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Analysis of perennial temperature variations and behavioral ecology of insects for the region of the city of Plovdiv, Bulgaria

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Abstract. Climate change is significantly affecting both natural ecosystems and human-managed systems on a global scale. The stressors associated with the Anthropocene are diverse and intricate, including invasive species, habitat degradation, pesticide application, and pollution. However, none of these stressors are as pervasive or interconnected with various other factors as climate change. Consequently, understanding the effects of anthropogenic climate change on natural systems is a paramount challenge for environmental sciences in the 21st century. The Intergovernmental Panel on Climate Change (IPCC) defines climate change as "a shift in the climate's state that can be recognized (using statistical methods) by alterations in the average and/or the variability of its attributes, persisting for a long time, generally for decades or longer". This definition encompasses any changes in climate over time, whether resulting from natural variations or human-induced activities. Climate-related variables, such as temperature, water availability, and carbon dioxide levels, critically affect the characteristics of ecosystems that facilitate food production, including both freshwater and marine environments, agriculture, and forestry. Any fluctuations in these variables present a risk to global food security. This research, therefore, is crucial in understanding and mitigating this risk.

Key words: climate; temperature; insect; variation; trend.

Introduction

Climate change is a major challenge for humanity in the 21st century, causing significant concern and research. Projections indicate that near-surface temperatures in Central Europe may rise by about 1.6°C to 2.4°C by 2050 (Shukla et al., 2022). Insects, crucial as pests in agriculture and contributors to ecosystem services (Bonelli et al., 2022), are a focus of study regarding climate change impacts (Skendžić et al., 2021; Srivastava et al., 2020). Their distribution and abundance are heavily influenced by climate, making it essential for entomologists to understand models that quantify these impacts. Temperature specifically affects insect phenology, including mating, development rates, and seasonal emergence.

Research shows that temperature fluctuations significantly impact insect life cycles, influencing their development, distribution, and success across different habitats. Various studies have highlighted how rising global temperatures affect insect populations, with key references from Akers & Nielsen (1984) and Allsopp & Butler (1987).

Being poikilothermic, insects rely heavily on external temperatures to regulate biological processes such as metabolism and reproduction. Temperature influences their life cycle from egg hatching to adulthood, affecting developmental rates and behavioral patterns like foraging and mating. Due to their small size and high surface area-to-volume ratio, insects are especially vulnerable to temperature changes, making population and distribution trends sensitive to climatic variations (Wojda, 2017).

High temperatures can increase metabolic rates and nutrient consumption, potentially leading to mortality without adequate food or hydration (Harvey et al., 2023). Conversely, low temperatures can freeze bodily fluids, causing dehydration and death, with varying resistance levels within species and developmental stages (Genoud et al., 2023).

Insects thrive within specific temperature ranges, where development rates accelerate until an optimal threshold, after which they decline at maximum temperatures (Arbab et al., 2008). Temperature also influences enzyme activity, which is critical for the function of poikilothermic organisms (Higley et al., 1986).

This study aims to analyze long-term temperature variations in the region of the city of Plovdiv and assess their impact on the behavioral ecology of insects, with a focus on changes in phenology, distribution, and population dynamics. Additionally, the study seeks to identify potential risks to agricultural production and ecosystem services arising from climate-driven shifts in the population dynamics of key insect species.

Materials and methods

The analysis used data from the National Institute of Meteorology and Hydrology (NIMH), focusing on the average daily values of three temperature measurements in Plovdiv, Bulgaria, over 50 years from 1974 to 2024. Plovdiv, located at an altitude of 160 meters along the Maritsa River, exhibits a unique morphological structure that influences local climate patterns, including significant temperature inversions through 81% of the year.

Data was processed using Climpact, a comprehensive software package designed to calculate pertinent climate indicators across various sectors, including health, agriculture, water, and other socio-economic areas. Climpact, developed by the World Meteorological Organization's Expert Team on Sector-Specific Climate Indices (ET-SCI), enables researchers to provide valuable and applicable climate information to sector users. This initiative has received support from the Australian Research Council Centre of Excellence for Climate Extremes and the Green Climate Fund. The Climpact software, which uses a range of climate indices to assess the impact of climate change, is accessible at www.climpact-sci.org.

Results

Plovdiv, a city rich in history and culture, has a transitional continental climate. From 1974 to 2024, the average annual temperature has gradually increased, with the lowest recorded temperature at -31.5°C and the highest at 45.0°C in July 2000 (Fig. 1). The first 25 years showed stable annual temperatures between 0.05°C and 0.39°C. Still, after 2013, the average exceeded 13°C. Overall, the average temperature for the study period was 12.9°C, reflecting a warming trend consistent with global climate patterns. July was the warmest month, with an average temperature of 24.3°C. Summer heat often demonstrates extreme variability, as evidenced by the record high of 45.0°C in 2000. In contrast, January is the coldest month, with an average temperature of 1.3°C. The temperature data indicates that January experienced its lowest average temperature of -3.9°C in 2017, while 2023 saw a relatively milder January, peaking at an average of 5.8°C.

A detailed analysis of the monthly average temperatures from 1974 to 2024 reveals a positive linear trend with a slope of 0.03 and a statistical significance level of $\rho = 0.055$, indicating a plausible yet modest rise in average temperatures over the years. The winter season of 2023 was particularly notable, as it emerged as the warmest winter recorded in the city since 1974. When temperatures exceed 10°C, a more pronounced positive trend is observed, with a trend slope of 0.375 at a significance level of $\rho = 0.004$, suggesting a significant increase in warmer days, conversely, the trend analysis of the number of days each year experiencing daytime temperatures below 10°C reveals an inverse relationship, indicating a decrease in the frequency of cooler days as the climate warms. This combination of data illustrates the ongoing climatic shifts that Plovdiv is experiencing, highlighting the need for local adaptation strategies and greater awareness of environmental changes.

The average temperature exhibits a range of variation defined by the maximum temperature (TX). The Daily Maximum Temperature Index is a valuable tool for examining climate variability and changes over an extended period. Research conducted in the Plovdiv region between 1974 and 2024 aimed to determine the average maximum annual temperature, which ranged from 17.2°C to 21.8°C (Fig. 2). The highest value was recorded in 2024, while the lowest occurred in 1991. On average, Plovdiv experienced a maximum annual temperature of 18.7°C. Notably, after 2015, the average maximum temperature consistently surpassed 19°C.

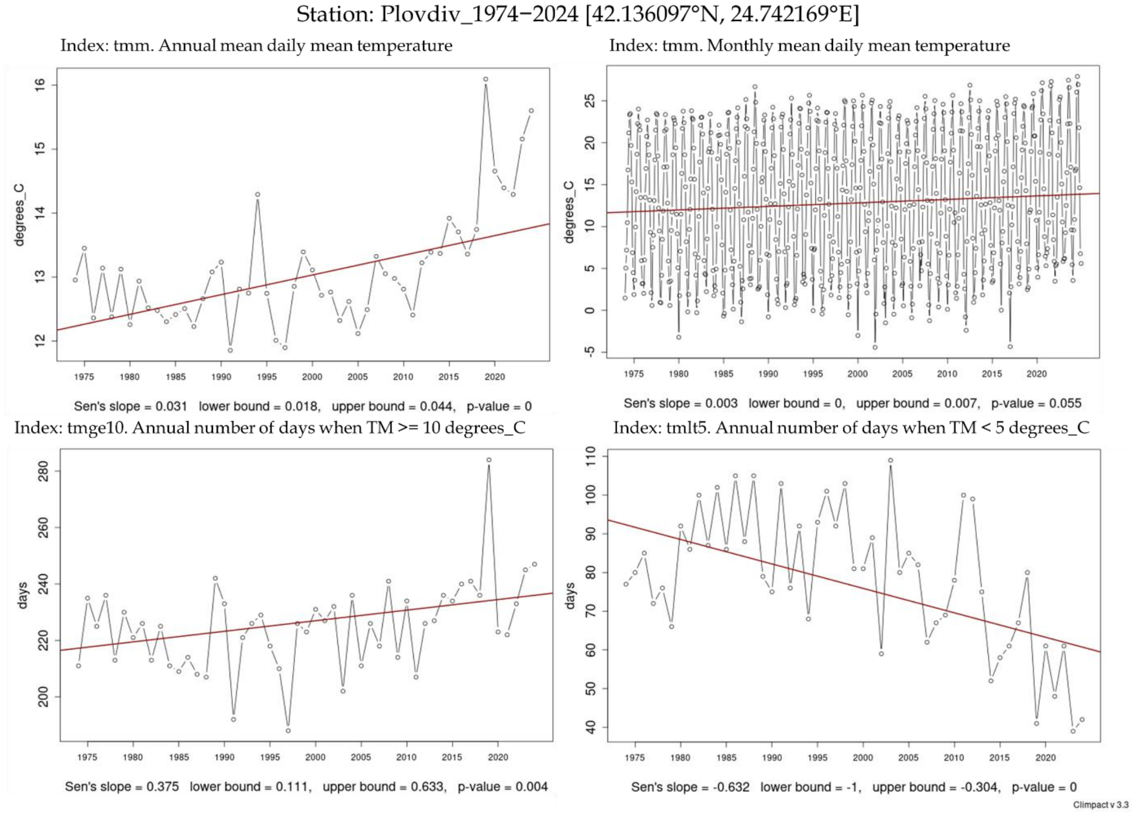

Fig. 1. Analysis of trends in annual and monthly temperatures, as well as the frequency of days exceeding and falling below 10°C, in the city of Plovdiv, covering the period from 1974 to 2024.

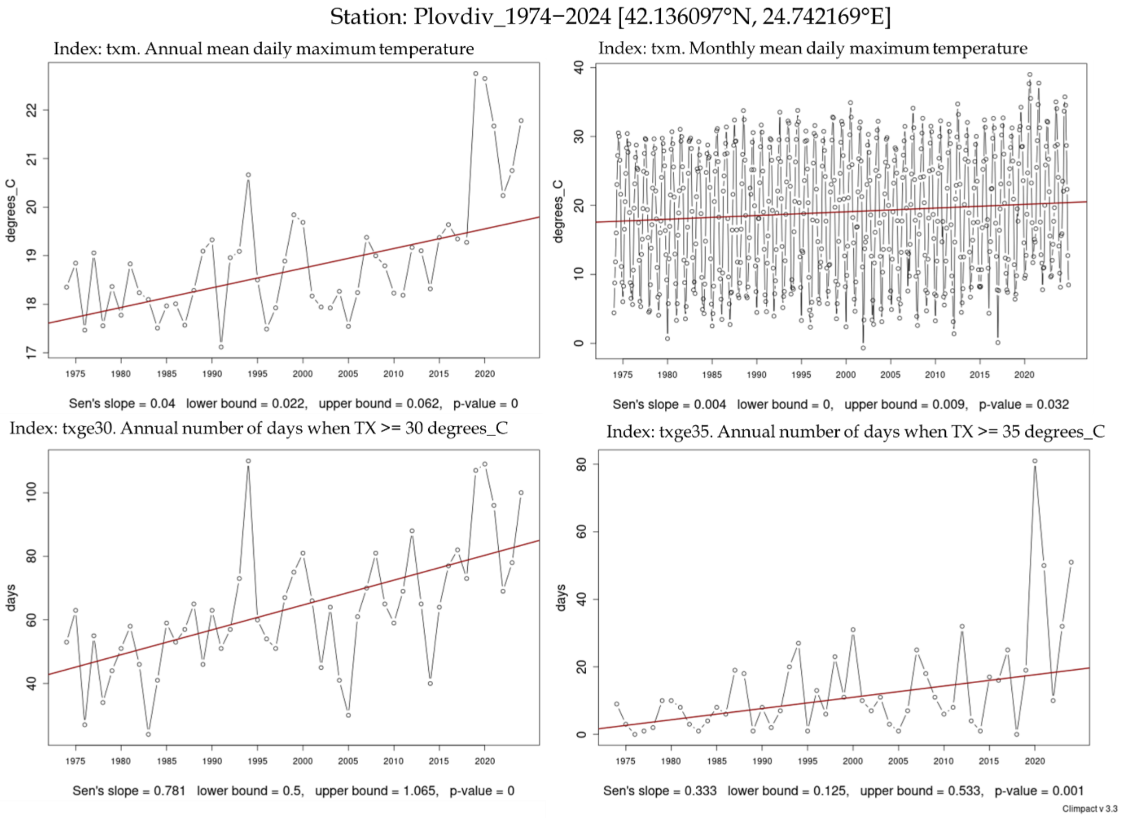

Fig. 2. Trend in maximum annual and monthly temperature changes, along with the number of days above 30°C and 35°C, for the city of Plovdiv from 1974 to 2024.

An upward linear trend has been established for the annual average maximum temperature, with a slope of 0.04 and a significance level of ρ = 0.00. A similar upward trend is also observed in the average monthly maximum temperature, with a slope of 0.004 and a significance level of ρ = 0.032.

In the city of Plovdiv, the lowest average monthly maximum temperature is typically recorded in January at 5.6°C, while the highest occurs in July at 31.1°C. For July specifically, the average maximum temperature varied from 28.4°C in 2005 to 35.7°C in 2024. An upward linear trend has been observed in the number of days with maximum temperatures exceeding 30°C, with a slope of 0.781 and a significance level of ρ = 0.00. The fewest days below 30°C were recorded in 1983 (fewer than 40 days), while the highest occurred in 1994, 2019, and 2020 (over 100 days).

An upward linear trend was also detected in the number of days with maximum temperatures exceeding 35°C, with a trend slope of 0.333 and a significance level of ρ = 0.001. The record high for the observed period from 1974 to 2024 occurred in 2020, with 80 days above this threshold.

The average minimum temperature is an important aspect of the overall average temperature, second only to the average maximum temperature. While it does not capture the full range of temperature fluctuations, it provides insight into changes in extreme temperatures.

From 1974 to 2024, four instances of minimum temperatures below the 25th percentile were noted, indicating significant cold extremes. Notably, in January 1980, temperatures in Bulgaria dropped to -22.0°C, and in January 1993, to -23.0°C due to a cold front. Additionally, in March 1986 and 2018, minimum temperatures were recorded at -13.0°C and -14.0°C, respectively.

In the city of Plovdiv, the average minimum temperature from 1974 to 2024 was 7.3°C. The lowest recorded average minimum temperature occurred in 1997 at -5.8°C, while the highest was noted in 2023 at 9.5°C (Fig. 3). After 2013, the minimum temperatures consistently exceeded the average for the reporting period of 1994 to 2024. A slight upward linear trend was also observed in the monthly averages, with a slope of 0.002 at a significant level of ρ = 0.166. The coldest months in Plovdiv were January (-2.6°C), February (-1.2°C), and December (-1.0°C). In January, minimum temperatures during the observed period fluctuated between -8.8°C (in 2017) and 4.1°C (in 2004).

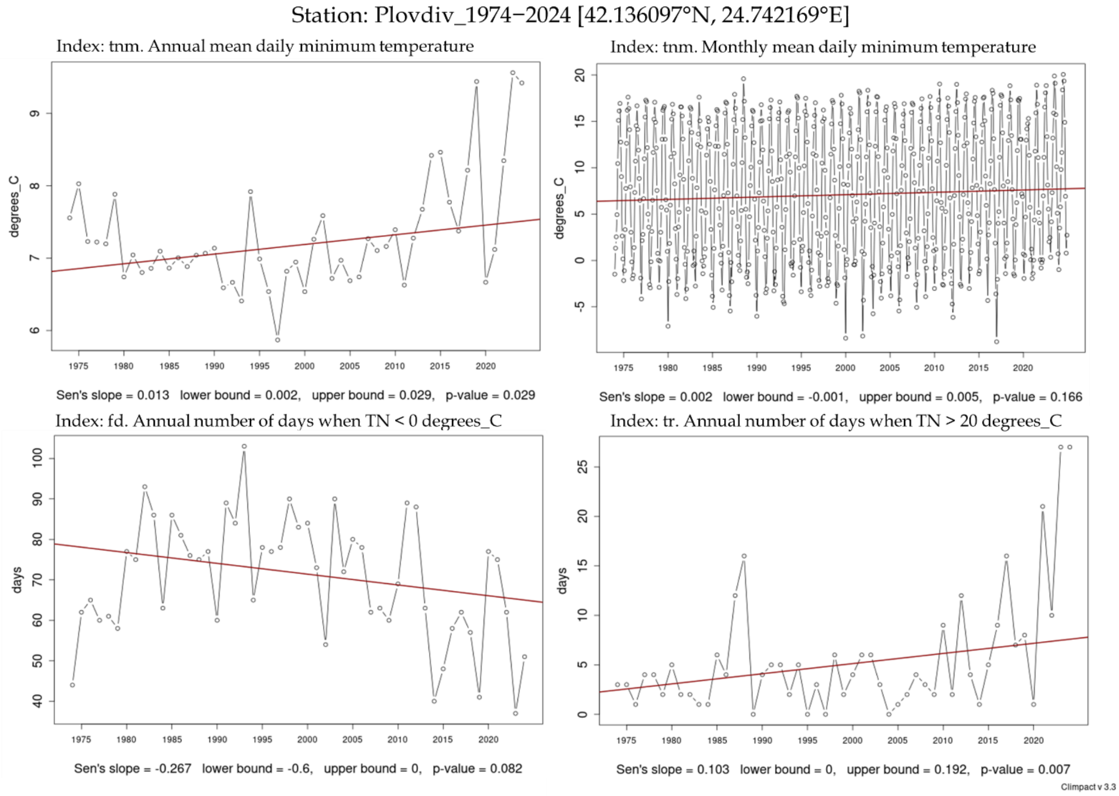

Fig. 3. Trends in minimum annual and monthly temperature changes, along with the number of days below 0°C and above 20°C, for the city of Plovdiv from 1974 to 2024.

When examining trends in the number of days with minimum temperatures below 0°C (frost days), a downward trend was observed, with a slope of -0.267 at a significance level of ρ = 0.082. The analysis indicated that in 1993, the number of frost days exceeded 100, while in 2023, it fell below 40. Conversely, the trend in the number of days with minimum temperatures above 20°C (tropical nights) showed an upward trend, with a slope of 0.103 at a significance level of ρ = 0.007. The highest number of tropical nights recorded occurred in the last two years of the observed period (1974–2024).

The length of the growing season can vary greatly depending on several factors, such as latitude, altitude, and local climate conditions. In general terms, the growing season is defined as the period of the year during which weather conditions are suitable for plant growth and insect development. When tracking the average number of days at an average daily temperature above 5°C, a positive linear trend with a slope of 1.188 at ρ = 0.00 was found (Fig. 4). A positive linear trend was also found when analyzing the total reading of the degree days at an average daily temperature above 10°C, with a slope of 6.995.

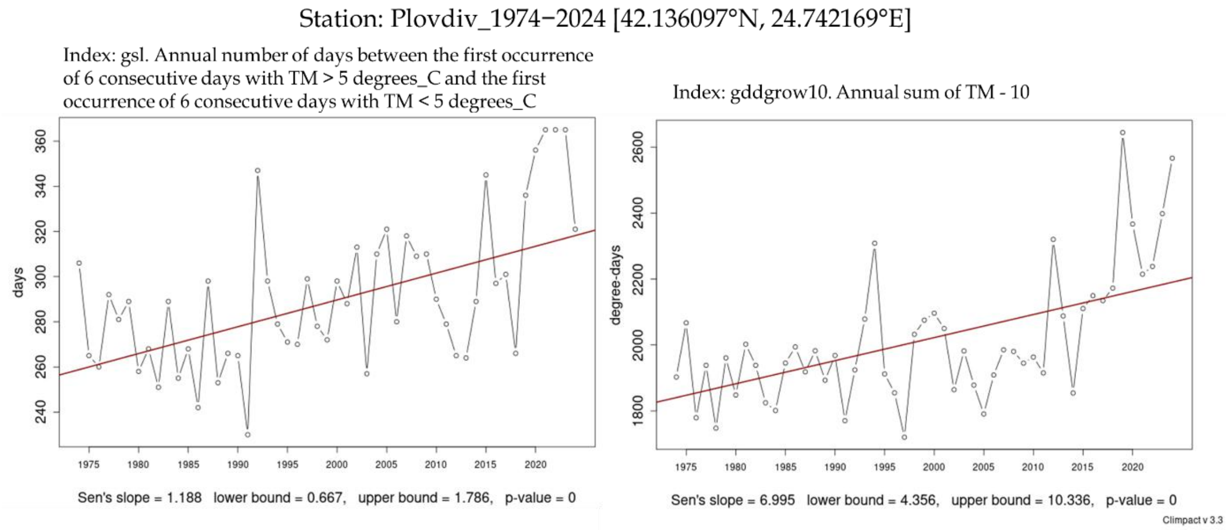

Fig. 4. Duration of the vegetation period and degree-days above 10°C for the Plovdiv region from 1974 to 2024.

Discussion

Climate warming is a significant environmental stress due to human activities, affecting biodiversity and exacerbating other threats. Its implications are particularly critical for species conservation and ecosystem services. Insects, essential to many ecosystems, are among the most impacted by climate change, influencing their physiology, behavior, phenology, distribution, and interspecies interactions. Additionally, the increasing frequency of extreme events — like heatwaves, cold spells, wildfires, droughts, and floods—further affects these factors (Harvey et al., 2023).

Ambient temperature significantly influences insects' physiological functions, including respiretion, immunity, metabolism, growth, and reproduction. These physiological factors consequently impact various biological characteristics such as behavior, locomotion, distribution, longevity, and survival (González-Tokman et al., 2020; Kingsolver et al., 2015).

Insects have developed various physiological strategies to adapt to seasonal temperature variations and rising temperatures. For example, adaptations to warmer conditions may involve a shift from active periods to phases of rest through mechanisms such as diapause or estivation (Salman et al., 2019) or by increasing the number of generations produced annually (Altermatt, 2010).

Research by Held & Spieth (1999) shows that in southern Spain, populations of the butterfly *Pieris brassicae* L. undergo pupal aestivation during summer due to high temperatures and long daylight. They do not enter winter diapause under these conditions, likely as a local adaptation to extreme heat that limits food availability. Conversely, *P. brassicae* in milder climates avoid reproduction in summer and enter diapause in winter.

Climatic factors significantly influence species distribution and are subject to variability, expanding or contracting during prolonged climatic fluctuations (Hewitt, 2000). For example, the emperor dragonfly (*Anax imperator* L.) has experienced a northward shift in its distribution and an increase in elevation in Europe since the year 2000 as a response to rising temperatures (Platts et al., 2019). This species exhibits enhanced viability at higher altitudes; however, the ongoing warming trend presents a substantial threat to this vulnerable subspecies (Parmesan et al., 2015).

Moreover, the functional responses of the facultative hyperparasitoid *Gelis agilis* Fabr. are intricately linked to ambient temperature. Their capacity to exploit hosts is markedly impaired at elevated temperatures (Chen et al., 2019). Demographic models for the leaf beetle *Cephaloleia belti* Baly, when assessed in conjunction with long-term temperature data, indicate that even a modest increase of just 2°C may precipitate population declines. At the same time, average elevations could serve as refuges against the impacts of global warming (García-Robledo & Baer, 2021a,b).

Increased temperatures contribute to an extended growing season, which, in combination with accelerated developmental rates, enables certain insect species to increase their generational output within a given year, a phenomenon referred to as voltinism (Bradshaw & Holzapfel, 2001). The occurrence of recurrent heat waves during summer or elevated temperatures in winter—whether one or both—can generate inappropriate ecological cues that compel insects to enter developmental traps. This includes premature development resumption during midwinter (Boggs, 2016; Forrest, 2016). In a study made for the site of the city of Plovdiv for the period 2020-2023, it was found that the composition of mining moths: ribbed apple leaf miner (*Leucoptera malifoliella* Costa), the spotted tentiform leaf miner (*Lithocoletis blancardella* F.), and the banded apple pigmy (*Stigmella malella* Stt.) has increased in recent decades. In areas with large apple, pear, or quince orchards, the multiplication of the pest is favored by abiotic (climatic), biotic (natural regulators), and human factors (inept use of insecticides). The resulting decrease in apple production caused by leaf-mining moths is estimated from 4.6 to 23.4. The results show a significant shift in the beginning of the flight of *L. malifoliella*, *Ph. blancardella*, and *Ph. corylifoliella* 20 days earlier due to the warmer winters observed in the region of Plovdiv (Ivanov, 2024). In the period 2021-2023, the codling moth (*Cydia pomonella* Linnaeus) developed two full and partial third generations. Through visual observations, it has been found that climate change strongly influences the development of the pest of the partial third generation (Ivanov & Filyova, 2024).

For example, atypically warm fall conditions can disrupt the life cycle of the wall brown butterfly, *Lasiommata megera* L., by adversely affecting diapause at the conclusion of its second generation. This disruption renders the third generation particularly susceptible to winter mortality, resulting in a significant population decline of this butterfly species across much of Western Europe (van Dyck et al., 2015). Furthermore, elevated winter temperatures have been observed to impact honey bee colony phenology, resulting in mismatches with available floral resources (Nürnberger et al., 2019). Additionally, warmer winter periods stimulate colony growth activity, thereby benefiting their principal parasite, the invasive mite *Varroa destructor* Anderson & Trueman (Nürnberger et al., 2019; Vercelli et al., 2021).

A recent meta-analysis indicates that exposure to climate extremes, especially heat waves, generally undermines the adaptability of insects within terrestrial ecosystems (Thakur et al., 2021). In certain cases, this has culminated in local extinctions, as evidenced by various populations of the butterfly *Parnassius apollo* L. in France that experienced extreme winter temperatures followed by lower, more typical spring conditions (Nakonieczny et al., 2007).

The detrimental effects of extreme temperature events on insects may also be correlated with the stress induced in plants, with many insect species maintaining close associations (Pincebourde et al., 2017). For instance, larvae of the moth *Lobesia botrana* Denis & Schiffermüller, which feed on heat-stressed, suboptimal-quality plants, exhibit adverse effects on their development and immune responses (Iltis et al., 2021). Additionally, consistent exposure to excessively warm nights diminishes both the longevity and fertility of the cereal aphid *Sitobion avenae* Fabr. in the following days (Zhao et al., 2014).

Climate change is anticipated to have a profound impact on the geographical distribution of insect pests, with low temperatures often proving to be more influential than high temperatures in this context. By the year 2055, projections indicate a shift of pest ranges to higher altitudes, resulting in an increased number of generations occurring in Central Europe. For example, the European corn borer (*Ostrinia nubilalis* Hubner) has migrated over 1,000 kilometers to the north. According to the study by Gutierrez et al. (2009), the range of the olive fly (*Bactrocera oleae* Rossi) in both Europe and North America is expected to retreat southward while simultaneously expanding northward, driven by warmer summer temperatures and milder winters that affect adult fly populations. The species *Synanthedon myopaeformis* Borkh. Preferring higher altitudes has expanded its distribution area to lower altitudes, higher levels of population density, and an increase in damage to the Plovdiv region has been found (Ivanov, 2023).

Furthermore, when the brown marmorated stink bug (*Halyomorpha halys* Stål) is in its nymphal stages, its entire population is susceptible to decline (Musolin, 2007). In contrast, areas farther south benefit from a sufficiently long growing season, which allows this generation to mature before the onset of winter. In these regions, the brown marmorated stink bug has effectively outcompeted the previously dominant pest species, the oriental green stink bug (*Nezara antennata* Scott) (Bale & Hayward, 2010; Tougou et al., 2009). Although no economic impact is known so far in Europe, future stable establishment and mass development of *Halyomorpha halys* in Bulgaria will most probably be a problem in agriculture jointly accumulated with recently observed damages caused by *N. viridula* in some Bulgarian regions (Simov et al., 2012). When monitoring the insect, a spread in the region of Plovdiv was also found (Hristozova & Harizanova, 2024).

Recent studies indicate that numerous invasive insect pest species are anticipated to expand their geographical range and exhibit increased population density and reproductive cycles as a result of projected climate change scenarios (Hill et al., 2016; Walther et al., 2009). This phenomenon poses significant risks to sustainable agricultural production. Extreme weather events, including storms, strong winds, hurricanes, and high waves, can facilitate the transportation of pests to new areas where they may find favorable environmental conditions for establishment (FAO, 2020).

A prominent example of this issue is the invasion of the spotted Drosophila (*Drosophila suzukii* Matsumura), which is known for its adaptability and potential for significant agricultural damage across North America, South America, and Europe. It is believed that this pest was introduced via the fresh fruit trade, with initial populations reproducing undetected in the egg or larval stages within large shipments of fresh fruit imported from Southeast Asia (Rota-Stabelli et al., 2013). The model predicts that under the current climatic conditions, *D. suzukii* can be established on the whole territory of the country and develop 3–7 generations per year for the region of Plovdiv. In the region of Plovdiv, the number of trapped flies was significantly higher than in Blagoevgrad and Kyustendil (Karadjova et al., 2016).

Conclusions

Temperature is one of the primary factors influencing insect phenology. Changes in temperature patterns can disrupt the established relationship between thermal and photoperiodic conditions, significantly impacting insect seasonal behaviors, including their reproductive cycles. Generally, elevated temperatures during the growing season expedite the development of ectothermic organisms.

The European Union has prioritized the mitigation of climate change and the adaptation to its impacts on the planet and its ecosystems. Annual reports produced by the National Institute of Meteorology and Hydrology, along with the World Meteorological Organization, indicate a notable increase in abiotic factors. The Hydrometeorological Bulletins and the WMO Statement on the State of the Global Climate for the relevant years substantiate this trend.

Research indicates that the climate in the city of Plovdiv and its surrounding region has experienced substantial changes. Analyses of average annual temperatures from 1974 to 2024 demonstrate a consistent rise. Since 2013, the average annual temperature in the Plovdiv region has maintained levels at or above 13°C. Furthermore, there is a persistent upward trend in the average annual temperature within this region.

Monthly temperature assessments for June and July reveal a distinct upward trajectory. Additionally, a positive monotonic trend in maximum temperatures has been documented for the summer months, with the most pronounced increase noted in August. A consistent rise has also been observed in the minimum temperatures recorded for August.

Conversely, a decreasing linear trend has been established in the average number of days exhibiting daily temperatures below 5°C (TM < 5°C) and below 10°C (TM < 10°C). Simultaneously, an increasing linear trend has been identified in the average number of days with daily temperatures exceeding 30°C (TX > 30°C) and 35°C (TX > 35°C) within the Plovdiv region.

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