 2–3 days per decade, and on the Black Sea coast (Kobuleti) it exceeds 4 days per decade. At the same time, the contribution of the trend to the total variability of the number of frost days in Kobuleti reaches 38%.

The trends in ID and FD change are consistent with previous studies [28], according to which for the period 1971–2010, over Georgia, the average number of ice days changed by −1.0 days/decade, frost days by −3.3 days/decade.

For several indices, particularly ice days (ID) and cold extremes, the detected trends are statistically significant but explain less than 10% of the total variance. This discrepancy highlights the importance of distinguishing between statistical detectability and physical relevance. In such cases, the trends may reflect long-term tendencies embedded within highly variable time series rather than consistent monotonic changes.

Growing season length (GSL) increases on the plains of Eastern Georgia with greater speed (Tbilisi—up to 6 days per decade), than in the mountains of the Caucasus (Pasanauri—1 day per decade).

One of the main indicators of warming is summer days (SU). The rate of increase in the number of summer days is greatest in continental and mountain areas (Tbilisi, Mt. Sabuetti, Pasanauri—4–5 days per decade with more than 30% contribution of the trend to their variability), and the least on the Black Sea coast (Kobuleti—1.5 days per decade).

The observed increase in summer days in mountainous regions may be influenced by multiple interacting factors, including changes in snow cover duration and land–atmosphere interactions. However, the present analysis does not explicitly quantify these processes; therefore, such mechanisms should be considered as plausible hypotheses rather than confirmed drivers of the observed trends.

Tropical nights (TR) are among the most sensitive indicators of global warming. Their speed of increase on the Black Sea coast, in the Kolkheti Lowland, and in the plains of eastern Georgia is 6–8 days per decade. At the same time, the contribution of the trend to the total variability of the number of tropical nights exceeds 50–60%.

These changes of SU and TR also correspond to findings in previous studies [28], according to which, for the period 1971–2010 over Georgia, the average number of summer days changed by 3.4 days/decade, and tropical nights by 1.7 days/decade.

The hottest day temperature (TXX—Monthly maximum value of daily maximum temperature) and the coldest night temperature (TNn—Monthly minimum value of daily minimum temperature) were considered, and for the evaluation of extremely warm episodes in winter and extremely cold episodes in summer, the coldest day temperature (TXn—Monthly minimum value of daily maximum temperature) and the hottest night temperature (TNX—Monthly maximum value of daily minimum temperature) were considered.

Indices based on temperature distribution percentiles are also studied: Warm days (TX90p)—the number of days, when the maximum air temperature exceeds the threshold value, the 90% percentile of the maximum temperature and Cool nights (TN10p)—the number of days when the minimum air temperature is below the threshold value, the 10% percentile of the minimum temperature.

Table 4 presents the rates of change of these indices and the corresponding coefficients of determination in different physical and geographical conditions of Georgia, allowing us to judge the contribution of the trend to their total variability.

Table 4. Rate of change of temperature indices per decade (K) and corresponding coefficients of determination (R^2) in various physical and geographical conditions.

Index, Units	Weather Station											
	Kobuleti		Kutaisi		Mt. Sabueti		Tbilisi		Tsalka		Pasanauri	
	K	R^2	K	R^2	K	R^2	K	R^2	K	R^2	K	R^2
TX _x , °C	0.16	0.01	0.14	0.01	0.44	0.02	0.34 *	0.15 *	0.35*	0.11*	0.43*	0.02
TN _n , °C	0.35	0.05	−0.1	0	0.33	0.05	0.47 *	0.09 *	0.4	0.02	0.13	0
TX _n , °C	0.22	0.04	0.01	0	0.22	0.03	0.46 *	0.13 *	0.25	0.03	0.64	0.02
TN _x , °C	0.58 *	0.45 *	0.16	0.02	0.34 *	0.20 *	0.56 *	0.51 *	0.13	0.06	0.03	0
TX90p, days	3.56 *	0.14 *	7.51 *	0.20 *	5.78 *	0.25 *	7.9 *	0.42 *	7.35 *	0.35 *	6.59 *	0.28 *
TN10p, days	−7.17 *	0.56 *	−5.62 *	0.19 *	−4.41 *	0.25 *	−6.3 *	0.52 *	−2.35 *	0.10 *	−1.80 *	0.06 *

Note. Statistically significant values are highlighted in bold and with *.

It follows from Table 4 that almost at all points there is a positive trend in the change in the maximum value of daily maximum temperature (the hottest day—TX_x), the monthly minimum value of daily minimum temperature (the coldest night—TN_n), the monthly minimum value of daily maximum temperature (the coldest day—TX_n) and the monthly maximum value of daily minimum temperature (the hottest night—TN_x).

Although, the coefficients of determination are not high, the positive trend indicates that all the characteristics of extreme temperatures are increasing. Thus, (the hottest day—TX_x) maximum value of daily maximum temperature for the research period increased on the Black Sea coast (Kobuleti) and the Kolkheti Lowland (Kutaisi) at a rate of (0.14–0.16) °C, in eastern Georgia (Tbilisi) and on the southern Georgian highlands (Tsalka)—at a rate of (0.34–0.35) °C, and in mountainous areas of the Likhi range and Caucasus (Mt. Sabueti, Pasanauri)—at a rate of (0.43–0.44) °C per decade. The minimum value of daily minimum temperature (the coldest night—TN_n) during the same period increased somewhat faster—on the Black Sea coast and the Likhi range at a rate of (0.33–0.35) °C, in eastern Georgia (Tbilisi) and on the southern Georgian highlands (Tsalka)—at a rate of (0.40–0.47) °C, and in the mountains of the Caucasus somewhat slower—at a rate of 0.13 °C per decade. The minimum value of daily maximum temperature (the coldest day—TX_n) and maximum value of daily minimum temperature (the hottest night—TN_x) also increased significantly, up to 0.64 °C and 0.58 °C per decade. This means that the background temperature of the indicated indices for the entire period (1961–2020) of the study increased by 3–4 °C.

It also follows from the table that, unlike extreme temperatures, the change in temperature percentages is more significant. The rate of change of the 90th percentile of the annual maximum temperature is positive and fluctuates within 3–8 days, and the rate of change of the 10th percentile of the annual minimum temperature is negative and fluctuates between 2–7 days per decade. The growth of maximum percentiles and the decrease of the minimum temperature percentiles are obvious and explain the increase in hot days and tropical nights.

An integrated comparison of temperature metrics reveals a distinct asymmetry between daytime and nighttime climate dynamics across Georgia's physical-geographical zones. Nighttime temperature extremes show a more cohesive and robust warming signal than daytime metrics. For instance, the increase in Tropical Nights (TN), and the shifting of the lower tail of minimum temperatures (TN10p) demonstrate higher statistical significance and less regional variance than the corresponding daytime metrics (SU and TX90p). Geographically, this asymmetrical warming is highly modulated by altitude

and continentality. While high-mountain environments show acute sensitivity in absolute maximum thresholds (TX_x), the low-lying eastern continental basins exhibit the most pronounced shift in nighttime thermal baselines. In contrast, the maritime-dominated zones maintain a high degree of interannual noise, dampening the deterministic progression of linear trends and producing lower overall explanatory power (R^2).

4. Discussion

A key feature emerging from the analysis is the spatial heterogeneity of warming signals across Georgia. Continental and high-altitude regions demonstrate stronger and more consistent increases in warm-related indices compared to the Black Sea coastal zone. This contrast likely reflects the moderating influence of maritime conditions in western Georgia versus the higher continentality and radiative sensitivity of eastern and mountainous regions. Such differentiation suggests that regional climate responses to global warming are strongly modulated by local physical–geographical factors.

Compared to previous studies conducted for Georgia [28,29], the present analysis extends the temporal coverage to 2020 and confirms the persistence of asymmetric warming, with nighttime extremes increasing more rapidly than daytime extremes. However, the relatively low explanatory power of linear trends in several indices suggests that the recent decades may be characterized by increased variability and potential non-linear behavior, which cannot be fully captured by simple trend models.

The assumption of linearity in long-term trend analysis represents a simplification that may not fully capture the complexity of climate dynamics. Visual inspection of several time series indicates possible periods of accelerated warming and relative stabilization, suggesting temporal non-stationarity. Future studies should consider the application of non-linear methods or breakpoint analysis to better resolve these features.

The documented increases in tropical nights, summer days, and growing season lengths, alongside escalating extreme temperature indices, present immediate challenges for agriculture through altered crop vegetative periods and heightened heat stress conditions. This thermal intensification directly impacts water-resource management by accelerating evapotranspiration demands, while simultaneously straining energy systems due to surging peak cooling demands during summer months. From a societal standpoint, these trends elevate public health vulnerabilities by increasing thermal stress and the frequency of severe heat waves. Collectively, these findings underscore the urgent need for targeted climate adaptation planning and localized risk assessments. This is particularly crucial in mountainous and continental regions, where the observed warming signals are most pronounced and ecosystem sensitivities are highly acute.

The stark statistical contrast in trend magnitudes between the distinct physical–geographical zones offers important clues regarding regional climate dynamics, though these links must be interpreted as potential mechanisms rather than confirmed causal relationships. The muted shifts in temperature extremes observed across the humid subtropical Black Sea coast and Kolkheta Lowland point to a plausible buffering effect driven by maritime moisture and localized thermal inertia. Conversely, the more pronounced warming signals detected in eastern continental basins and high-altitude mountain ranges suggest a heightened localized sensitivity, potentially modulated by lower relative humidity, reduced cloud cover, or altered surface-albedo feedbacks in alpine terrains. Because the present study does not directly integrate environmental variables such as sea surface temperature (SST), humidity profiles, or snow cover dynamics, these spatial variations are presented as localized tendencies that warrant future physical validation through integrated meso-scale climate modeling.

Although linear trends provide a useful first-order description of long-term changes

in climate extremes, they may not fully capture the complexity of climate variability. Some of the observed fluctuations may reflect non-linear behavior, abrupt shifts, or changes in the underlying climate regime associated with large-scale atmospheric circulation patterns. The relatively low R^2 values obtained for several indices suggest that a substantial proportion of variability remains related to natural interannual and decadal fluctuations. Future studies could therefore benefit from the application of breakpoint and change-point detection techniques, segmented regression approaches, or other non-linear statistical methods to identify possible regime shifts and temporal non-stationarity in temperature extremes across Georgia.

While this study aligns with and builds upon the core regional warming patterns identified by Keggenhoff et al. [28,29]—such as the systemic reduction in frost and ice days alongside an inflation of summer days and tropical nights—it introduces several critical advancements that substantially update the regional climate narrative. First, by extending the temporal horizon to 2020, this work captures a highly accelerated decade of global warming (2011–2020) omitted in earlier assessments, thereby establishing that percentile-based thresholds (TX90p and TN10p) operate with significantly higher decadal sensitivity than absolute indices. Second, unlike previous iterations that relied on broad regional groupings or fewer observation points, this analysis utilizes an expanded, homogenized network of 20 stations stratified across highly granular physical-geographical zones. This structural refinement reveals a key interpretative nuance: despite strong underlying warming tendencies, many statistically significant trends yield relatively low coefficients of determination ($R^2 < 0.1$). This reveals that local topographies and the buffering influence of the Black Sea modulate large-scale radiative forcing, meaning these shifts represent emerging, micro-climatological tendencies rather than uniform deterministic trends. Consequently, these methodological and spatial expansions elevate the study from a temporal update to a multidimensional evaluation of topographically driven climate vulnerability in Georgia.

5. Conclusions

This study provides a comprehensive regional assessment of temperature extremes in Georgia, contributing to a better understanding of climate change patterns in a complex mountainous environment.

This study analyzed long-term changes in the temperature regime of Georgia for the period 1961–2020. On the basis of climate indices recommended by WMO and ETCCDI, it was possible to identify stable and statistically significant manifestations of modern global warming, expressed with different intensity depending on the physical and geographical conditions of the region.

The results indicate that in all considered regions of the country, there is a tendency to increase both daily maximum and minimum air temperatures, as well as extreme temperature characteristics. These changes are most noticeable in the continental and mountainous regions of eastern Georgia, the southern Georgian highlands, and the middle mountain zone of the Greater Caucasus, where there is a reduction in the number of ice days and frost days while simultaneously increasing the number of summer days, tropical nights, and growing season length. The rate of change of a number of indices reaches several days or tenths of a degree per decade, which leads to a significant shift in the temperature background for the entire investigated period.

In the conditions of the wet subtropical climate of the Black Sea coast and the Colchis lowland, changes in most temperature indices are weaker, which indicates the softening influence of the Black Sea and humid landscapes. At the same time, even here, a statistically significant increase in the number of tropical nights was revealed, indicat-

ing an increase in night temperatures and an increase in thermal stress.

The analysis of percentile indices showed that they are the most sensitive indicators of global warming: an increase in the 90th percentile maximum temperature and a simultaneous decrease in the 10th percentile minimum confirm the strengthening of thermal extremes and the redistribution of the temperature regime towards warmer conditions. An increase in minimum absolute maximums and maximum absolute minimum temperatures indicates an increase in background extreme values, which has important climatic and practical consequences.

Although several indices exhibit statistically significant trends, the associated coefficients of determination are generally low in many cases ($R^2 < 0.1$), indicating that only a small fraction of the total variability is explained by the linear trend component. This suggests that interannual and decadal variability remains dominant, and that the identified trends should be interpreted as weak signals rather than strong deterministic changes.

This study provides an updated, comprehensive assessment of temperature extreme dynamics across Georgia from 1961 to 2020 by employing a robust 20-station network categorized by physical-geographical characteristics. The empirical evidence points toward long-term progressive warming tendencies that align with broader global observations. However, we conclude that these manifestations are neither uniform nor strictly deterministic. The prevalence of low R^2 values across numerous statistically significant trends underscores that linear climate trajectories explain only a minor fraction of regional interannual variance. Climate change in Georgia operates not as a homogeneous shift, but as a topographically modulated tendency that coexists with intense localized natural variability, with alpine and continental settings exhibiting the highest vulnerability, and coastal lowlands presenting distinct thermal resilience.

Several limitations of the present study should be acknowledged. First, the analysis is based on linear trend estimation, which may not fully capture the non-linear behavior, temporal non-stationarity, or possible regime shifts that can characterize climate variability and change. Second, although the meteorological station network provides broad coverage of Georgia, station density remains relatively limited in some high-mountain regions, which may reduce the spatial representativeness of the results in areas with complex topography. Third, the study focuses primarily on the statistical characteristics of temperature extremes and does not explicitly investigate the influence of large-scale atmospheric circulation patterns, climate teleconnections (e.g., the North Atlantic Oscillation), or other physical drivers that may contribute to the observed variability and trends. Finally, the analysis relies exclusively on homogenized station observations and does not incorporate complementary information from reanalysis products or climate-model simulations, which could provide additional insight into the mechanisms and future evolution of temperature extremes. Future research should address these limitations through the application of non-linear statistical approaches, change-point detection techniques, circulation-based analyses, and the integration of observational, reanalysis, and climate-model datasets.

Author Contributions: Conceptualization, methodology, writing—original draft preparation, supervision, reviewing, final approval of the version: N.C. and M.E.; data curation, analysis, interpretation of data: I.K. and N.S.; investigation, research conclusions: E.E., G.D. and G.G. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Shota Rustaveli National Science Foundation of Georgia (SRNSFG) grant number: FR-24-13403.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available on request from the corresponding author.

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

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