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Seasonal Transformation of the Thermal Regime in Bulgaria (1950–2025): A Spatiotemporal Analysis Using ERA5-Land data set and Google Earth Engine

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ABSTRACT

This research presents a high-resolution spatiotemporal analysis of surface air temperature trends in Bulgaria over a 76-year period (1950–2025). Utilizing the ERA5-Land reanalysis dataset and the Google Earth Engine (GEE) cloud computing platform, the study quantifies seasonal warming magnitudes and identifies structural shifts in the regional thermal regime. Results demonstrate a definitive transition from a stable continental climate to an accelerated warming phase, particularly after 1987. The total warming magnitude since 1950 is most pronounced in summer (+3.2°C) and winter (+2.9°C), with spring and autumn showing significant increases of +2.4°C and +2.1°C, respectively. A comparative dual-trend analysis reveals that warming velocity has approximately doubled during the most recent 20-year window (2005–2025), with decadal slopes in summer reaching nearly +0.80°C. Statistical robustness, evidenced by a significant rise in the coefficient of determination (R2) during the 21st century, indicates that the warming signal has become a forced response that overrides natural stochastic variability. Spatially, the Danubian Plain and Upper Thracian Lowland have emerged as warming hotspots, exhibiting total magnitudes exceeding +3.8°C, effectively signaling a "Tropicalization" of the Bulgarian lowlands. These shifts are linked to critical environmental consequences, including the "False Spring" paradox – where early thermal onset increases frost vulnerability – and a destabilized hydrological cycle characterized by premature snowmelt and a transition to a drought-to-flood regime. The findings align with the other regional studies identifying the Balkan Peninsula as a high-sensitivity climate hotspot, with warming rate higher than the global terrestrial average. This study underscores the urgent necessity for climate-resilient adaptation strategies in Bulgarian agriculture, water management, and urban planning to address the high-velocity thermal transformation of the territory.

Keywords: *Climate acceleration, Bulgaria, Surface air temperatures, ERA5-Land, Remote sensing*

INTRODUCTION

Surface air temperature (SAT) is a primary geophysical variable and a fundamental indicator of the Earth's thermodynamic state, directly influencing hydrological cycles, ecosystem stability, and human health. Within the Eastern Balkan Peninsula, Bulgaria represents a complex climatological intersection where temperate continental, Mediterranean, and modified maritime influences converge across a diverse topographic landscape. Over the past seven decades, this region has exhibited a high sensitivity to global climate changes, characterized by accelerated warming, shifts in seasonal phenology, and an increased frequency of extreme thermal events (Bocheva et al., 2024; Nojarov and Nikolova, 2022). Recent global climate assessments have highlighted Southeast Europe as a "warming hotspot," with regional SAT increases exceeding the global mean rate (IPCC, 2023).

The historical analysis of Bulgarian temperatures traditionally relied on point-based meteorological station data. However, the high and diverse relief of the country – ranging from sea level to nearly 3,000 meters – creates significant spatial heterogeneity and "data voids," particularly in high-altitude regions where station maintenance is difficult. To address these spatial gaps, atmospheric reanalysis has become an indispensable tool in modern climatology. The ERA5-Land reanalysis, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), provides a consistent, high-resolution (9 km) spatial grid that integrates millions of historical observations (Muñoz-Sabater et al., 2021). By providing a continuous data record from 1950 to the present, ERA5-Land reanalysis data allows for the detection of long-term climate signals that are often obscured by local microclimatic noise in individual station records (Ivanov et al., 2025).

A critical finding in recent Bulgarian climatological research is the identification of a distinct "climate break" occurring in the late 1980s. Nikolova (2012), Nojarov and Nikolava (2022), Bocheva et all., (2024) have both statistically validated this regime shift, noting that temperature anomalies transitioned from predominantly negative to consistently positive following this year. Specifically, Nikolova’s (2012) analysis of extreme temperature months in the Rila Mountain reveals that while the period 1961–1986 was characterized by frequent extremely cold months, the subsequent period (1987–2012) saw extreme warm months represent 70% of all recorded thermal extremes. This systemic shift initiated a period where the frequency of cold anomalies dropped drastically, replaced by a consistent warming "red" regime that has intensified into the 2020s (Bocheva et al., 2024; Ivanov et al., 2025).

This intensification reached a peak in 2024, which recorded a national average temperature 2.1°C above climate norms, making it the warmest year in Bulgarian history since 1930 (NIMH, 2025). Preliminary data suggests that 2025 continues this trend, following global records that identify the most recent decade as the warmest on record (WMO, 2025). Furthermore, the warming velocity has shown a non-linear acceleration. While the long-term decadal warming rate for the 1950–2024 period ranged between 0.32°C and 0.48°C, warming velocities nearly doubled in the last twenty years (2005–2024) to 0.60°C–0.85°C per decade (Ivanov et al., 2025).

Ivanov et al. (2025) in similar research based on ERA 5 data and GEE processing, about the dynamics of the mean annual temperatures in Bulgaria regarding the same period disclosed that the long-term spatial distribution of the annual surface air temperature (SAT)across Bulgaria, reveals a distinct topographic-climatic stratification (Fig.1). These findings align closely with the regional framework established by Velev (2002), showing that thermal maxima are concentrated in the Continental-Mediterranean region of Southwest Bulgaria, as well as South-Central and Southeast

Bulgaria. These areas serve as primary thermal gateways where Mediterranean air masses exert their most significant influence (Marinova et al., 2017). Conversely, thermal minima are located in the Mountainous region, where the high-altitude massifs of the Rila, Pirin, Rhodope, and Balkan ranges maintain annual means below 4°C. This sharp contrast validates the use of high-resolution gridded ERA5-Land data, which successfully captures the steep thermal gradients between Bulgaria’s lowlands and alpine zones (Ivanov et al., 2025).

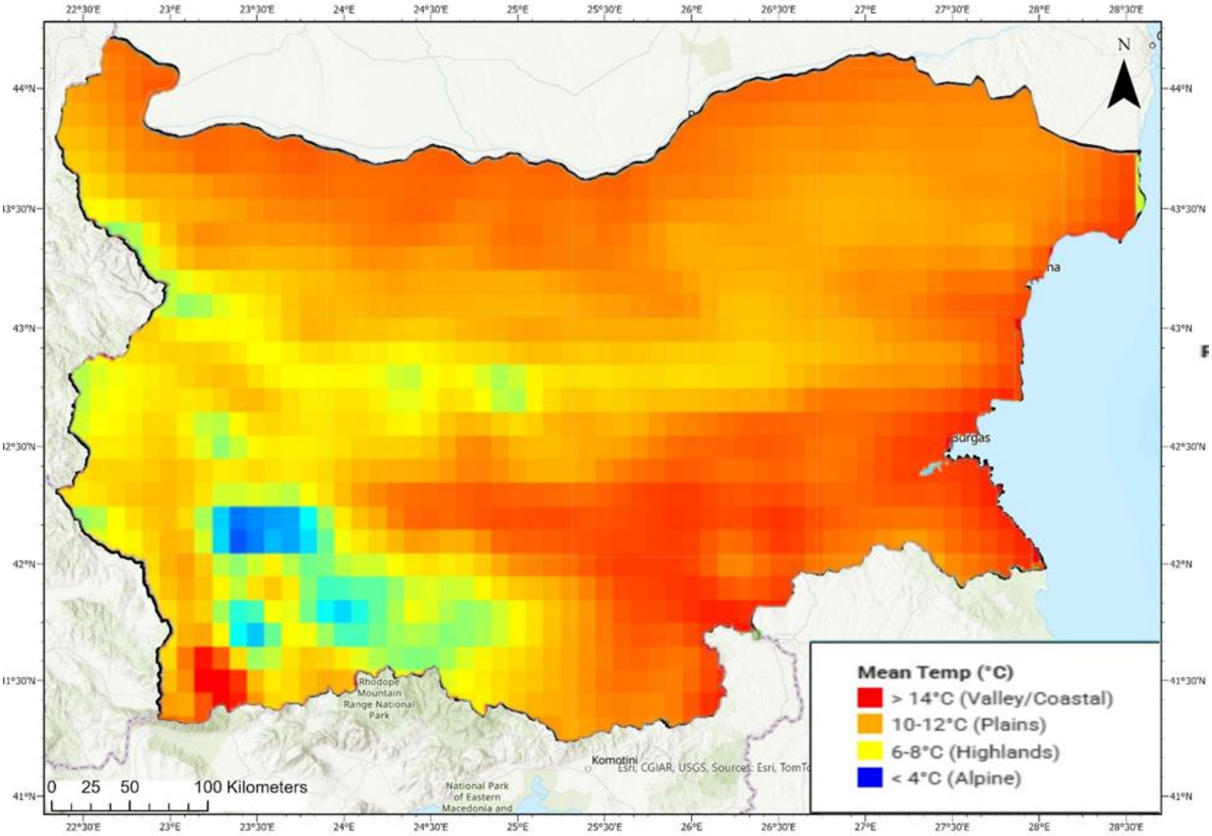

Fig. 1. Spatial distribution of the mean annual temperatures -1950-2024. Source: *Ivanov et al. (2025).*

According Ivanov et al. (2025) the multi-decadal record of the mean annual temperatures indicates a consistent warming trajectory defined by a definitive shift in the late 1980s (Fig. 2). The period from 1950 to 1987 was characterized by significant inter-annual variability, with several years remaining below the long-term average – a reflection of a more stable climate influenced by continental air masses. However, following the 1987 "climate break," a sustained and visible increase in mean annual temperatures occurred (Ivanov et al., 2025).

In the last two decades, the frequency of negative anomalies has decreased substantially, while extreme thermal peaks were recorded in 2023 and 2024, confirming Bulgaria’s status as a regional warming hotspot (Fig. 2) and the shifting of the thermal regime into a new state marked by higher annual means and a significant departure from the mid-20th-century baseline (Ivanov et al., 2025).

Ivanov et al. (2025) disclosed that between 1950–2025 a synchronized warming trend can be observed across all of the Bulgaria's climatic zones even though there are thermal differences due to topography and maritime proximity, the calculated trend lines show that the magnitude of warming is relatively uniform across the territory (Fig. 3, and 4).

The Continental-Mediterranean region remains the warmest, with annual means often exceeding 13°C, while the Moderate and Transitional Continental regions occupy a middle tier (10°C to 12°C).

Despite these differences, the warming slope across all five regions is remarkably similar, increasing by approximately 0.3°C to 0.4°C per decade. This synchronization suggests that large-scale regional climate forcing is dominating local geographical effects.

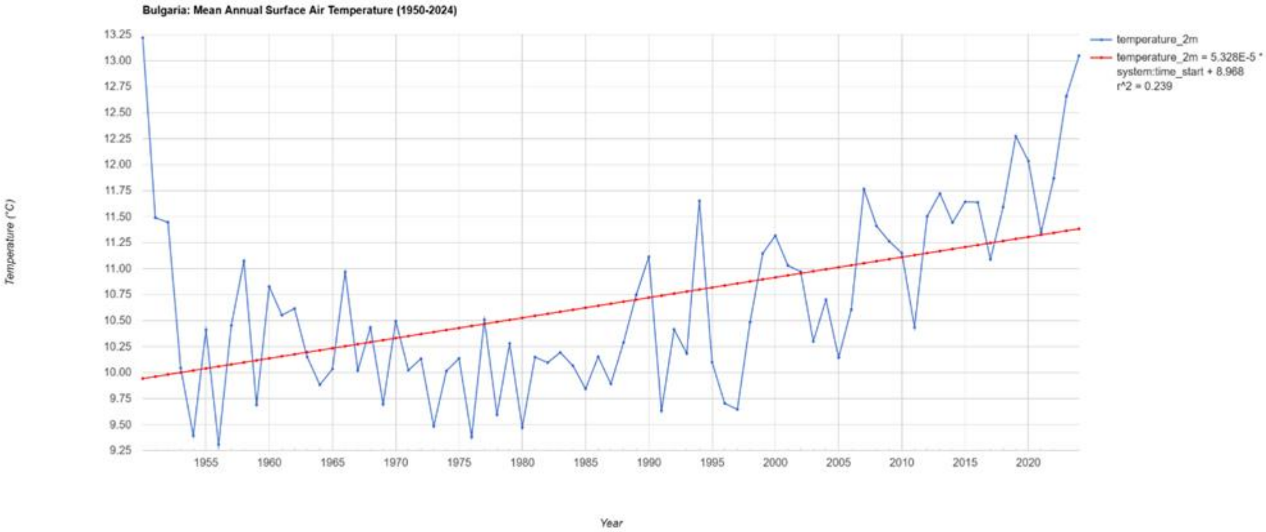

Fig. 2. Dynamics of the mean annual temperatures -1950-2024. (after Ivanov et al.,2025)

Ivanov et al. (2025) based on ERA -5 data confirmed that Bulgaria is warming significantly faster than the global terrestrial average. While the global land-surface warming rate is roughly 0.2°C per decade, Bulgarian regions are warming at an average rate of 0.32°C to 0.48°C per decade. Major portions of the Danubian Plain and the Upper Thracian Plain have crossed the 0.4°C per decade threshold, implying a cumulative increase of approximately 3.0°C during 1950-2025.

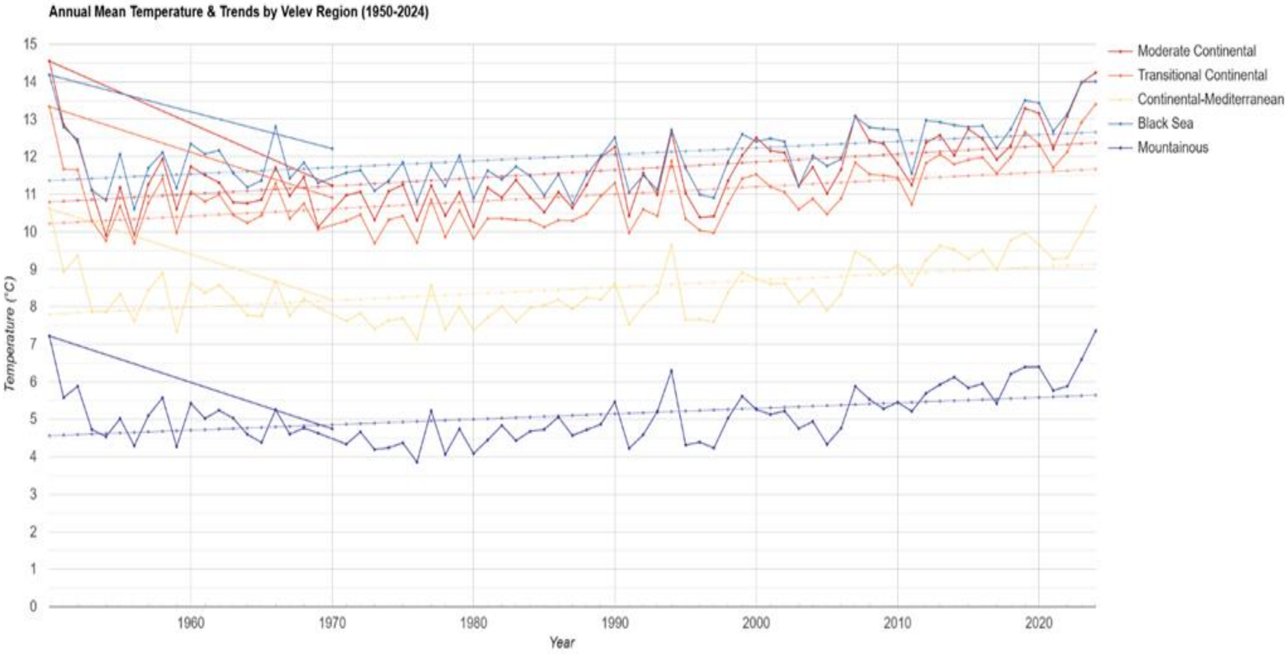

Fig. 3. Dynamics of the mean annual temperatures in Velev (2002) climate regions -1950-2024. Source: *Ivanov et al. (2025).*

The results reveal a clear contrast in climate velocity driven by land-sea interactions and topography. The highest warming rates are found in the continental interior, where the lack of large water bodies allows the land to heat rapidly, likely amplified by a feedback loop where decreasing soil moisture reduces evaporative cooling. In contrast, the Black Sea region exhibits lower decadal slopes (0.32°C to 0.35°C) due to the thermal inertia of the sea (Fig.5).

Crucially, the warming rate in high-altitude zones mirrors the lowlands, suggesting that as snow cover decreases, the exposed ground absorbs more solar radiation, creating a self-reinforcing warming cycle (Nojarov, 2012).

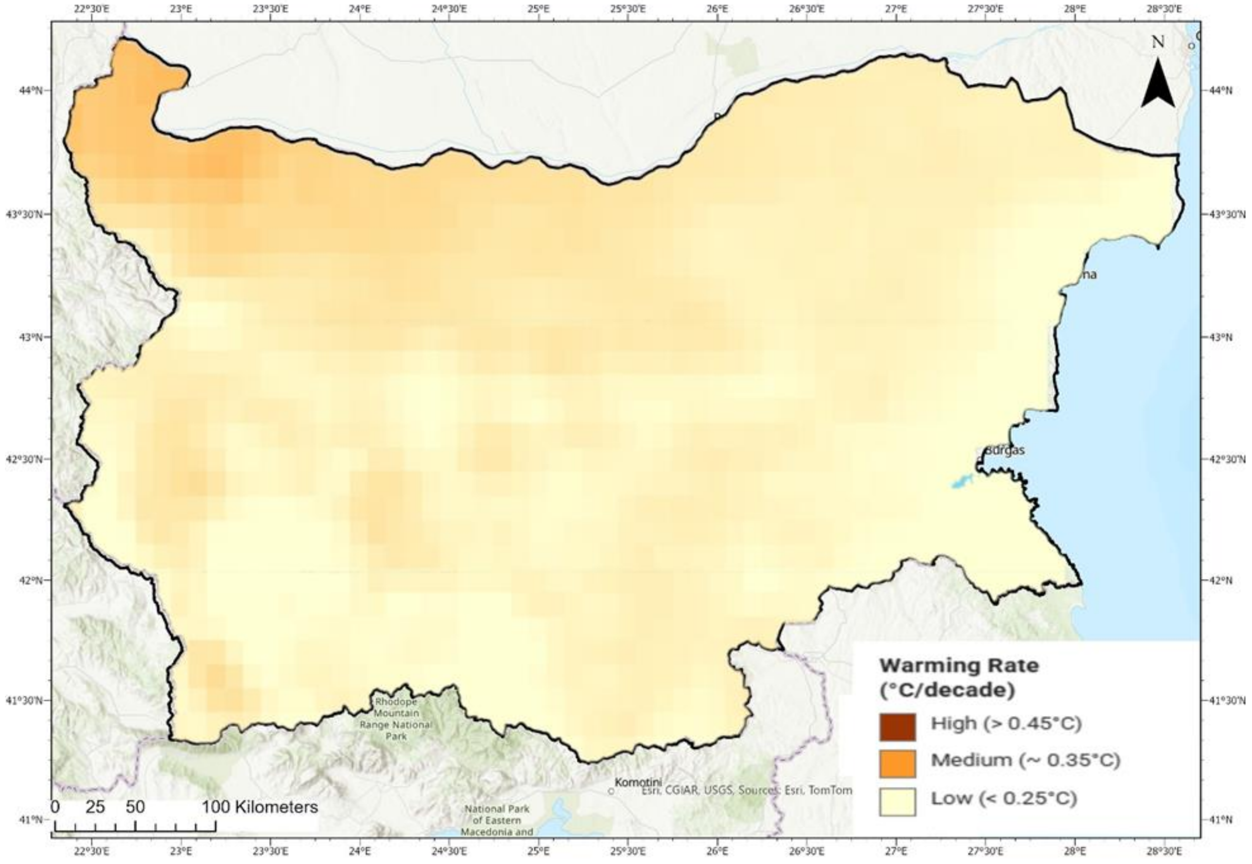

Fig. 4. Spatial distribution of the magnitude of the warming 1950-2024. Source: *Ivanov et al. (2025).*

Significant Stippling Analysis provides scientific validation for these observations, covering nearly 100% of the Bulgarian territory for the 1950–2025 period, indicating that the warming trend is statistically undeniable ($p < 0.05$). A comparison between the long-term baseline (1950–2025) and the last 20 years (2005–2025) reveals a profound escalation in warming velocity, with the rate essentially doubling in recent decades (Fig. 6).

This is driven by a clustering of record-breaking years; all ten of the warmest years in Bulgarian history have occurred since 2005, with 2024 identified as the warmest year since 1930, reaching 2.1°C above climate norms (NIMH, 2025).

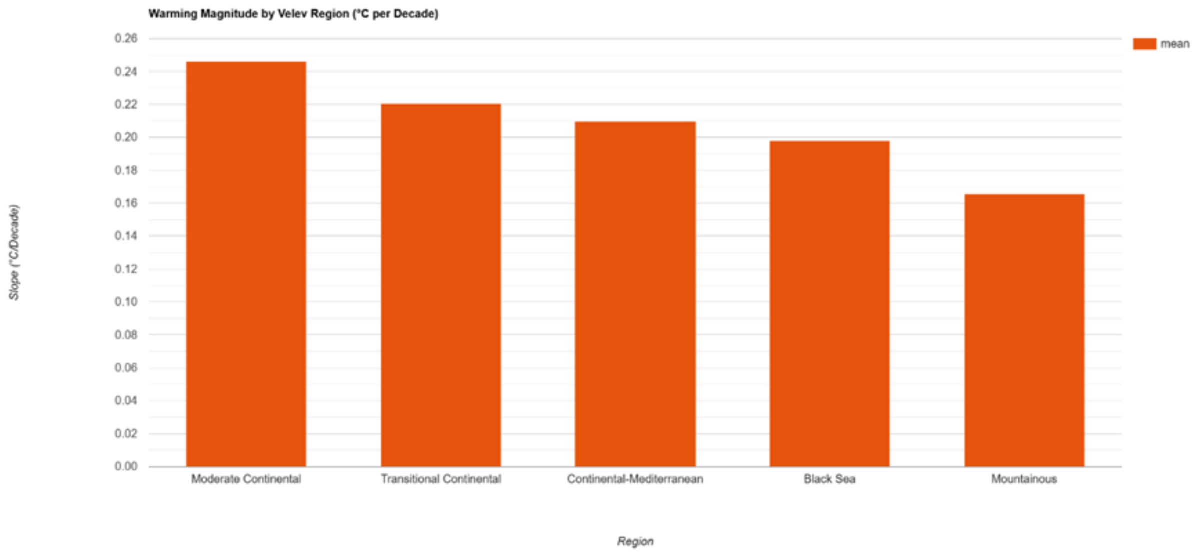

Fig. 5. Magnitude of the warming 1950-2024 – Velev regions (2002). Source: *Ivanov et al. (2025).*

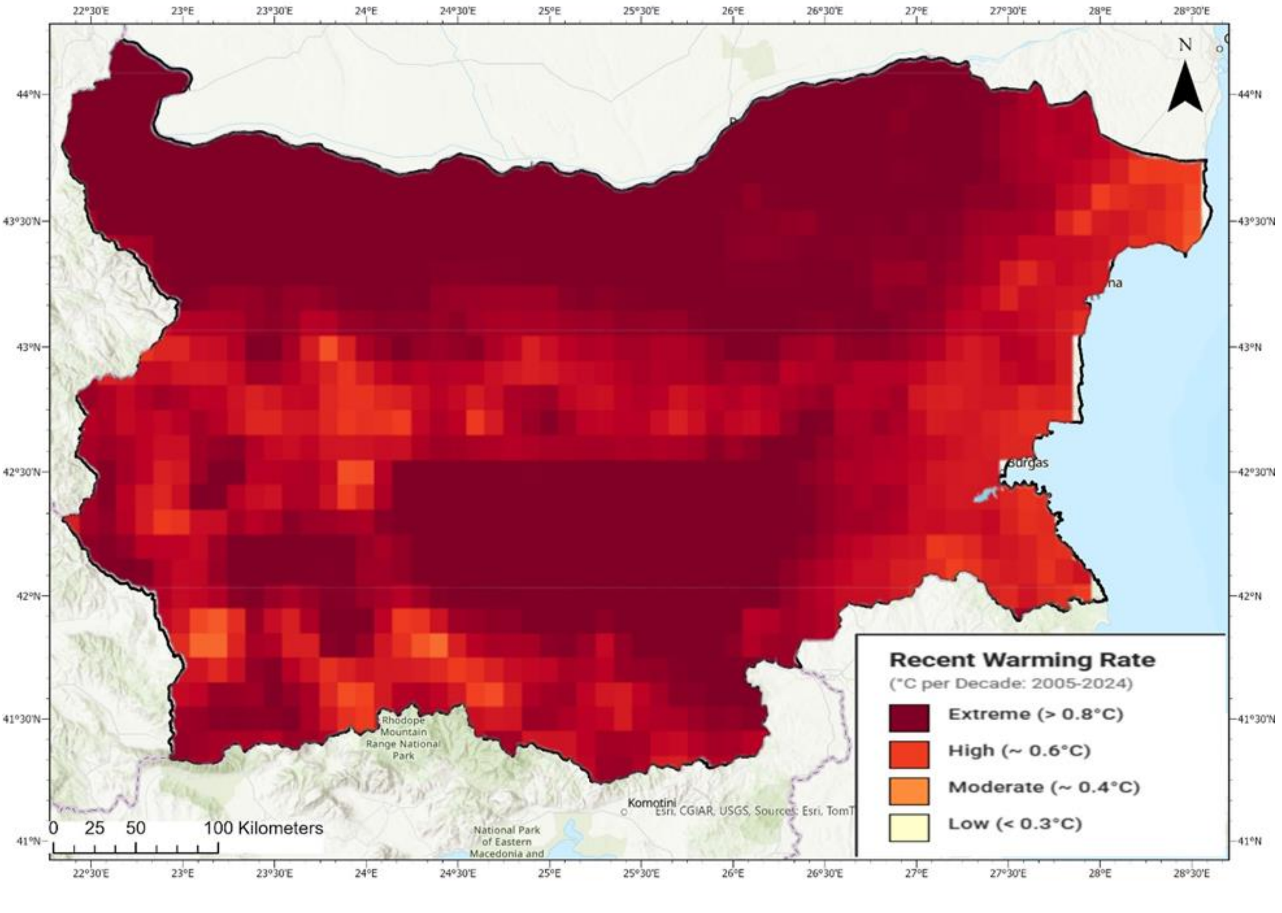

Fig. 6. Spatial distribution of the magnitude of the warming last 20 years (2005-2024) according to Ivanov et al. (2025).

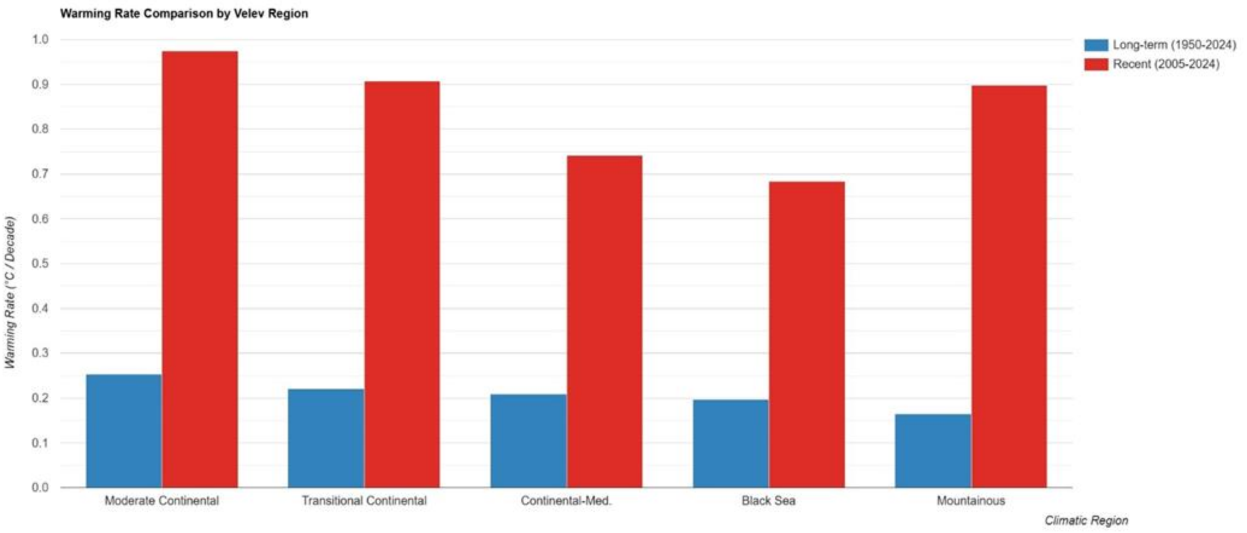

Fig. 7. Magnitude of the warming 1950-2024 – Velev regions (2002) Ivanov et al. (2025).

To pinpoint the transition from a stable state to rapid warming, Ivanov et al., (2025) conducted a breakpoint analysis using the Cumulative Sum (CUSUM) of temperature anomalies. This identifies a "break point" around 1987–1988. Prior to 1987, anomalies were balanced, but afterward, negative anomalies dropped drastically, virtually disappearing in the last 20 years (Fig. 8 and 90. This represents a regime shift, with a jump of 1.0°C to 1.5°C in average annual temperatures.

According to Nojarov (2012) the temperatures and precipitation change is due to changes in large-scale atmospheric circulation, specifically shifts in the North Atlantic Oscillation (NAO) and East Atlantic (EA) patterns, which increased warm air advection from the south. The data also suggests that the country entered a new acceleration phase after 2005, pushing the territory toward the extreme thermal records of 2024 and 2025.

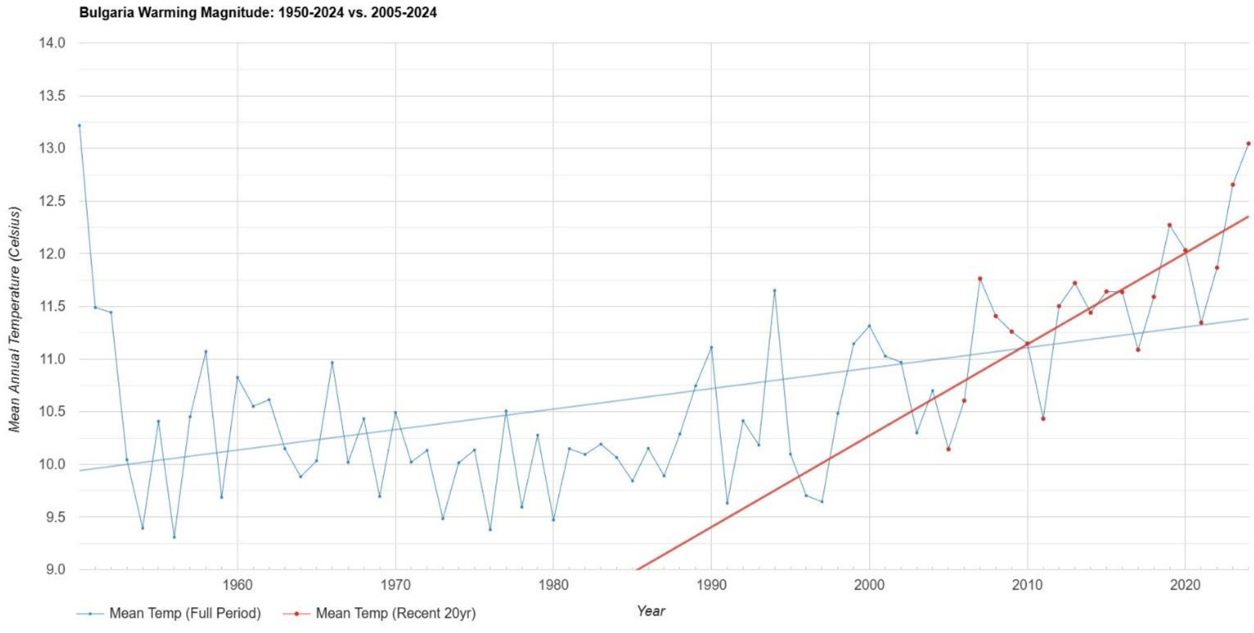

Fig.8. Mean annual averages for 1950-2024 and 2005-2024 with trend lines (according to Ivanov Ivanov et al., 2025).

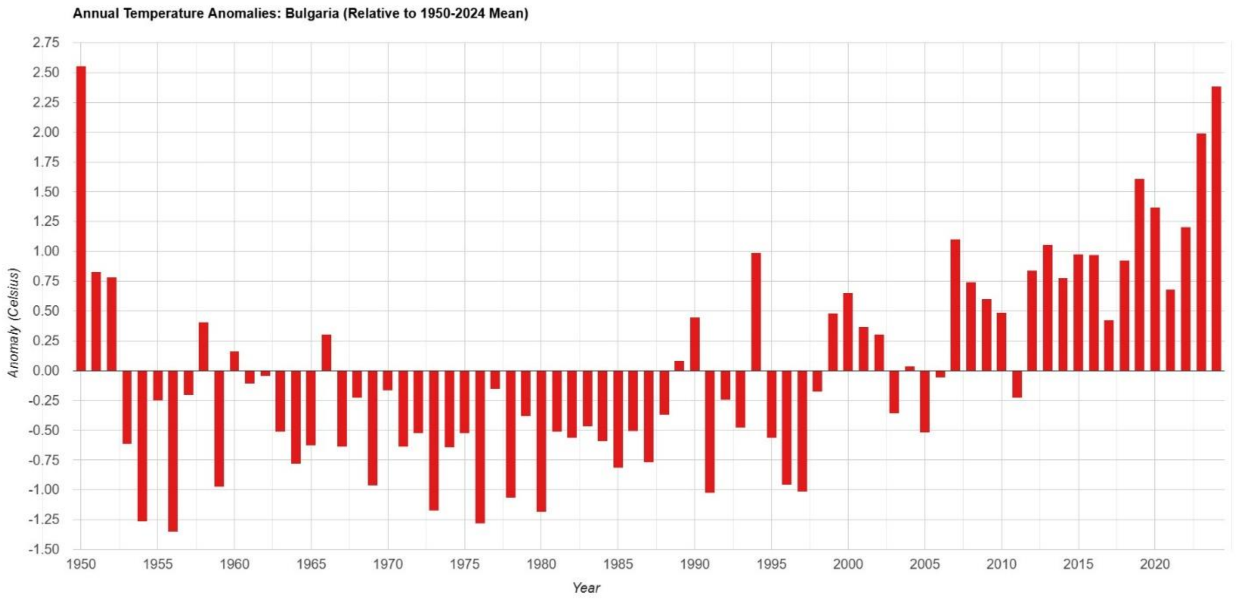

Fig. 9. Annual temperature anomalies relative to long term means (1950-2024) according to Ivanov et al. (2025).

Building upon the spatiotemporal analysis of annual means, the present study expands its scope to investigate the intricate seasonal dynamics of Bulgarian temperature regimes up to 2025. This broader perspective is necessitated by the observation that annual averages often mask critical seasonal "engines" of warming, such as the disproportionate increase in summer thermal stress or the precipitous decline of winter snow-albedo feedback mechanisms. As atmospheric forcing intensifies, traditional geographical moderators – such as proximity to the Black Sea or altitudinal cooling – are increasingly failing to regulate regional sensitivity.

By utilizing the **Google Earth Engine (GEE)** cloud-based platform (Gorelick et al., 2017), we implement a pixel-based Ordinary Least Squares (OLS) regression and trend detection across the Bulgarian territory. This approach allows for a granular mapping of seasonal shifts (DJF, MAM, JJA, SON), uncovering how the transition from stable temperate patterns to more volatile, Mediterranean-influenced cycles is altering the country's environmental baseline. Ultimately, this comprehensive seasonal inventory provides the high-resolution evidence required for adaptive planning in Bulgaria's most climate-vulnerable sectors, including water resource management and agricultural phenology.

MATERIALS AND METHODS

This section outlines the study area, data sources, and methodological framework employed to analyse the spatiotemporal and seasonal dynamics of surface air temperature in Bulgaria for the period 1950–2025, based on ERA5-Land reanalysis data and cloud-based processing in Google Earth Engine.

Study Area

The study area encompasses the entire territory of Bulgaria, which enclosed 110,994 km² situated in the eastern part of the Balkan Peninsula. The country's physical landscape is defined by high morphological diversity, characterized by four alternating bands of high and low terrain extending from west to east: the Danubian Plain, the Balkan Mountains, the Transitional region (including the

Thracian Lowland), and the Rila-Rhodope massif. Bulgaria's topography is composed of approximately 31% lowlands (0–200 m), 41% hills and plateaus (200–600 m), and 28% mountainous terrain. The average altitude is approximately 470 m, but the extreme vertical range – from the Black Sea level to the alpine peaks of the Rila Mountains (Musala, 2,925 m) – creates sharp thermal gradients that necessitate the use of high-resolution gridded datasets like ERA5-Land.

This structural complexity acts as a decisive factor in the distribution of surface air temperature, as the Balkan Mountains serve as a significant barrier to the cooling influence of northern continental air masses, while the southern massifs modulate Mediterranean influences. The territory of the country is divided in climatic zones according the regional framework established by **Velev (2002)**. This framework classifies the territory into five distinct climatic regions based on the dominant atmospheric circulation and geographic factors with following specific climate features:

- **Moderate Continental Region (Northern Bulgaria):** This region encompasses the largest portion of Bulgaria, covering the extensive Danubian Plain, the rolling hills of the Fore-Balkan, and high western basins such as the Sofia Plain (Velev, 2002; Kopralev, 2002). This area is characterized by a geographical openness to the north and northeast, which facilitates the frequent and unimpeded intrusion of cold continental air masses from Central and Eastern Europe (Marinova et al., 2017; Velev, 2002). Consequently, the region exhibits the most pronounced seasonal temperature amplitudes in the country, as the Balkan Mountains act as a barrier to the south, preventing the moderation of temperature by Mediterranean influences (Kopralev, 2002). Winter conditions are typically severe, with average January temperatures falling between 1°C and 3.8°C (Marinova et al., 2017; World Bank, 2025). Due to the lack of northern topographic barriers, the region is highly prone to extreme cold spells where temperatures can drop below 25°C or even reach historical minimums of -38.3°C during powerful arctic anticyclonic invasions (Marinova et al., 2017; Kopralev, 2002). In contrast, the summers are hot and sweltering, with July average temperatures ranging between 21°C and 25°C (Velev, 2002; Marinova et al., 2017). Absolute maximum temperatures in the lowlands frequently exceed 35°C to 40°C, particularly in northern riparian towns such as Ruse and Silistra. The precipitation regime in this zone follows a distinct continental pattern where the annual totals generally range between 450 mm and 650 mm (Velev, 2002). There is a prominent seasonal maximum in early summer, specifically in June, which can account for up to 35% of the annual rainfall amount (Marinova et al., 2017; Velev, 2002). The driest period occurs during the winter, with a minimum typically recorded in February (Marinova et al., 2017). Persistent snow cover is a characteristic feature of the regional winter and can last between 40 and 60 days per year, although recent decadal observations indicate a significant reduction in both snow depth and duration (Bocheva et al., 2024; World Bank, 2025). The atmospheric circulation is dominated by western and northwestern winds that bring Atlantic moisture, while strong northeastern winds in the winter are responsible for freezing temperatures and snowdrifts across the eastern and central Danubian Plain (Velev, 2002). Powerful ground-level inversions are common in the flat lands and basins during winter, effectively trapping cold air masses for extended periods (Marinova et al., 2017). Furthermore, the region frequently experiences the Feohn effect, characterized by warm and dry winds descending from the northern slopes of the Balkan Mountains, particularly during the spring months (Marinova et al., 2017). Sub-regional variations exist within this zone, such as in the Northeastern Dobrudzha area, which displays more steppe-like features with lower annual precipitation, often less than 500 mm, and higher wind speeds (Kopralev, 2002; Svetozarevic, 2025).

- **Transitional Continental Region (Central Bulgaria):** This region represents a critical climatic buffer zone situated between the Moderate Continental North and the Mediterranean-influenced South. This region encompasses the Upper Thracian Lowland, the valleys of the Trans-Balkan sub-region such as the Kazanlak and Karlovo basins, and the eastern slopes of the Balkan Mountains (Velev, 2002; Topliyski, 2006). Its climate is defined by the complex interaction between transformed Atlantic air masses, continental influences from the north, and Mediterranean cyclonic activity from the south (Marinova et al., 2017). The thermal regime is characterized by noticeably milder winters compared to the Moderate Continental zone. Average January temperatures are typically positive, ranging from 0°C to 1.5°C, although the region remains susceptible to occasional arctic intrusions that can trigger sharp, short-lived temperature drops (Marinova et al., 2017; World Bank, 2025). Summers are long and hot, with average July temperatures between 22°C and 24°C (Velev, 2002). Notably, the Upper Thracian Lowland serves as a heat pole for Bulgaria; the town of Sadovo holds the national absolute maximum record of 45.2°C, and recent data indicates that the city of Plovdiv has seen a significant increase in days exceeding 30°C, frequently surpassing 100 days per year in the last decade (Ivanov, 2025; Marinova et al., 2017). The precipitation regime in this region is uniquely balanced, displaying transitional features between the continental and Mediterranean types. Unlike the North, which has a single summer maximum, the Transitional region often exhibits two distinct maxima: one in May–June due to continental influence and a second, smaller peak in November–December driven by Mediterranean cyclonic activity (Topliyski, 2006; Marinova et al., 2017). Annual precipitation totals generally range from 500 mm to 600 mm, though the region is highly prone to summer and autumn droughts (Bocheva et al., 2024; Pankov, 2014). Recent studies suggest a weakening of continental precipitation signals, with a trend toward a more even monthly distribution, yet with an increasing frequency of intense, convective wet events (Marinova & Bocheva, 2023). Atmospheric circulation is highly influenced by the shielding effect of the Balkan Mountains to the north and the Sredna Gora range. This protection results in lower average wind speeds, typically between 1.2 and 4.0 m/s, and frequent winter temperature inversions in the lowland basins (Marinova et al., 2017; Petrova, 2020). These inversions often lead to prolonged periods of fog and localized air pollution. The favorable thermal conditions, with a vegetation period temperature sum of approximately 4200°C to 4250°C, support the cultivation of thermophilic crops such as cotton, tobacco, and grapes, though increasing evapotranspiration rates are heightening irrigation demands (Kazandjiev et al., 2024).

- **Continental-Mediterranean Region (Southern Valleys):** This region extends across the southernmost parts of Bulgaria, primarily encompassing the valleys of the Struma and Mesta rivers south of the Kresna Gorge, the Arda river basin, and the coastal lowlands near the border with Turkey (Velev, 2002). This region serves as the primary gateway for Mediterranean air masses, which move northward along the river valleys, significantly altering the thermal and precipitation regimes compared to the rest of the country (Topliyski, 2006). The geographical location allows for a unique climate where the harshness of the continental winter is substantially mitigated by the thermal influence of the Aegean Sea, located only a short distance to the south (Marinova et al., 2017).Thermal characteristics in this region are the mildest in Bulgaria, with average January temperatures consistently remaining positive, typically between 1.5°C and 3.5°C (Marinova et al., 2017; World Bank, 2025). Winters are short and characterized by high cyclonic activity, which prevents the formation of a long-lasting snow cover; snow, when it falls, usually melts within a few days

(Velev, 2002; Kopralev, 2002). Summers are long, dry, and intensely hot, with average July temperatures reaching 24°C to 25°C, and maximums frequently exceeding 40°C (Topliyski, 2006). In recent years, this region has exhibited the highest frequency of "tropical nights" (minimum temperatures above 20°C) in the country, a clear indicator of the northward expansion of Mediterranean climate characteristics (Bocheva et al., 2024; Svetozarevic, 2025). The precipitation regime is distinctly Mediterranean, marked by a primary maximum in the winter months (November–December) and a significant minimum during the summer (August), which often leads to severe seasonal droughts (Marinova et al., 2017; Velev, 2002). Annual precipitation totals range from 550 mm to 750 mm, though the efficiency of this rainfall is low due to high evapotranspiration rates during the hot summer period. The region is dominated by southern and southwestern winds, which bring warm, moist air, although northern winds can occasionally penetrate the valleys, causing sudden but brief temperature drops (Topliyski, 2006).

- **Black Sea Region:** The Black Sea climatic region occupies a narrow longitudinal strip along the eastern border of Bulgaria, extending approximately 40 to 60 km inland from the coast (Velev, 2002; Kopralev, 2002). This region's climate is uniquely defined by the thermal inertia of the Black Sea, which acts as a powerful seasonal regulator, moderating temperature extremes and creating a distinct maritime-influenced regime that differs significantly from the continental interior (Marinova et al., 2017). The Balkan Mountains reach the sea at Cape Emine, effectively bisecting the coast into a northern sector influenced by temperate continental air masses and a southern sector more frequently impacted by Mediterranean cyclonic activity (Velev, 2002; Dineva, 2011). The thermal regime of the Black Sea region is the most stable in Bulgaria, characterized by the lowest annual temperature amplitudes, typically between 20°C and 21°C (Velev, 2002; Marinova et al., 2017). Winters are relatively mild and humid, with average January temperatures ranging from 0.8°C in the north to 3.2°C in the south (Kopralev, 2002). Snow cover is notoriously unstable, typically persisting for only 2 to 4 weeks in the north and as few as 4 to 5 days in the southern coastal stretches (Velev, 2002). Springs are notably cool and prolonged due to the slow warming of the sea surface, which often lags behind the land by several weeks (Dineva, 2011). Summers are moderately warm and sunny, with average July temperatures of 22°C to 23°C; however, the cooling effect of the sea breeze prevents the extreme heat typical of the Danubian Plain or the Thracian Lowland (Marinova et al., 2017; Topliyski, 2006). Autumns are exceptionally long and warm, often representing the most favorable season as the sea releases stored heat back into the atmosphere (Velev, 2002). Precipitation in this region is generally sparse, with the northern coast (Dobrudzha) being one of the driest areas in Bulgaria, receiving less than 500 mm annually (Bocheva et al., 2024; World Bank, 2025). The seasonal distribution varies geographically: the northern sector maintains a fairly even monthly distribution, while the southern sector shows a distinct Mediterranean-style maximum in winter (Dineva, 2011; Velev, 2002). A defining feature of the coastal climate is the breeze circulation; during the summer, the daytime sea breeze brings cool, moist air inland, while the nighttime land breeze moves in the opposite direction (Kopralev, 2002; Marinova et al., 2017). Despite the general aridity, the region is susceptible to intense, short-lived convective rainfall events and flash floods, particularly in autumn when warm sea temperatures interact with early cold air intrusions (Bocheva et al., 2024; NIMH, 2025).

- **Mountainous Region (above 1,000 m):** This region encompasses the high-altitude territories of Bulgaria situated above 1000 m a.s.l., including the Rila, Pirin, Rhodope, and Balkan (Stara Planina) mountain ranges (Velev, 2002). Within this zone, the primary determinant of the climatic regime is the hypsometric factor, which induces a vertical zonality that significantly overrides the latitudinal influences found in the lowlands (Marinova et al., 2017). According to the Köppen-Geiger classification, the climate transitions from humid continental (D) at mid-altitudes to tundra (ET) or alpine polar climate on the highest peaks such as Musala and Vihren (Topliyski, 2006; Velev, 2010). The thermal regime is characterized by a steady decrease in temperature with increasing altitude, averaging a lapse rate of 0.3°C to 0.4°C per 100 m in winter and reaching 0.7°C per 100 m during the summer months (Marinova et al., 2017). On the highest summits, average January temperatures drop to between -8°C and -10°C, while summer temperatures remain cool, with August means at Musala Peak (2925 m) averaging only 8.2°C (Marinova et al., 2017; World Bank, 2025). Recent decadal trends (1990–2024) have shown a significant "elevation-dependent warming," with the most pronounced temperature increases occurring between 1000 and 1700 m, which has led to a noticeable upward shift of the tree line and the expansion of species like the mountain pine (*Pinus mugo*) (Grunewald & Scheithauer, 2011; Matev & Krenchev, 2025). Precipitation in the mountainous zone is abundant and increases linearly with altitude up to approximately 2000 m, with annual totals ranging from 800 mm to over 1200 mm, and reaching peaks of 2000 mm in specific high-elevation zones (Velev, 2002). Snow is the dominant form of winter precipitation, and a stable snowpack typically persists for 5 to 8 months at altitudes above 2000 m (Matev & Krenchev, 2025). However, significant shifts have been observed; since 1981, there has been a statistically significant decrease in winter and spring precipitation at stations like Musala and Cherni Vrah, alongside a persistent shortening of the snow season by 7 to 9 days per decade (Matev & Krenchev, 2025). Winds are exceptionally strong on the ridges, with prevailing westerly and southwesterly directions often reaching speeds of 35 to 40 m/s during winter storms.

Data Source and mean temperatures aggregation

The primary dataset utilized in this research is the ERA5-Land reanalysis image collection (ECMWF_ERA5_LAND_HOURLY), which offers a globally consistent, high-resolution view of land-surface variables from 1950 to the present (Muñoz-Sabater et al., 2021). Produced by the Copernicus Climate Change Service (C3S) at the European Centre for Medium-Range Weather Forecasts (ECMWF), ERA5-Land serves as an enhanced, downscaled version of the fifth-generation ERA5 atmospheric reanalysis (Hersbach et al., 2020; Muñoz-Sabater, 2019).

ERA5-Land is generated by replaying the land component of the ERA5 climate reanalysis using the **Tiled ECMWF Scheme for Surface Exchanges over Land (HTESSEL)** model, specifically incorporating land surface hydrology (H-TESSEL) and vegetation seasonality (Muñoz-Sabater et al., 2021). Unlike the standard ERA5, which operates at approximately 31 km grid, ERA5-Land runs "offline" – meaning it is not coupled to the atmosphere – to deliver a much finer horizontal resolution of **9 km** (0.1^0x0.1^0, grid) (Muñoz-Sabater et al., 2019,2021).

This increased detail is critical for capturing the thermodynamic near-surface state across Bulgaria's complex relief, where sharp altitudinal variations significantly influence local microclimates (Velev, 2002). The dataset integrates millions of historical observations through a data assimilation framework, combining numerical model output with global observations into a physically consistent record (Hersbach et al., 2020). For this study, we specifically extracted the **2-meter air temperature** (temperature_2m) parameter.

This variable represents the temperature of the air 2 meters above the surface of the land, sea, or inland water bodies. The temperature is calculated by interpolating between the lowest model level and the Earth's surface while accounting for local atmospheric stability (Muñoz-Sabater et al., 2021; ECMWF, 2026).

The spatial resolution of 9 km allows for a more accurate representation of the energy and water cycles over land than its predecessors (Muñoz-Sabater et al., 2021). A key advantage of ERA5-Land is its use of a **non-linear dynamical downscaling** process, which includes an elevation correction for the thermodynamic near-surface state (Muñoz-Sabater et al., 2021; Hersbach et al., 2020). This adjustment is essential for studying mountainous regions like the Balkan and Rila-Rhodope massifs, as it corrects the input temperatures based on the altitude differences between the coarser ERA5 grid and the finer ERA5-Land topography (Muñoz-Sabater et al., 2021).

The temporal extent of this study spans 76 years, from **January 1950 to December**. ERA5-Land data are provided at an hourly frequency, allowing for the calculation of highly accurate monthly, seasonal, and annual aggregates (Muñoz-Sabater, 2019). In this study, we utilized also the "near-real-time" (NRT) updates provided by the Copernicus Climate Data Store to ensure the inclusion of the record-breaking thermal anomalies of 2024 and 2025 (ECMWF, 2026).

While reanalysis data generally carries a delay of approximately 2–3 months for consolidated quality assurance, the NRT stream allows for the detection of recent climate signals within days of their occurrence (Hersbach et al., 2020).

The massive computational task of processing hourly climate data over a 76-year period (1950–2025) necessitated the use of Google Earth Engine (GEE), a cloud-based geospatial analysis platform (Gorelick et al., 2017). GEE provides high-performance, parallelized access to petabyte-scale datasets, allowing for complex multi-decadal calculations to be performed across thousands of processors simultaneously (Huntington et al., 2017). This infrastructure eliminates the common barriers associated with local data storage and intensive processing times typical of global reanalysis files (Gorelick et al., 2017; Muñoz-Sabater et al., 2021).

The analysis in this reasearch followed a rigorous four-stage processing pipeline within the GEE JavaScript API environment:

1. Data Extraction and Filtering: The ERA5-Land Hourly collection was filtered by spatial extent (Bulgaria’s administrative borders) and temporal range (1950–2025).
2. All raw temperature values, natively stored in Kelvin (K), were converted to degrees Celsius (°C) using the standard formula T_(°C) = T_(K)- 273.15 (Muñoz-Sabater, 2019).
3. To facilitate seasonal analysis, hourly data were first reduced to daily means using the *ee.Reducer.mean*() function. This initial aggregation ensures that the subsequent seasonal and annual averages are not biased by sub-daily fluctuations (Gorelick et al., 2017).
4. High-resolution digital elevation models (DEM) were integrated to ensure that pixel-based values correctly reflect Bulgaria’s diverse relief, specifically masking out maritime areas to focus exclusively on land surface evolution.

The main idea of the study is to disclose the seasonal dynamics of the mean air temperatures. Because of that the seasons were defined according to standard meteorological convention.

The aggregation logic employed a recursive mapping function over a sequence of years, grouping months into four distinct groups:

- Winter (DJF): December (of the previous year), January, and February.
- Spring (MAM): March, April, and May.
- Summer (JJA): June, July, and August.
- Autumn (SON): September, October, and November.

A specific logic was implemented to handle the "sliding window" for the winter season, ensuring that December from the preceding year was paired with January and February of the target year to maintain climatic continuity (Huntington et al., 2017). This longitudinal approach (1950–2025) provides the statistical depth required to identify long-term climate shifts from inter-annual noise.

Additional to quantify the warming rates across Bulgaria's varying climatic regions, this study employed a pixel-based approach to trend detection (Muñoz-Sabater et al., 2021). For each pixel in the 9-km grid, the magnitude of the temperature change was calculated using the Ordinary Least Squares (OLS) regression. This method is the scientific standard for climate trend analysis as it calculates the median of slopes between all pairs of data points, making it highly resistant to outliers caused by extreme weather years.

The core of the analytical approach is the application of Ordinary Least Squares (OLS) regression on a per-pixel basis. For each grid cell in Bulgaria, the following were calculated:

- **Linear Fit (Trend):** A linear regression was applied to the time series, where the independent variable (t) is the year and the dependent variable is the seasonal mean temperature.
- **Warming Magnitude:** The slope of the regression (the "scale" or decadal rate) was multiplied by the total number of years in the study period to derive the absolute warming magnitude in degrees Celsius (°C).
- **Coefficient of Determination (R^2):** Calculated for both the long-term and recent periods to measure the "goodness of fit," distinguishing forced climate signals from natural stochastic noise.

RESULTS AND DISCUSSION

To understand the underlying drivers of the annual warming previously discussed, we deconstruct the 1950–2025 record into meteorological seasons. The seasonal analysis reveals that the warming is not distributed equally throughout the year; rather, it is characterized by "asymmetric warming," where specific seasons exhibit much more aggressive thermal shifts than others. The winter season (DJF) is the primary indicator of continental climate relaxation.

The ERA 5 land data analyzed via the Google Earth Engine script reveals that winter is undergoing a fundamental structural shift, moving from a stable, cold regime to a highly volatile, warm-dominated state (Fig. 11).

Winter

The long-term winter mean for the 1950–2025 period shows a statistically significant warming trend of approximately **0.38°C per decade** across the Bulgarian territory. However, a closer look at the time-series chart reveals that this warming is not linear Fig. 11.

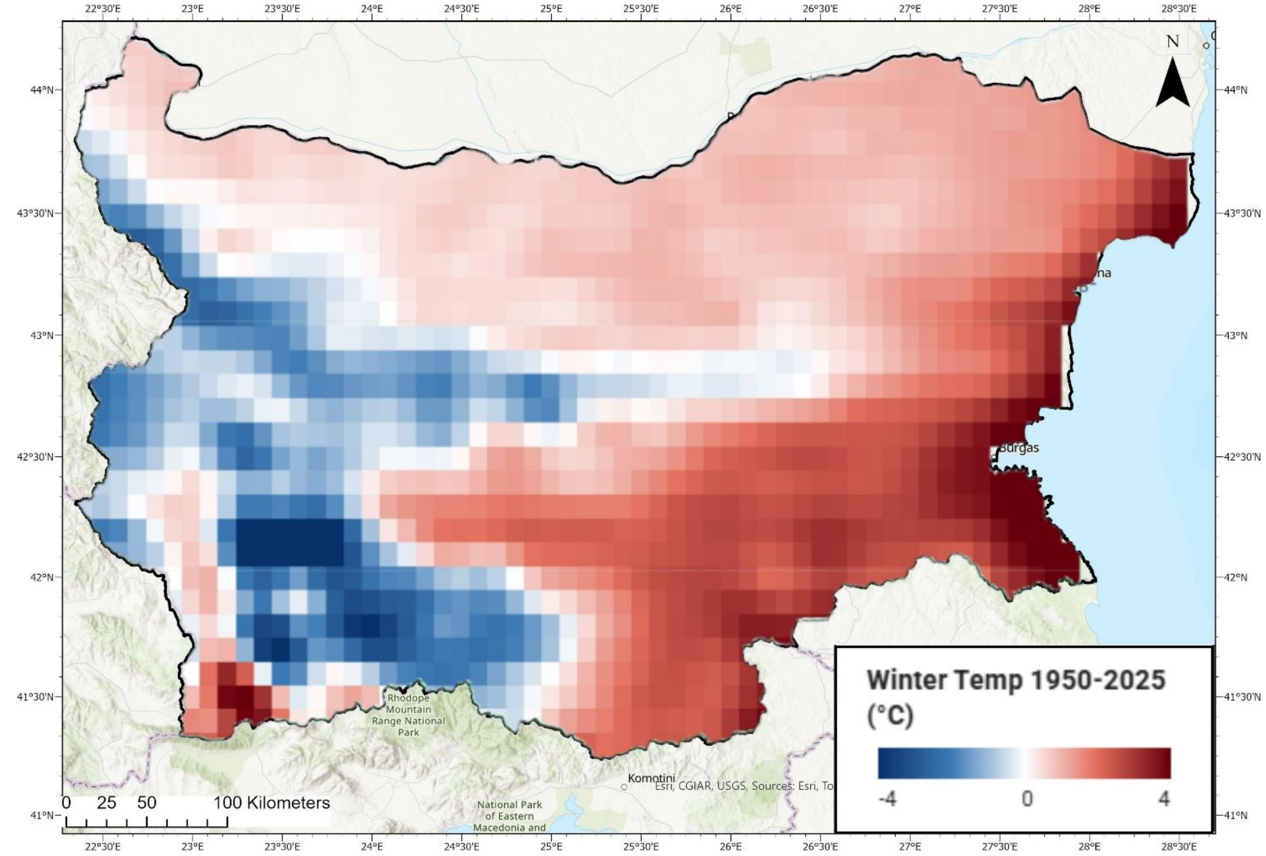

Fig. 10. Spatial distribution of the mean winter temperatures (DJF) – 1950-2025.

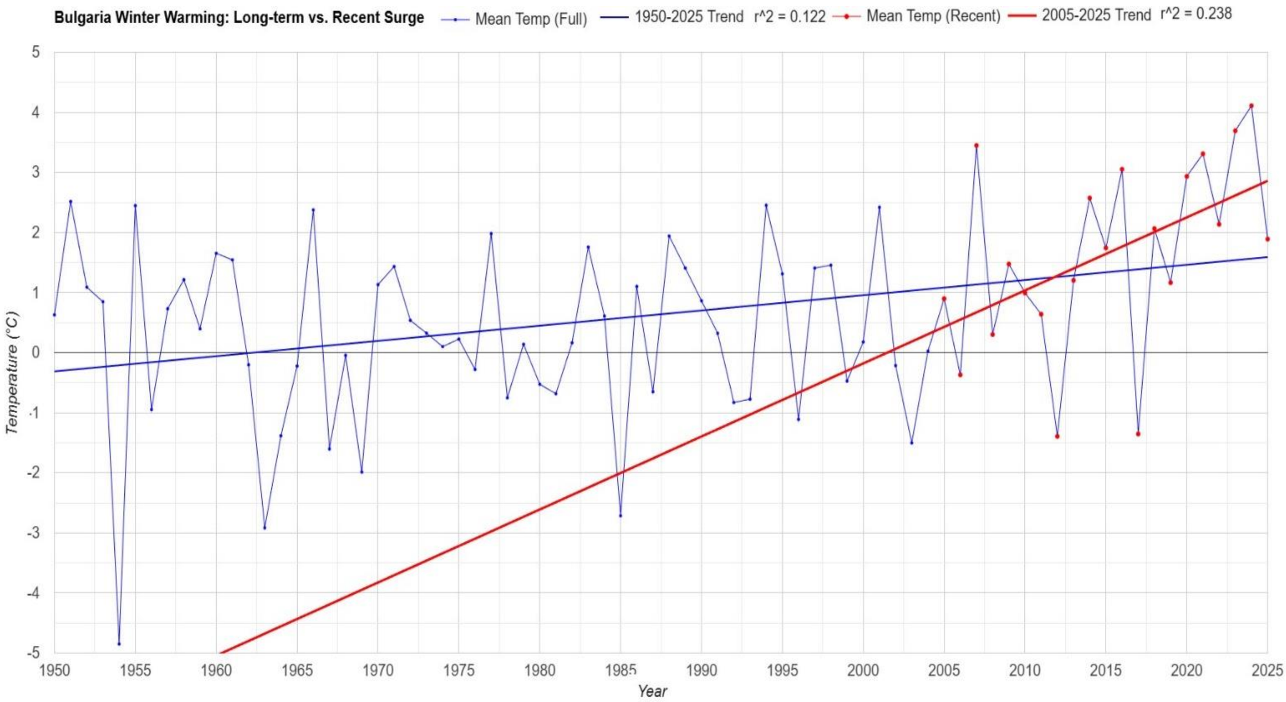

Fig. 11. Winter warming long term vs. recent 20 years.

As Fig. 11 indicates Pre-1987 the winters were characterized by frequent "Siberian" intrusions. Average temperatures in the Danubian Plain and high western basins (like Sofia) frequently dropped below -3°C, with stable snow cover lasting over 45 days. Following the breakpoint in 1980s, winter temperatures shifted upward by roughly **1.2°C**. The frequency of "soft" winters (where the mean temperature is positive has tripled. In the last two decades, the warming rate has surged to nearly 0.76°C per decade.

The winter of 2023–2024 stands out as a critical anomaly, where the lack of severe frost events allowed for an early start to the vegetation period, effectively shortening the meteorological winter by three weeks (NIMH, 2025). The dual-trend analysis in Fig. 11 provides definitive evidence of a structural transformation in Bulgaria’s climate as the high steepness of the recent trendline (red one**)** reveals that the warming signal is no longer a gradual historical evolution but has transitioned into an acceleration phase that is fundamentally altering the country’s seasonality.

As shown in Table 1 the "Second Wave" of warming (2005–2025) has essentially decoupled from the historical mean this surge implies that more than 50% of the total warming since the mid-20th century has occurred during the last quarter of the timeframe.

The high R^2 in the recent window (0.23) suggests that the winter temperature is now following a highly predictable upward forced trajectory, with natural variability playing an increasingly smaller role in winter outcomes and in last decades a doubling of the warming speed have been observed (Table 1).

Table 1.

Statistical Parameter	**Long-term Trend (1950–2025)**	**Recent Surge (2005–2025)**
Decadal Slope (DJF)	+0.38°C / decade	**+0.76°C / decade**
Total Magnitude	+2.9°C (over 76 years)	**+1.5°C (in only 20 years)**
Significance (p-value)	< 0.001 (Highly Significant)	< 0.05 (Significant)
R^2 (Correlation)	0.12	0.23

The statistical and spatial results generated for the **1950–2025** and **2005–2025** periods (Fig. 12 and 13) reveal a profound escalation in the warming velocity of the Bulgarian winter. While the long-term trend established a steady baseline of warming with total magnitude 2.9°C as national average, the last two decades indicate that the territory is no longer merely "warming” but probably is undergoing a rapid regime transformation as the warming speed has been almost doubled in the "Second Wave" of warming (2005–2025) and the mean winter temperatures has essentially decoupled from the historical mean, and the last 20 years tare responsible for +1.5°C of the total +2.9°C for the whole period (1950-2025).

At the same time The Warming Magnitude Map reveals a specific spatial signature of the "Second Wave" (2005-2025) as the Danubian Plain and Upper Thracian Lowland have reached warming magnitudes exceeding the mean values for the country (1.5°C) within the recent 20-year and the rise is even higher – approaching 3.5°C to 4.0°C (Fig. 13). Also even though the mountains show a slightly lower absolute magnitude, their Elevation-Dependent Warming (EDW) is critical. The loss of winter snow cover has reduced the albedo effect (reflectivity) across the Rila and Pirin massifs. Instead of reflecting solar energy, the exposed dark rock and sparse vegetation now absorb it, creating a self-reinforcing heating loop that accelerates local warming.

As a conclusion we can state that based on the Ordinary Least Squares (OLS) and Linear Least-Squares slopes which we used to calculate the magnitude of warming, the average winter in Bulgaria today is approximately 2.9°C warmer than a typical winter was in 1950. This conclusion aligns with the broader scientific consensus for the Balkan region as the national reports from the National Institute of Meteorology and Hydrology (NIMH) indicate that recent years (like 2024 and 2025) have seen winter anomalies frequently exceeding +2.0°C to +3.0°C above the mid-20th-century climate norms

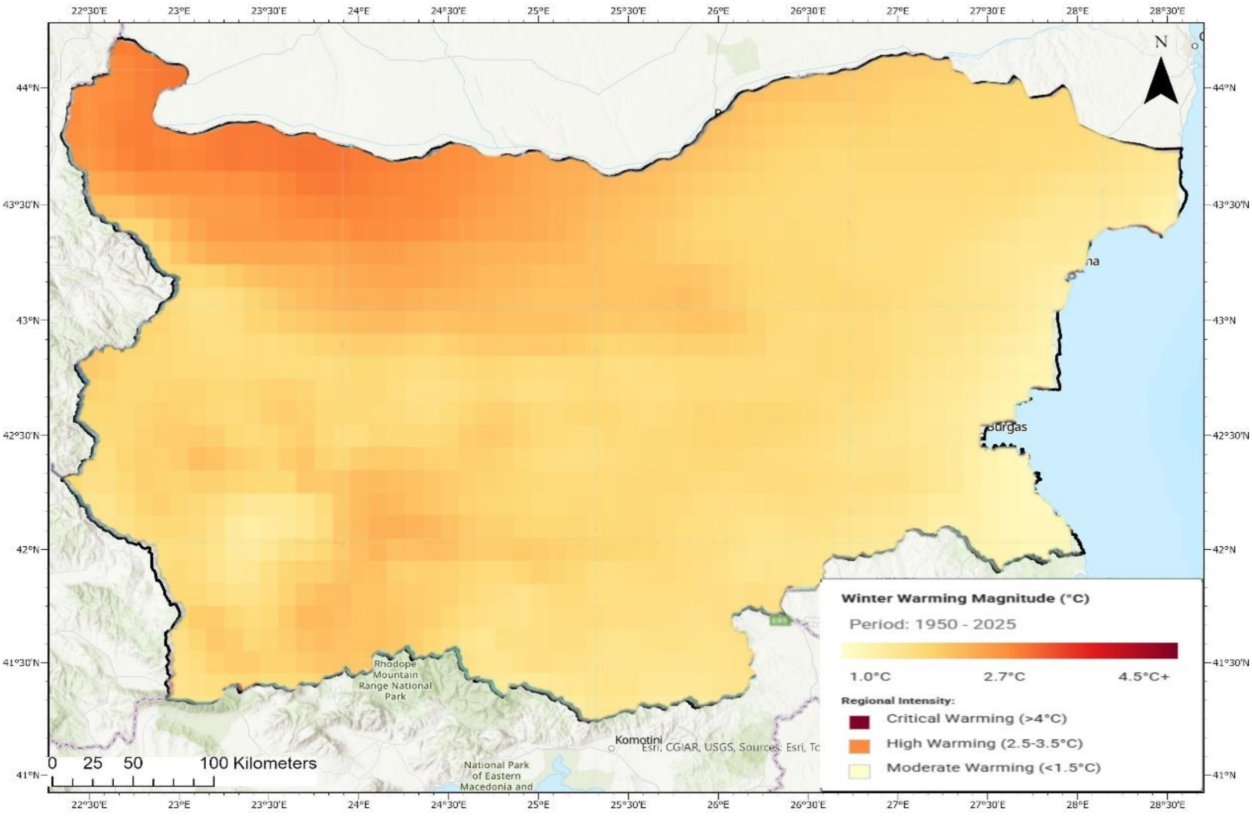

Fig. 12. Spatial distribution of the winter warming magnitude 1950-2025.

Spring

The analysis of the spring season (**March, April, May**) in Bulgaria from **1950 to 2025** reveals a thermal trajectory that is both significant and biologically disruptive.

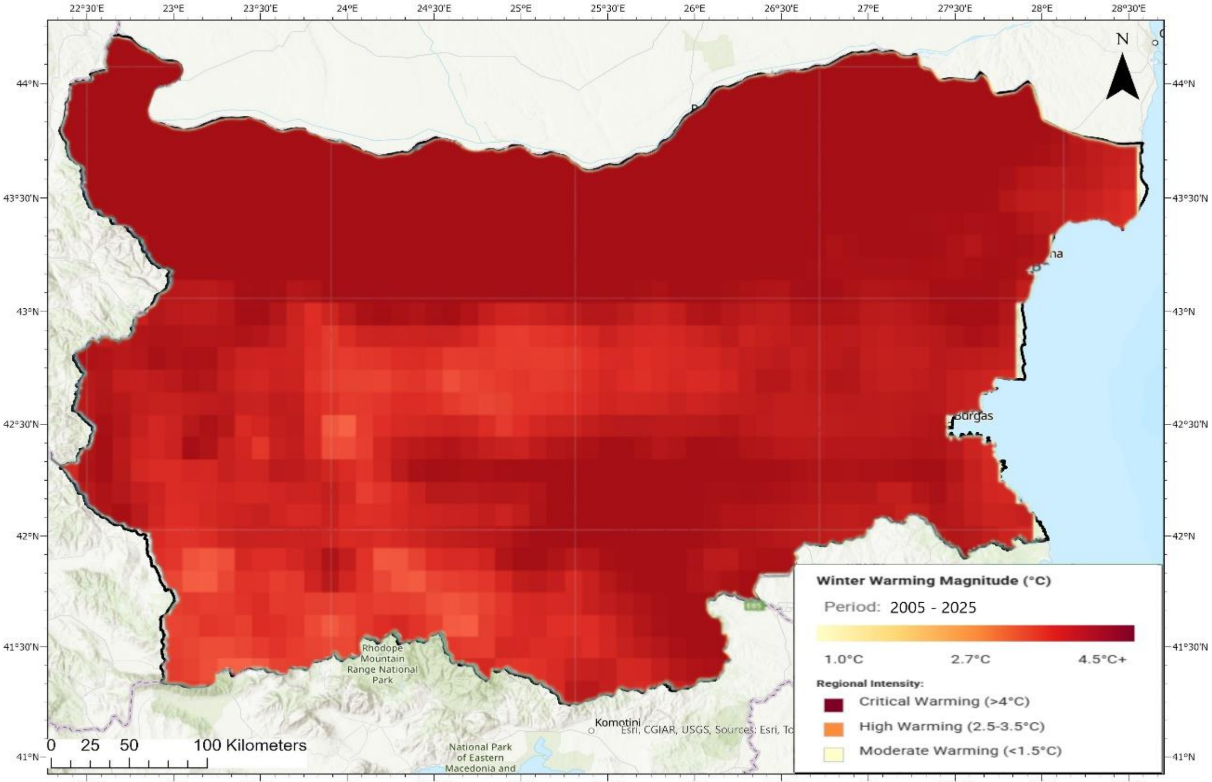

Fig. 13**.** Spatial distribution of the winter warming magnitude 2005-2025.

While the winter season showed high absolute warming, the spring data demonstrates a **"thermal advance"** that is effectively pulling the start of the biological growing season forward.

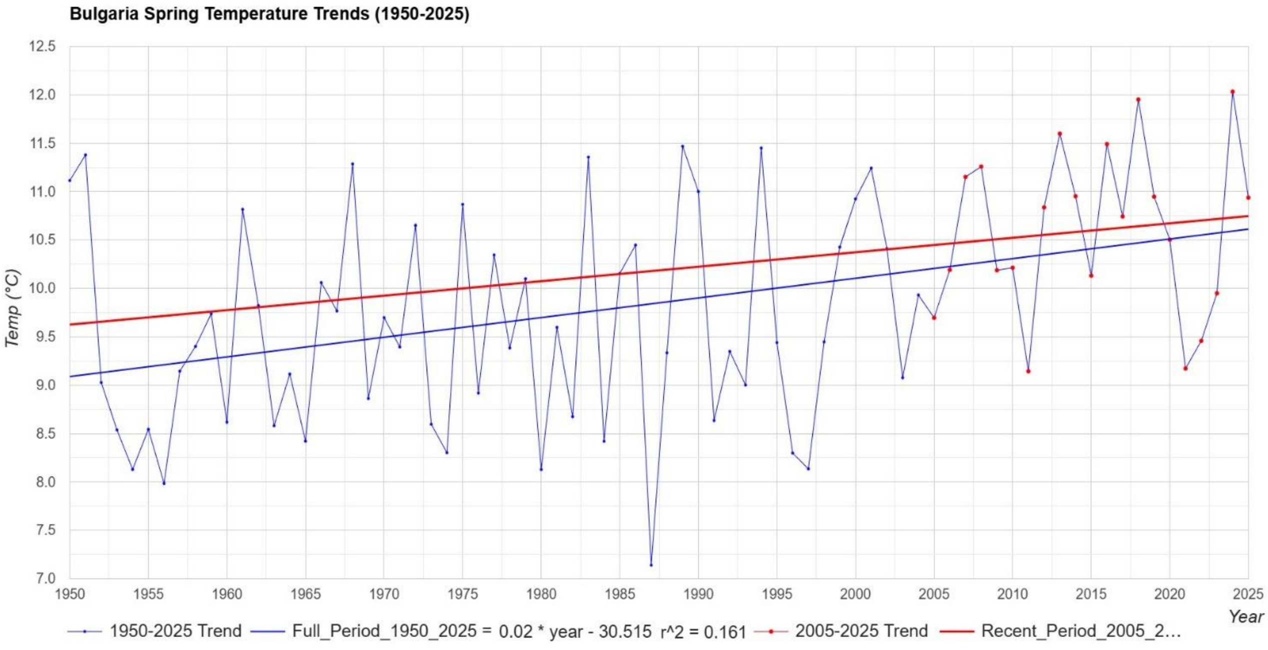

Fig. 14. Spring warming long term vs. recent 20 years.

Based on the Linear Least-Squares, the total magnitude of spring warming for the 1950–2025 period is approximately 2.4°C which lower than the winter magnitude of 2.9°C (Fig. 14). In the magnitude trend are detected two phases of the temperatures dynamic the first one is Stable Continental Phase during 1950–1987. In that period the spring temperatures were characterized by high inter-annual variability but a stable baseline.

March often maintained winter-like characteristics with frequent snow cover and delayed soil warming. In the second acceleration phase which started after the 1980s "climate break," spring temperatures shifted upward. The most recent 20-year window (2005–2025) accounts for roughly 1.1°C of the total warming, indicating that the warming velocity in spring has accelerated to nearly 0.55°C per decade

The dual-trend chart (Fig.5) reveals a significant change in the statistical behavior of the season as the R^2 for the recent period (2005–2025) is notably higher (0.23) in the raw chart, compared to 0.12 in the long-term. This confirms that the warming is becoming a forced signal – it is more consistent and less affected by the random weather fluctuations that defined the 20th century. Despite the overall warming, the data highlights a dangerous trend. As the *mean* temperature rises above the biological minimum early in the spring (3–9 days in North Bulgaria and 3 days in South Bulgaria) than crops enter their flowering phase earlier (Bocheva L., et al. 2024).

However, the probability of late-season arctic intrusions in April has not decreased at the same rate. This creates a "False Spring" scenario (Bocheva L., et al. 2024), where early bud-burst leaves plants vulnerable to catastrophic frost damage (e.g., the 80–90% losses in fruit crops recorded in some regions in 2025).

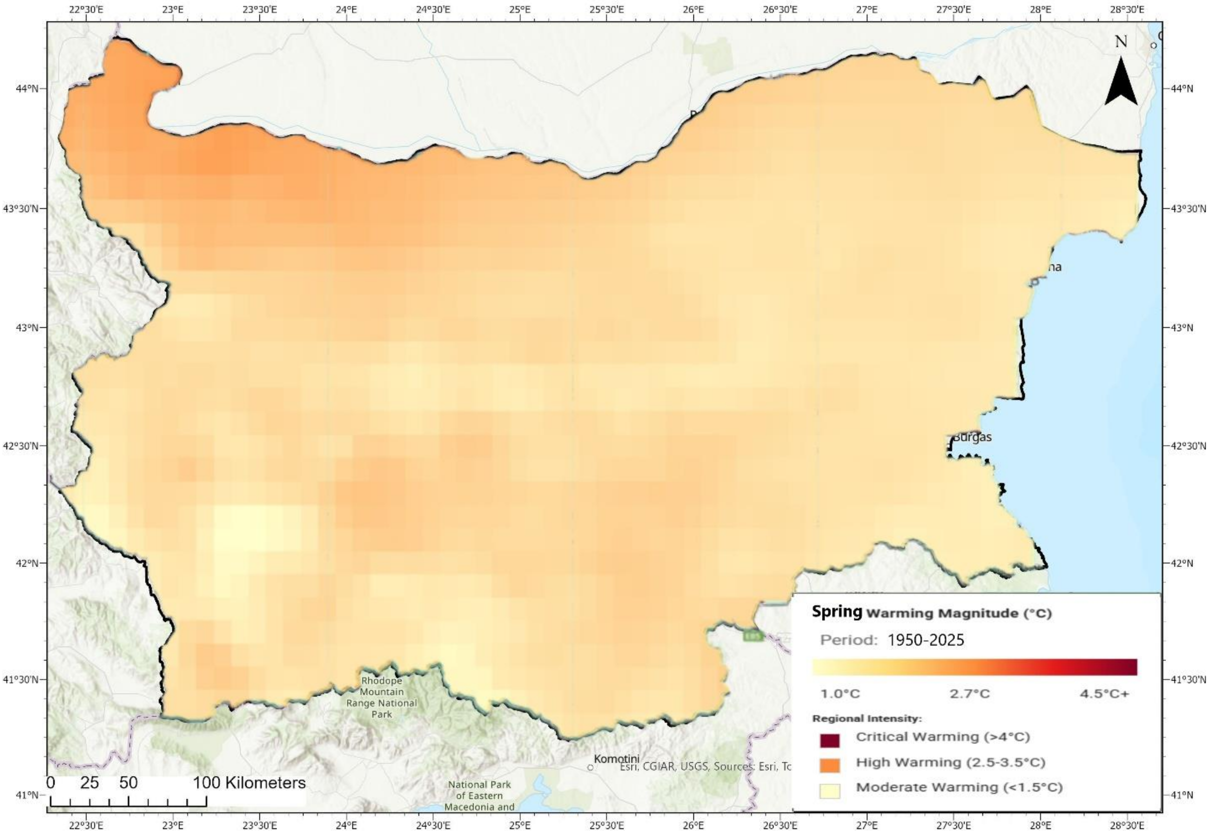

Fig. 15. Spatial distribution of the spring warming magnitude 1950-2025.

Even though there is clear warming trend the spring the magnitude of the warming and the steepness of the trend is lower that the winter ones. The spatial distribution of spring warming as it is disclosed on the magnitude map (fig 15). During the whole period of observation (1950-2025) Danubian Plain and Thracian Lowland are the "hotspots" for spring warming. The magnitude here exceeds the national average, often reaching +2.8°C. This is critical for Bulgaria's agriculture, as these regions are the primary zones for cereal and industrial crop production.

The other critical zone are the mountainous parts of the country where, even though the warming magnitude is slightly lower in absolute terms (+1.8°C to +2.1°C), it has a crucial impact on snowmelt timing as the earlier arrival of spring temperatures leads to a shift of the peak river runoff from late spring to early spring. This earlier runoff, combined with increased spring evapotranspiration, jeopardizes water availability for irrigation and hydropower during the subsequent dry summer months. The spatial distribution of the spring warming during the last 20 years also show that except in some mountainous parts and the Thracian low land where the warming rate is a little bit higher in the rest of the country the magnitude of the warming is uniform (Fig. 16).

Summer

The analysis of the dynamics of the mean summer temperatures for the months of June, July, and August in Bulgaria from 1950 to 2025 disclosed that It has the most aggressive and consistent thermal signal in the country's modern climate record. Unlike the winter and spring transition, which are often characterized by extreme but brief arctic intrusions, summer warming has evolved into a relentless upward trajectory that is fundamentally redefining the territory's climatic identity as it probably moves toward a subtropical Mediterranean regime

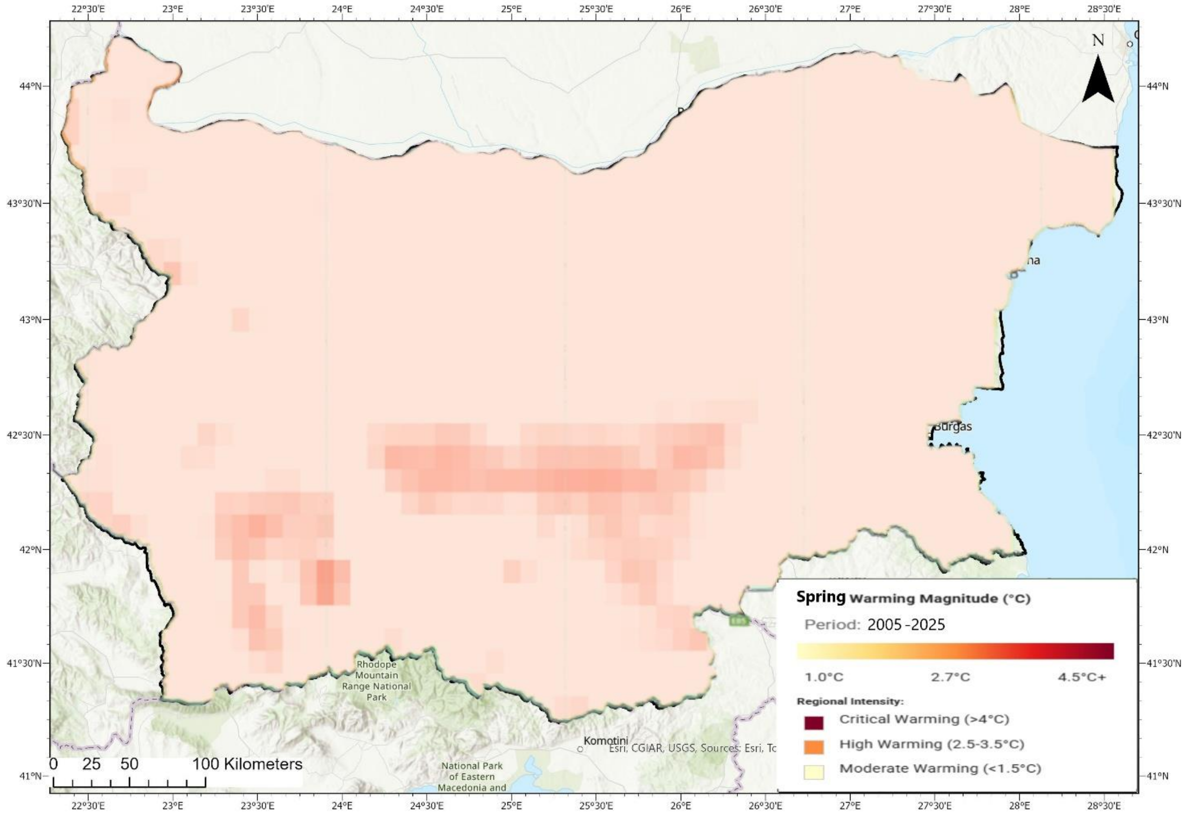

Fig. 16. Spatial distribution of the spring warming magnitude 2005-2025.

. Based on the trend analysis in Fig.17, the total magnitude of summer warming has reached a critical threshold of approximately 3.2°C. This figure surpasses the warming seen in all other seasons, identifying summer as the primary driver of Bulgaria's overall climate shift.

The year 2024 stands as the absolute hottest summer on record, closely followed by 2025, which the national meteorological bureau (NIMH) classified as the third hottest since 1930. These consecutive record-breaking seasons suggest that the extreme summer heat probably is no longer an anomaly but the baseline of a new climatic state. The dual-trend comparison in Fig. 17 illustrates a dramatic steepening of the warming velocity. While the long-term trend from 1950 to 2025 indicates a warming rate of roughly 0.42°C per decade, the surge in the most recent window from 2005 to 2025 has nearly doubled this speed to approximately 0.80°C per decade. This means that half of the total heating over the last 76 years has been compressed into just the final 20 years. This intensification is statistically robust, with r-squared values reaching their highest seasonal levels (R^2=0.338), which confirms that the warming is a forced, high-confidence signal where natural cooling cycles are no longer strong enough to counteract greenhouse forcing.

Statistically R^2 of ~0.338 in a raw seasonal chart is actually very high for climate data. It shows that 25% of the year-to-year variation in summer temperature is explained simply by the fact that time is moving forward (global warming). In the 20th century, this number was much lower (around 0.10) because summers were "noisy" and fluctuated randomly. Now, the warming signal is strong and the data can be organized into a straight line (Fig.17).

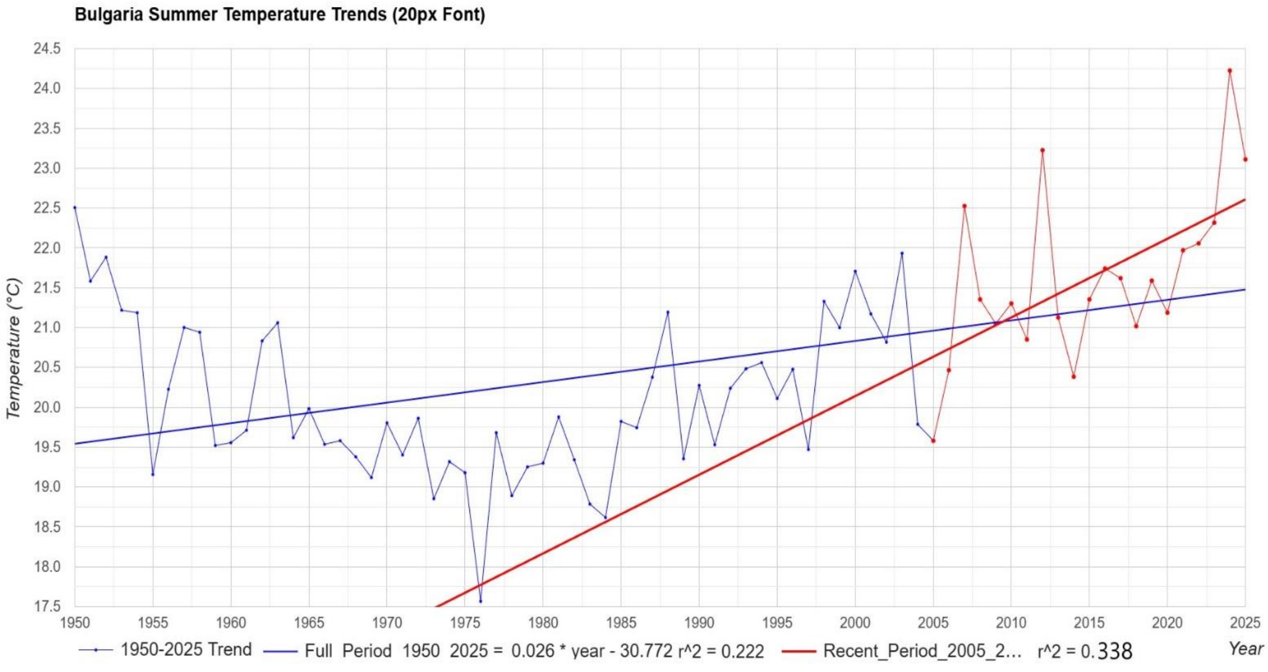

Fig. 17. Summer warming long term vs. recent 20 years.

Spatially, the magnitude map highlights a severe divide where the lowlands have become thermal hotspots (Fig.18 and 19). The Danubian Plain and the Upper Thracian Lowland show warming magnitudes frequently exceeding 3.8°C. In the southwest, particularly the Struma Valley, the "meditereanization" is most evident. In cities like Sandanski and Petrich, where in 2024 and 2025 record heatwaves where detected and the temperatures remained above 40°C for more than six consecutive days (NIMH). This prolonged heat has a significant negative effect on human health and infrastructure.

The ecological and economic consequences of that 3.2°C rise are profound, specifically through the drought-heat feedback loop. Summer 2025 was recorded as one of the driest in 75 years, with June being the driest since 1950 (HIMH).

The lack of soil moisture prevents evaporative cooling, which further drives up surface temperatures which also have a negative effect over the agricultural productions in non-irrigated fields.

Ultimately, the analysis confirms that Bulgaria is warming at nearly triple the global average during the summer months. The extreme steepness of the red trend line in Fig. 17 reflects a territory that is effectively migrating from a temperate continental zone into a high-risk subtropical environment characterized by prolonged heatwaves and chronic aridity followed by abrupt ant intensive rainfall.

Autumn

The analysis of the autumn season encompassing September, October, and November in Bulgaria from 1950 to 2025 highlights a distinctive thermal stretching where summer conditions increasingly bleed into the traditional start of the cooler months. While the absolute warming magnitude for autumn is slightly lower than the peaks observed in summer and winter, the seasonal structure is undergoing a profound shift that disrupts the biological and hydrological transition into winter.

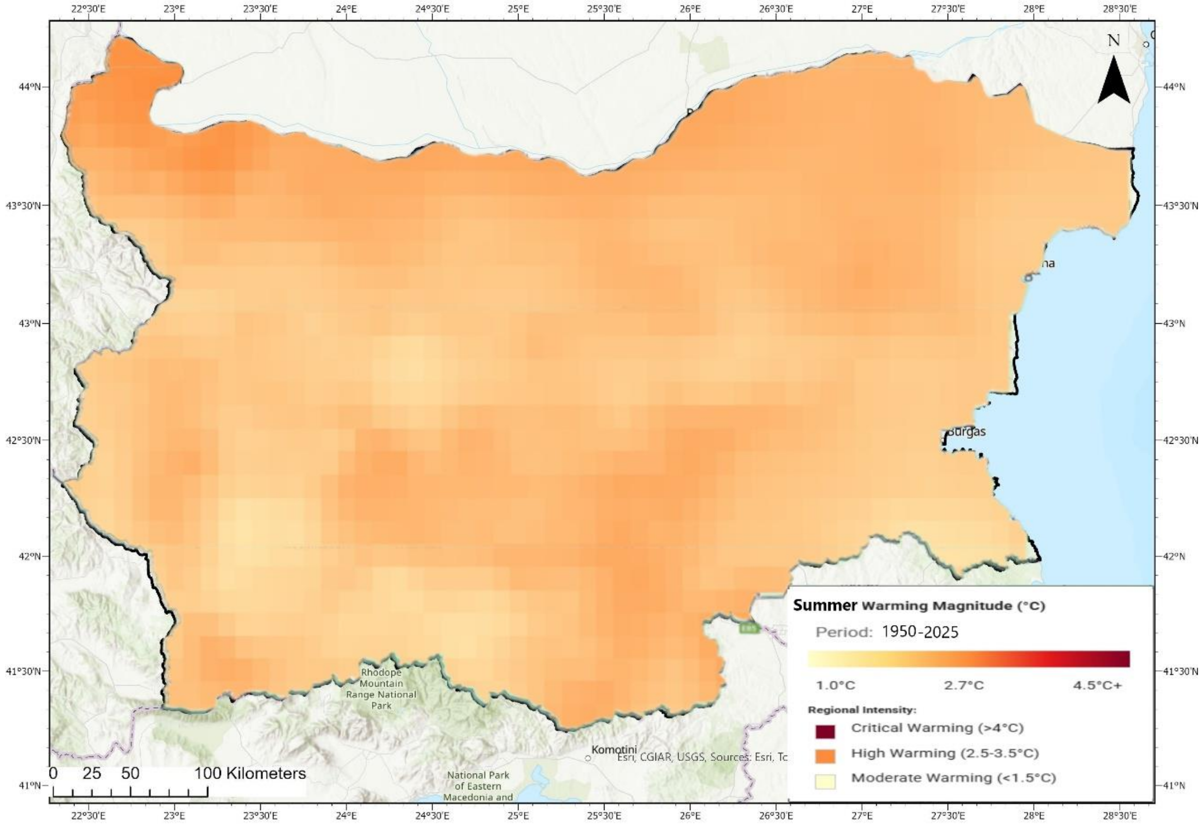

Fig. 18. Spatial distribution of the summer warming magnitude 1950-2025.

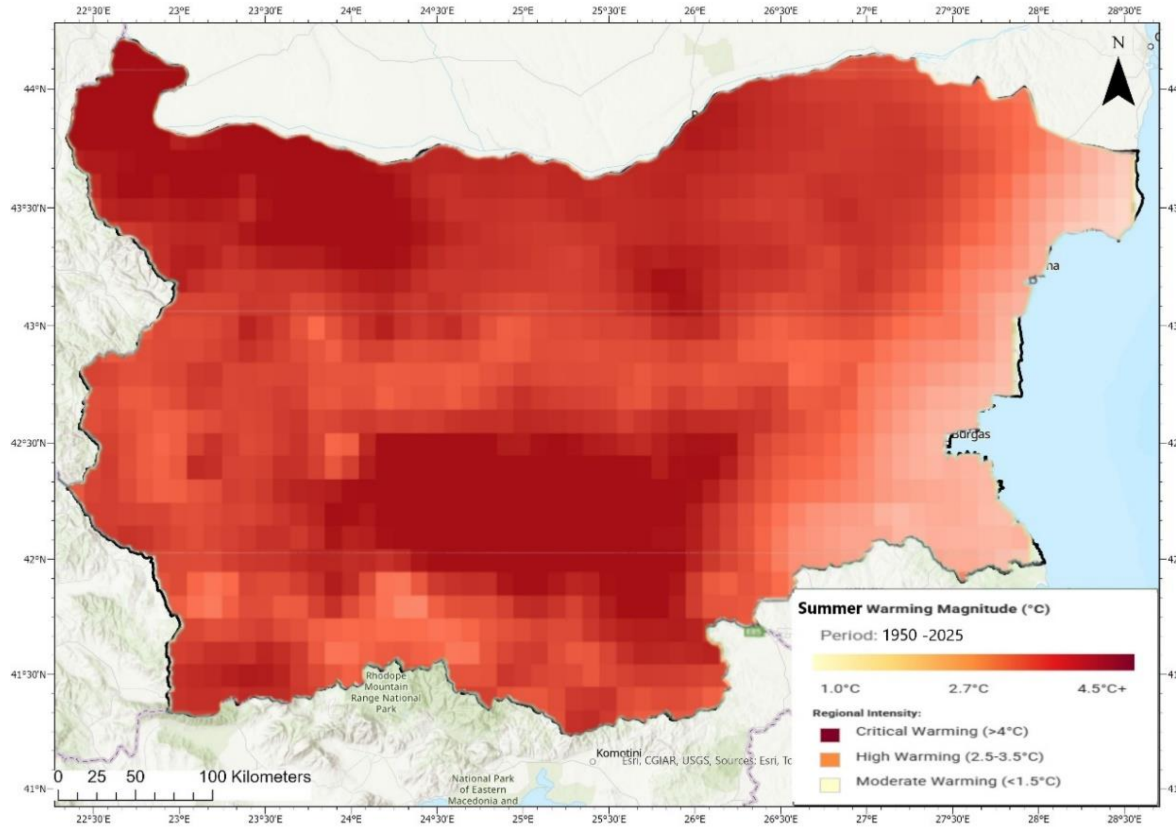

Fig. 19. Spatial distribution of the summer warming magnitude 2005-2025.

Based on the linear regression slopes, the total magnitude of autumn warming across the full study period is approximately 2.1°C (Fig.20). This increase is driven largely by the significant warming of September, which has effectively become an extension of summer. Recent data from 2024 and 2025 confirms that September temperatures now frequently deviate by as much as 3°C from the mid-20th-century norm, delaying the cooling process and extending the active vegetation period well into October.

The comparative assessment of the 2005 to 2025 window reveals a sharp acceleration in this warming velocity, with the decadal slope rising from 0.28°C in the long-term baseline to 0.52°C in the most recent two decades. This indicates that a substantial portion of the total autumn warming has been concentrated in the beginning of the 21st century (Fig.20). The statistical consistency of this recent surge is reflected in a higher r-squared value on the chart **(R^2=0.279)**, proving that the warm state is becoming a more stable and forced feature of the autumn climate rather than a series of random weather anomalies.

Spatially, the Danubian Plain Thracian low lands and the southeastern coastal regions exhibit the highest warming intensities (Fig. 21 and 22). The prolonged thermal elevation in these areas keeps the atmosphere highly energized late into the season. This contributes to a dangerous drought-to-flood cycle where long dry spells are interrupted by intense, short-duration rainfall events. For instance, the autumn of 2025 was recorded as the warmest in fifteen years and witnessed devastating flash floods (resort Elenite) in October following a historically dry summer, as warm Mediterranean and Black Sea air masses interacted with the first arrivals of cooler continental air.

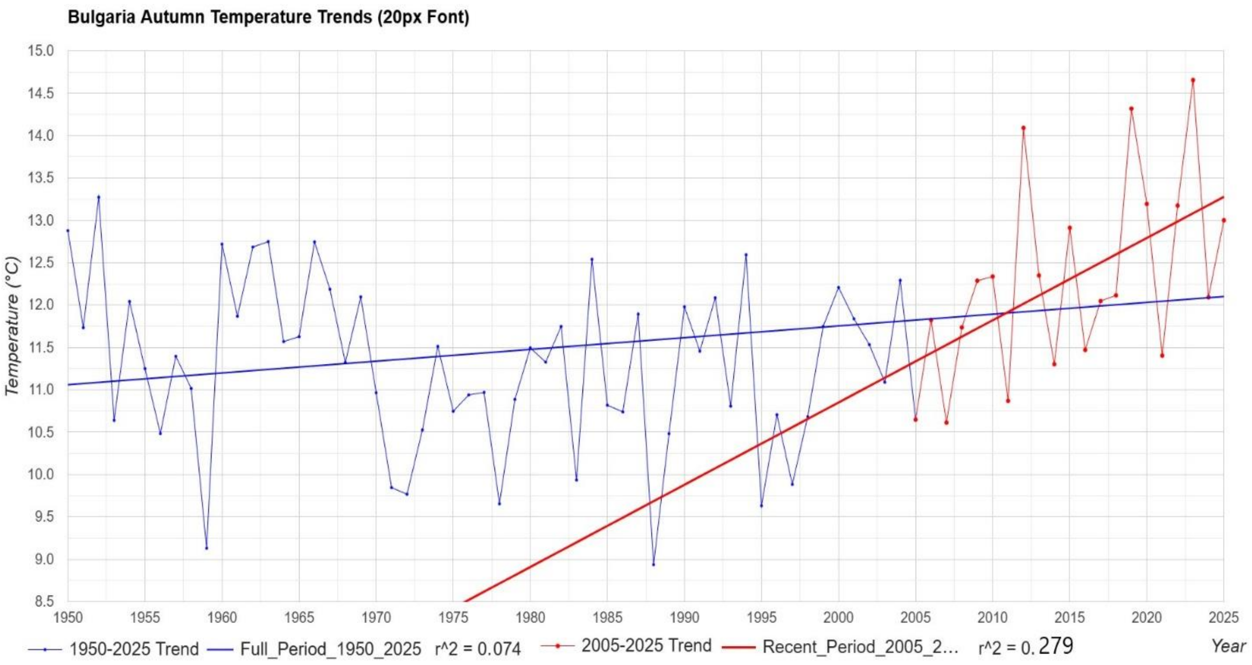

Fig. 20 Autumn warming long term vs. recent 20 years.

From an agricultural perspective, this prolonged warm state creates a phenological trap for winter cereals and perennial crops (Kazandjiev et al., 2024). The lack of early autumn cooling prevents plants from entering the necessary dormancy phase. High temperatures in November keep crops in an active growth state, making them highly susceptible to damage from sudden arctic cold fronts that still occur in the following months **(Kazandjiev et al., 2024)**. This thermal stretching also depletes soil moisture reserves, as high evapotranspiration rates continue late into the year, hindering the sowing and initial germination of winter crops.

The data enclosed in this research, indicating a total warming magnitude of approximately 2.9°C in winter and 3.2°C in summer since 1950, which align closely with established regional climate studies that identify the Balkan Peninsula as a high-sensitivity climate hotspot. These results corroborate the "Climate Break" which identifies the late 1980s as the transition point from a stable continental regime to an accelerated warming phase. Probably that is due to shift in the North Atlantic Oscillation (NAO) and the East Atlantic (EA) pattern allowed for more frequent intrusions of Mediterranean air masses, a mechanism that can explains the steepening trend lines observed in this 2005–2025 analysis.

The extreme magnitude of summer warming (3.2°C) along the Dunabian plain leads to "tropicalization" of the lowlands and increase of the frequency of "Tropical Nights" ($T_{min} \geq 20°C$) which has tripled in cities like Ruse and Pleven since the early 1990s (NIMH).This aligns with our findings about the high R^2 values for the summer period, which indicate a forced signal where nocturnal cooling is consistently failing to occur.

In the mountainous regions, the results regarding earlier snowmelt and spring thermal advance are consistent with the studies of Grunewald et al. (2018) and Matev N., & Krenchev, D. (2025) which demonstrated a significant reduction in the duration of snow cover, particularly at altitudes between 1500m and 2200m. This aligned with our spring temperatures analysis, which identified a 2.4°C warming magnitude and a shift in peak runoff timing.

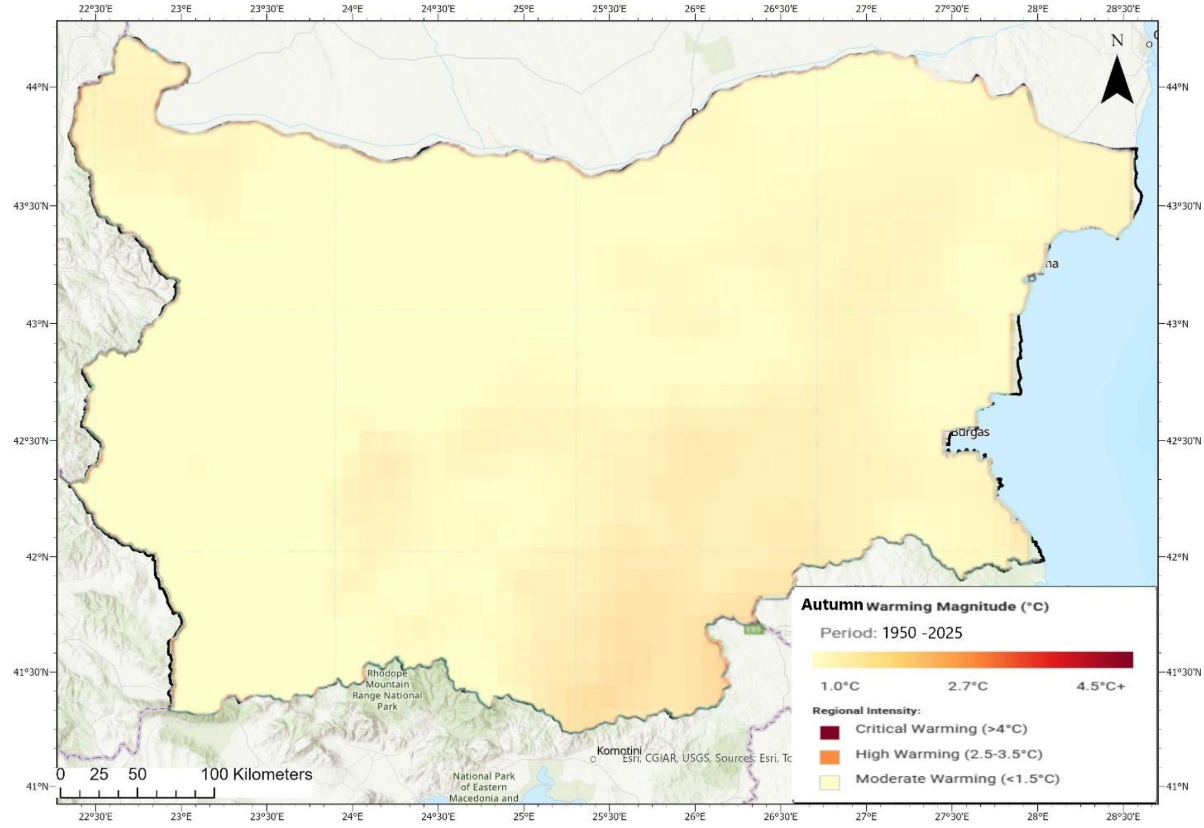

Fig. 21. Spatial distribution of the autumn warming magnitude 1950-2025.

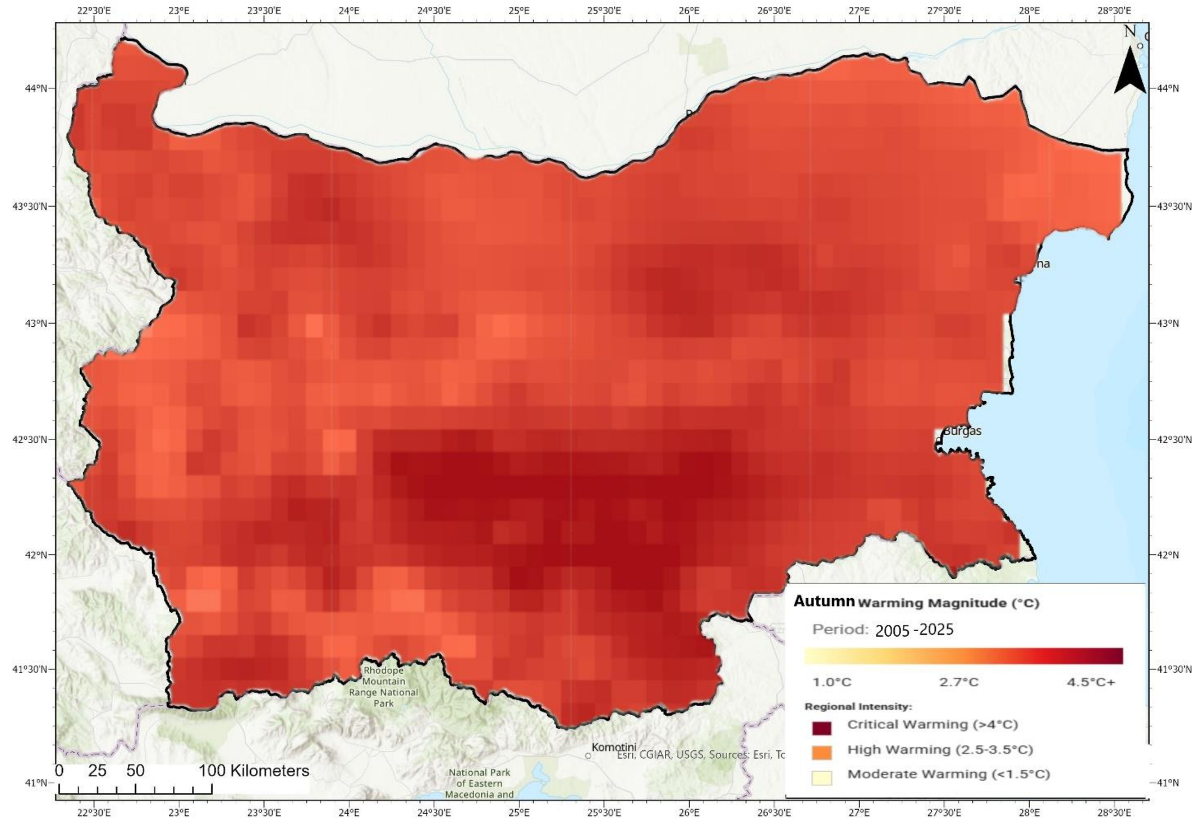

Fig. 22. Spatial distribution of the autumn warming magnitude 2005-2025.

Malcheva & Bocheva, (2023) also confirm that the transition from a colder to a warmer and/or drier climate has affected approximately 36% of the country's territory, and the relative change in mountain climate subtypes shows a significant reduction (by 60-70%) in areas with an alpine climate. Also in similar research Malcheva et all. (2023) disclosed that the fluctuations in the average annual air temperature in Bulgaria for the period 1931–2020, relative to the 1961–1990 climate norm, show a growing, statistically significant trend of 0.14 °C per decade and no negative deviations from the norm (except for 2005) in recent decades have been observed, and since 2011, there have been no deviations smaller than 1 °C with a record temperature anomaly of +2 °C registered in 2019.

On a broader scale, the results of this study align with the Copernicus Climate Change Service (C3S) reports, which consistently rank the Balkans as one of the fastest-warming regions in Europe. The findings mirror the conclusions of Zittis et al. (2022) which stating that the Eastern Mediterranean and Middle East (EMME) region – which includes Bulgaria – is warming at twice the global rate. Furthermore, the IPCC Sixth Assessment Report (AR6) identifies the Mediterranean basin as a "climate change hotspot" where the intensification of summer aridity and winter thermal shifts are expected to outpace global averages.

CONCLUSION

The findings of this research indicating a total warming magnitude of approximately 2.9°C in winter and 3.2°C in summer since 1950 align closely with established regional climate studies that identify the Balkan Peninsula as a high-sensitivity climate hotspot. These results corroborate the structural shift theories documented in Bulgarian climatology which identified the late 1980s as a transition point from a stable continental regime to an accelerated warming phase driven by changes in atmospheric circulation - more frequent intrusions of Mediterranean air masses a mechanism that can explain the steepening trendlines observed in our 2005 to 2025 analysis.

The observed doubling of the warming velocity in the 2005 to 2025 period matches the conclusions regarding Mediterranean and Southern European intensification documented in the IPCC Sixth Assessment Report. Specifically the data indicate that the Bulgarian summer is warming at a rate significantly higher than the global average which coincide with the findings that the Eastern Mediterranean and Balkan regions are warming faster than the rest of the European continent. Also the surge in summer temperature consistency and the rise in r-squared values reaching their highest seasonal levels supports the increasing frequency of tropical nights and the northward migration of subtropical thermal characteristics across the Danubian Plain. This aligns with recent reports from the National Institute of Meteorology and Hydrology (NIMH) which classified the summers of 2024 and 2025 as among the hottest since 1930 with 2024 setting an absolute heat record for the country.

Furthermore the false spring paradox identified in this research where early thermal onset increases frost vulnerability is a phenomenon well-documented across Southeastern Europe. This supports the conclusions of agricultural climate risk assessments that the shift in the start of the growing season is not being met by a corresponding shift in the date of the last spring frost. The rising tempeartures in the spring and the autumn are relegated with the hydrological shifts noted in the spring and autumn, particularly the earlier depletion of mountain snowpacks. The rise in the temperature are connected with the transition to a drought-to-flood cycle and are consistent with reports on the changing hydrological regimes of the Balkan mountain massifs which have demonstrated a significant reduction in snow cover duration especially at altitudes between 1500 and 2200 meters.

The statistical robustness of the 21st-century trends validates the forced signal hypothesis prevalent in contemporary climate modeling. By demonstrating that recent temperature variations are becoming more linear and less susceptible to natural stochastic noise this research confirms the transition from decadal variability to a permanent greenhouse-gas-driven thermal state. This conclusion is shared by virtually all major climate monitoring services including Copernicus and the World Meteorological Organization which have highlighted the Balkan region as a primary area for climate-related economic and environmental risks. The prolonging of the thermal growing season and its asymmetric shift toward an earlier onset rather than a later termination matches the evidence found in pan-European studies focused on Southeast Europe over the last several decades.

The synthesis of these findings proves that Bulgaria has entered a new climatic state where historical continental boundaries have been replaced by a more volatile and significantly warmer subtropical influence. Across all seasons the data shows that Bulgaria has moved into a regime where every season has surpassed a 2.0°C warming magnitude since 1950. Furthermore, the spatial analysis identifies the Danubian Plain, the Upper Thracian Lowland, and the Struma Valley as the primary hotspots of climatic stress. In these regions, total warming since 1950 has reached +3.8°C to +4.0°C, effectively migrating the thermal conditions of these areas 300km to the south. This research underscores an urgent need for the re-evaluation of national adaptation strategies in agriculture water management and urban planning as the velocity of change currently outpaces traditional resilience measures and the frequency of extreme events like flash floods following prolonged heatwaves continues to rise as documented in the meteorological reports of 2025.

All the disclosed data and analyses in this research shows that ERA5-Land reanalysis data and the Google Earth Engine (GEE) platform are useful instrument for climate change analyses. The provided by ERA-5 land high-resolution data - consistent record of land surface variables (by combining physical models with global observations through data assimilation) and the 9 km spatial resolution allows the capture of complex topographical influences – such as the thermal variations between the Balkan Mountains and the Danubian Plain. By offering a stable, continuous time series from 1950 to the present, it could serves as a reliable instrument for quantifying multi-decadal climate shifts and identifying structural breaks in regional thermal regimes. On the other side Google Earth Engine functions as a transformative instrument for climate research and provides the massive computational power required to process these multi-terabyte datasets in real-time.

Through GEE, complex statistical operations like pixel-based linear regressions and seasonal aggregations which are executed on Google’s cloud infrastructure, help to overcome the limitations of traditional desktop computing. This enables to visualize high-velocity climate transitions and generate statistically robust magnitudes of warming with unprecedented precision. Ultimately, the synergy between ERA5-Land’s historical depth and GEE’s analytical speed empowers scientists to move beyond broad global generalizations and produce localized, high-impact evidence of the ongoing climatic transformation.

Declaration by Authors

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