

Article

Investigating Warm-Season Heatwaves Along the Lithuanian Baltic Sea Coast Applying Copernicus Datasets

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Abstract

Extreme events have become an integral aspect of the unusually intensified climate change characterizing this century. This study examines extreme heat waves and tropical nights—phenomena historically uncommon in the mid-latitude Southeastern Baltic Sea region. Extreme heat and heat waves are defined as any period during which the daily maximum air temperature exceeds 30 °C, and a tropical night is one in which the daily minimum air temperature does not fall below 20 °C. Both in situ observations and model output from the Copernicus Climate Change Service were employed in the 1982–2024 analysis. The results reveal that the frequency of extreme heat waves is increasing. Since 2018, the southeastern Baltic Sea coast has experienced at least one extreme heat wave and one tropical night each year. The observed rise in mean air and sea-surface temperatures has driven an uptick in tropical night occurrence. Forecasts of tropical-night formation could be substantially improved by integrating sea-surface temperature assessments for the southeastern Baltic coast. Moreover, timely adaptation to evolving weather conditions—through enhanced forecasting techniques and the incorporation of high-resolution reanalysis datasets—is essential for optimizing early-warning systems capable of safeguarding human health and lives. Climate change increases the frequency and intensity of heat waves, posing significant challenges to public health, the economy, the environment, and infrastructure. Therefore, advancing the understanding of extreme heat events through the use of cutting-edge technologies, remote sensing, and Copernicus reanalysis data represents a key sustainability task. Such approaches enable more accurate assessments and forecasts of extremes, thereby supporting a safer, healthier, and more resilient future.

Keywords: extreme heat events; heatwaves; tropical nights; coastal climate; Baltic Sea region; sea surface temperature (SST); climate change trends



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1. Introduction

In recent decades, extreme heat events have emerged as one of the most significant indicators of accelerating climate change worldwide. New technologies, including remote monitoring, improve the monitoring, early warning, and forecasting of extreme climate events, contributing to sustainable environmental management and climate resilience [1].

Heat waves—prolonged periods of unusually high temperatures—are occurring with increasing frequency, intensity, and duration across the World, including regions historically characterized by moderate summers. Global warming is likely to increase the risk of heatwaves and tropical nights. Most of humanity recognizes that the climate, which began to change in the twentieth century and continues to evolve in the twenty-first century, is shifting at rates well beyond historical norms [2]. Therefore, the pursuit of sustainability and new knowledge is both timely and imperative, since human activities—fossil-fuel combustion, modification of natural environments to satisfy short-term needs, and pollution—have become global in scope, adversely affecting all of Earth’s geospheres.

Heatwaves and tropical nights hold immense significance in both understanding climate change and studying the sustainability needed for Earth’s ecosystems’ stability or adaptations. The unprecedented intensification of heat-related extremes is one of the most conspicuous signs of ongoing climate change. Larger shifts and anomalies from long-term climate norms are observed in the mid- and polar latitudes. For example, the European State of the Climate report [1] highlighted that Southern and Central Europe experienced record-breaking warm nights, while Northern Europe saw unprecedented warm-season anomalies, reflecting a poleward shift in extreme temperature patterns. The Copernicus 2024 Climate Change Summary reports that global surface temperature has, for the first time, exceeded the 1.5 °C threshold set by the Paris Agreement [2]. This milestone was reached earlier than anticipated, as previous projections had indicated that temperatures relative to the pre-industrial (1850–1900) baseline would not surpass this threshold until around 2030.

Scientists and researchers from various countries indicate that the ongoing warming trend has resulted in heat waves that are more frequent, longer-lasting, and more intense [3–5], with attendant impacts on human health and ecosystem stability. The European Environment Agency highlights that recent summers have produced repeated, multi-week heat waves—periods of sustained high temperatures that overwhelm physiological and societal coping capacities—leading to elevated mortality, heat stress syndromes, and strain on energy and water systems [6].

Early landmark studies [7,8] established that mid-latitude regions would see significant increases in heat-wave frequency under warming scenarios. More recent analyses confirm an acceleration of these trends: summers of 2022, 2023 and 2024 featured extreme heat events that occurred earlier and with greater spatial extent than climate models had projected. Copernicus reporting for southeastern Europe noted a record 66 days of “strong heat stress” in summer 2024, reflecting not only elevated air temperatures but compounding humidity and reduced night-time relief [9]. Increased atmospheric moisture reduces nocturnal cooling and enhances the perception of heat, leading to greater thermal discomfort during tropical nights. Parallel to daytime extremes, “tropical nights” (daily minimum air temperature ≥ 20 °C) have emerged as a significant dimension of heat-related risk. Once confined to Mediterranean climates, tropical nights have spread northwards, with long-term studies in Spain (1970–2023) demonstrating both increased annual frequency and shifts in seasonal distribution towards earlier months [10]. This analysis of tropical nights in Spain revealed that the minimum nighttime temperature can serve as one of the indicators of climate change. The European Climate-ADAPT indicator framework now includes tropical nights as an “Extreme Heat Hazard” metric, reflecting their physiological impact by preventing nocturnal cooling and elevating cumulative heat stress [11].

Spatiotemporal analyses of trends from 1950 to 2022 in the Mediterranean reveal that tropical night intensity and duration have risen significantly since the late twentieth century [12]. Hot or tropical nights have significant implications for human health, especially for vulnerable populations. Noted that the changes in the frequency of tropical nights,

which result in discomfort and heat-related illnesses due to insufficient nocturnal rest, are an illustration of a pertinent human health concern [13]. Swiss research links warmer nights to heightened mortality, especially in urban areas where heat storage exacerbates nocturnal temperatures [14].

Global assessments, including the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), emphasize that heat extremes are becoming more frequent, more intense, and longer lasting, especially in mid-latitude regions [3]. While Southern Europe is already experiencing recurring extreme summer temperatures often surpassing 30 °C and, in recent years, even 40 °C [1], WMO annual climate reports (2022, 2023) highlight new records of 40+ °C in Spain, Italy, and Greece. Northern Europe has traditionally been considered less exposed. However, recent studies suggest that the Baltic Sea region is increasingly vulnerable to warm-season extremes, making this area an important focus for climate impact assessments.

Northern Europe, which includes the Lithuanian area, has traditionally been considered less exposed to extreme summer heat due to its cooler maritime climate and geographical location. However, an increasing body of research demonstrates that the Baltic Sea region is becoming progressively more vulnerable to warm-season extremes. Long-term climatological analyses for Lithuania reveal significant growth in the frequency and intensity of high-temperature events, indicating a clear shift towards more severe heat extremes [15,16]. Comparable findings for the broader Baltic region confirm similar tendencies, with consistent increases in daily maximum and minimum temperatures, as well as reductions in diurnal temperature range across Lithuania, Latvia, and Estonia [17]. These regional patterns highlight that even in Northern Europe, where historical exposure has been relatively limited, coastal and continental parts of the southeastern Baltic are now emerging as climate-sensitive hotspots. Such evidence highlights the need to improve early warning systems for extreme events and to integrate multiple data platforms—including remote sensing—into climate impact assessments, digital model updates, and sustainability and adaptation planning. These efforts are particularly relevant for the Baltic Sea region, where local communities, ecosystems, and infrastructure are increasingly exposed to prolonged heatwaves and nighttime warming.

In Northern Europe, including the Baltic countries, daily maximum temperatures exceeding 30 °C are recognized as a critical threshold for defining extreme heat events. For example, the 2015 August heat wave in Poland was described as a mega heat wave and defined as an event where the maximum air temperature exceeds 30 °C for at least 6 consecutive days [18]. Such conditions, although less frequent than in Mediterranean countries, are associated with disproportionately high health impacts due to limited population acclimatization and less widespread adaptation measures [16,19]. For comparison, in Southern Europe the thresholds of human thermal stress are considerably higher, with values above 30–40 °C commonly used in defining extreme events [18]. This geographical contrast highlights the importance of context-specific definitions of extreme heat and underlines the role of local climatology in shaping vulnerability.

Recent analyses highlight that heat stress levels are effectively characterized by bioclimatic indices such as the Universal Thermal Climate Index (UTCI), which is adopted in the Copernicus ERA5-HEAT framework [19]. According to this classification, moderate heat stress occurs at +26–32 °C, strong heat stress at +32–38 °C, and very strong conditions above +38 °C. While the Mediterranean region frequently experiences “strong” or “very strong” categories, in the Baltic region, heat events often transition into the threshold range of +30 °C, corresponding to strong stress levels [16,18,19]. Therefore, an air temperature higher than +30 °C is chosen as a criterion for the extreme weather conditions in this paper as well.

Furthermore, it is important to emphasize the substantial regional differences in projected changes in heatwave characteristics depending on the level of global warming achieved. Perkins-Kirkpatrick and Gibson [20] demonstrated that between the 1.5 °C and 2 °C global warming thresholds, an additional 3 to 20 heatwave days may occur on average, while the maximum intensity of heatwaves is projected to increase by approximately 0.5 °C, depending on the region. These findings underline that even seemingly small increments in global mean temperature can translate into disproportionately large increases in regional heatwave frequency and severity, with significant implications for human health and adaptation planning in Northern Europe and the Baltic Sea region.

Beyond daytime extremes, nighttime warming has emerged as an equally critical stressor. Tropical nights, defined when the minimum daily air temperature does not fall below 20 °C, limit human recovery during prolonged heatwaves, exacerbate health risks, and increase mortality [13]. Recent studies across Europe show a significant upward trend in the frequency and duration of tropical nights, particularly in Southern and Central regions, with projections indicating further intensification in the coming decades [12]. Coastal zones are especially vulnerable, as higher air humidity and warm sea surface temperatures reduce nighttime cooling, leading to more persistent and intense events [16,21]. Nevertheless, studies focusing on tropical nights in the Baltic Sea region remain limited—particularly regarding the role of land–sea–atmosphere coupling in regulating nocturnal cooling processes. Moreover, most existing regional assessments have not yet translated their findings into operational early-warning frameworks, thereby reducing their practical value for public health advisories, climate services, and transformation towards sustainable management.

Lithuania's coastal area is understudied in terms of local-scale heat extremes. Despite recent progress, several research gaps remain. First, long-term observational analyses of heatwaves and tropical nights in the southeastern Baltic Sea are scarce, with only scattered case studies and national reports available. Second, most regional assessments of extreme events have not adequately integrated atmospheric circulation dynamics with land–sea interactions, which strongly modulate nighttime cooling and daytime heating along coastal zones. Third, the current network of ground-based meteorological stations remains too sparse to support detailed spatial analyses of extreme events. Remote sensing data integrated within the Copernicus program enables the analysis of heatwaves across larger areas and a better understanding of their formation and spatial distribution patterns, which can contribute to more accurate forecasting of heatwaves and tropical nights. Nevertheless, although Copernicus products provide harmonized datasets for assessing heat stress, their application in the context of the Lithuanian coastal zone remains insufficiently studied and validated against in situ data to be effectively implemented in practice.

This study seeks to address part of the knowledge gaps by combining long-term in situ meteorological observations with state-of-the-art remote sensing and reanalysis products. The analysis focuses on the frequency, duration, and intensity of extreme heatwaves (daily maximum temperature ≥ 30 °C for at least two consecutive days) and tropical nights (minimum temperature ≥ 20 °C), examining their formation mechanisms, long-term variability, and spatiotemporal distribution along the Lithuanian coastline of the southeastern Baltic Sea. Particular emphasis is placed on the compound influence of atmospheric circulation regimes, sea–air–land interactions, and sea surface temperature (SST) anomalies in shaping coastal extremes. By improving the understanding of extreme coastal heat events, this study aims to contribute to the broader goals of sustainability and climate resilience. The findings can support the development and introduction of early-warning systems, adaptive planning, and evidence-based strategies aimed at reducing the adverse impacts of heat stress on ecosystems, infrastructure, and human health in the Baltic Sea region. This study offers new insights into the changing frequency, duration, and

intensity of heatwaves and tropical nights in the southeastern Baltic Sea region, contributing to an improved understanding of climate impacts in coastal urban and resort areas.

2. Research Area, Data and Methods

The integration of high-resolution Copernicus ERA5 data, Copernicus Marine Environment Monitoring Service (CMEMS) reanalysis products, and multi-sensor satellite observations (e.g., MODIS Aqua) with long-term in situ measurements provides a novel perspective on the dynamics of coastal heat extremes in Northern Europe, particularly in Lithuania. This combined approach enables a more detailed assessment of the spatial and temporal variability of heatwave characteristics, especially in under-studied coastal areas where marine influences, land–sea interactions, and local atmospheric circulation modulate extreme temperature events.

While in situ observations provide accurate and consistent long-term air temperature records at specific coastal meteorological stations, their spatial coverage is limited. Reanalysis datasets such as Copernicus ERA5 complement these records by offering spatially continuous and temporally detailed air temperature data, which are essential for assessing trends and extremes over larger areas, including coastal regions. By integrating both in situ and ERA5 data, this study achieves a more comprehensive and spatially coherent evaluation of extreme heat events and tropical nights along the southeastern Baltic Sea coast. In addition, satellite-derived sea surface temperature (SST) data from the Copernicus Marine Environment Monitoring Service were used selectively to investigate the potential marine influence on the formation and persistence of tropical nights in nearshore areas.

This study focuses on the analysis of extreme heat days (eH), heatwaves (eHW), and tropical nights (TN) along the Lithuanian coastal zone of the southeastern Baltic Sea over the period 1982–2024. The research area encompasses the coastline surrounding Klaipeda and Nida, as illustrated in Figure 1. The research area covers the southwestern coast of the Baltic Sea (Figure 1). Lithuania, which belongs to the Baltic Sea region, is in the northern part of Europe, characterized by well-defined seasonality covering four seasons—spring, summer, autumn, and winter. In the geographical research area, two main cities of the Lithuanian Coast were studied: Klaipeda and Nida. Klaipeda is the third-largest city in Lithuania with ~200,000 inhabitants, and the main seaport of the country. Nida is a smaller resort city located in the Curonian Spit. Its proximity to both the Baltic Sea and the Curonian Lagoon makes it more affected by the water-land interactions.

The research on variations and long-term trends of extreme air temperature events, heatwaves, and tropical nights is based on daily air temperature data from the warm season (May–September). The historical in situ data of air temperature were obtained from the Lithuanian Hydrometeorological Service (LHMS) under the Ministry of Environment for the 1982–2024 period. Hourly, monthly average, daily maximum, and minimum in situ data of air temperature were obtained from Klaipeda (WMO No. 26509) and Nida (WMO No. 26603) meteorological stations (Figure 1). In situ observations from Klaipeda and Nida meteorological stations are reported as daily synoptic values, as per WMO standards.

In this study, Copernicus ERA5 reanalysis data were used to investigate both long-term trends and extreme heat events along the southeastern Baltic Sea coast. Monthly mean air temperature data were extracted for the period 1982–2024 in order to assess long-term changes in air temperature. Daily maximum ($T_{\max}$) and minimum ($T_{\min}$) air temperature data were employed to analyze the characteristics and frequency of extreme heat events, such as heatwaves and tropical nights.

The Copernicus ERA5 dataset, developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) under the Copernicus Climate Change Service, is the fifth-generation global reanalysis that spans from 1940 to the present [22,23]. It provides a

comprehensive reconstruction of past climate conditions by assimilating observations from ground-based stations, satellites, buoys, aircraft, and radiosondes into the Integrated Forecasting System (IFS). ERA5 delivers hourly estimates of atmospheric, land, and oceanic variables on a global $0.25^\circ \times 0.25^\circ$ latitude–longitude grid, corresponding to approximately 31 km at mid-latitudes. ERA5 air temperature data (2 m temperature) were obtained at an hourly resolution and subsequently aggregated to daily values (daily maximum, minimum, and mean temperatures), matching the structure of the in situ datasets. This temporal alignment allowed for direct comparison of daily extreme temperature indices such as $T_{\max} \geq 30^\circ\text{C}$ (extreme heat days) and $T_{\min} \geq 20^\circ\text{C}$ (tropical nights), ensuring methodological consistency across all datasets used in the analysis.

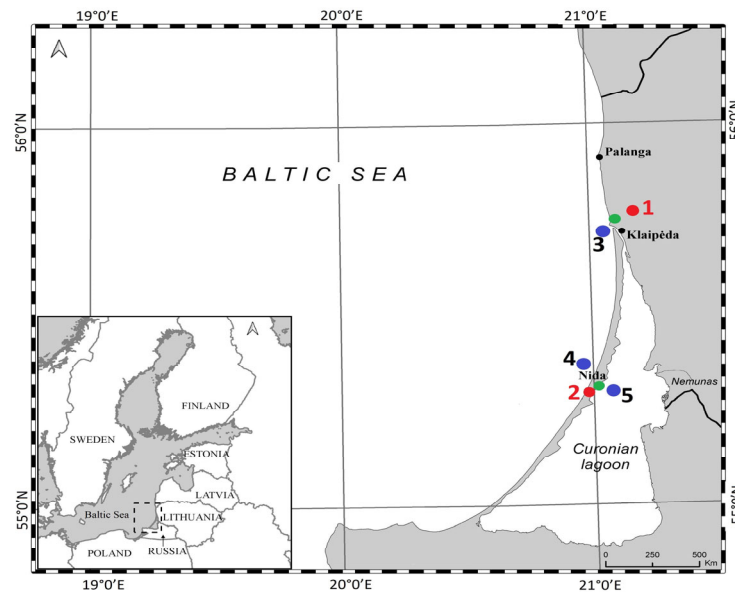


Figure 1. Research area in the Southeastern coast zone of the Baltic Sea near Lithuania. Stations performing in situ measurements (green circle): Klaipėda (WMO No. 26509) and Nida (WMO No. 26603). Locations of Copernicus ERA5 post-processed daily and monthly air temperature data (red circles): point No. 1 (Klaipėda) and point No. 2 (Nida). Sea surface temperature (SST) data from Copernicus Marine Service (blue circles): point No. 3 (Baltic Sea near Klaipėda), point No. 4 (Baltic Sea near Nida), and point No. 5 (Curonian Lagoon near Nida).

In this work, the reliability of Copernicus ERA5 data was evaluated by comparing it with in situ observations from Klaipėda and Nida meteorological stations (WMO No. 26509 and No. 26603, respectively). For this analysis, post-processed daily ERA5 statistics were used. Data were extracted for the nearest ERA5 grid points to the two coastal locations: Klaipėda (Location No. 1, 55.75°N , 21.25°E) and Nida (Location No. 2, 55.25°N , 20.95°E) (see Figure 1). Monthly average air temperature reanalysis data were also obtained for the same locations to investigate long-term changes.

To obtain a more detailed assessment of the occurrence and duration of tropical nights in the coastal zone, sea surface temperature (SST) data from the Copernicus Marine Environment Monitoring Service (CMEMS) were employed. These datasets are derived from multi-sensor satellite observations (e.g., MODIS Aqua), providing spatially consistent, daily averaged SST fields. Unlike ERA5 atmospheric reanalysis products, CMEMS SST data are specifically tailored for ocean monitoring and are thus better suited for capturing nearshore thermal variability and coastal SST patterns relevant to tropical night formation.

Historical in situ SST data were also obtained from coastal hydrological stations along the Baltic Sea coast and in the Curonian Lagoon, near Klaipėda and Nida. Measurements

were conducted twice daily (at 07:00 and 14:00 UTC), and daily SST values were derived from these records for comparison with CMEMS SST products.

For the Baltic Sea, the DMI Sea Surface Temperature Reprocessed Analysis (a Level 4 product) was used [24]. This dataset provides daily, gap-free SST fields at a spatial resolution of $0.02^\circ \times 0.02^\circ$ (~1–2 km) and is available from the Copernicus Marine Data Store [24]. The SST fields are generated using infrared satellite data from the ESA SST_cci v3.0 [25] and Copernicus C3S projects. Specifically, L2P data from (A)ATSRs, SLSTR, and AVHRR sensors were used for the period 1982 to 2021. For the years 2022 to 19 July 2024, L3U data from SLSTR and AVHRR were applied, while from 20 July 2024 onward, the fields are based on L2P data from SLSTR and AVHRR [24].

In this study, daily average SST values were extracted for three coastal locations with higher spatial resolution than air temperature datasets. Two points were selected along the Baltic Sea coast: near Klaipeda (No. 3; 55.72° N, 21.06° E) and near Nida (No. 4; 55.32° N, 20.96° E). A third point (No. 5; 55.30° N, 21.04° E) was chosen near Nida, on the Curonian Lagoon side (see Figure 1).

Two widely used temperature thresholds were applied in this study: $T_{\max} \geq 30^\circ\text{C}$ for extreme heat days and $T_{\min} \geq 20^\circ\text{C}$ for tropical nights. The threshold of $T_{\max} \geq 30^\circ\text{C}$ was selected to define extreme heat days, following regional climatological practices applied in Lithuania (Table 1) and other Baltic Sea coastal countries [16,17]. This threshold also corresponds to the “moderate thermal stress” category in the Copernicus ERA5-HEAT dataset, ensuring consistency with pan-European assessments of heat stress [19]. Tropical nights were identified using the standard criterion of $T_{\min} \geq 20^\circ\text{C}$. This threshold follows the international definition of tropical nights and is commonly used in climate monitoring and heat-related impact assessments [1,10,11].

Table 1. Extreme heat events classification in Lithuania.

Even Type	Abbreviation	Definition
Extreme Heat	eH	1 day, $T_{\max} \geq 30^\circ\text{C}$
Extreme Heat Wave	eHW	≥ 2 consecutive day(s) with $T_{\max} \geq 30^\circ\text{C}$
Severe Heat Wave	sHW	≥ 3 consecutive days with $T_{\max} \geq 30^\circ\text{C}$
Tropical Night	TN	$T_{\min} \geq 20^\circ\text{C}$ (for ≥ 1 consecutive night)

The extreme heat events were classified based on threshold values of daily maximum and minimum air temperature (Table 1). Heat is considered a hazardous meteorological phenomenon when the maximum daily air temperature reaches or exceeds 30°C . An absolute threshold of $T_{\max} \geq 30^\circ\text{C}$ was adopted to define extreme heat (eH) phenomena, and $T_{\max} \geq 30^\circ\text{C}$ duration ≥ 2 days as extreme heat waves (eHW), in line with the recommendations of the Lithuanian Hydrometeorological Service at the Ministry of Environment (Table 1). A severe heat wave (sHW) is defined as when the maximum air temperature reaches or exceeds 30°C for three or more consecutive days. A tropical night (TN) is defined as a night when the minimum air temperature does not drop below 20°C .

Linear regression analysis was applied to investigate long-term changes in extreme heat (eH) days, extreme heat waves (eHW), and tropical nights (TN) along the Lithuanian coast during the period 1982–2024. This approach enabled the quantification of change rates, with regression coefficients used to measure trends.

To examine the relationship between different datasets, such as in situ observations and Copernicus reanalysis products, linear regression and correlation analyses were performed. The regression model was based on the equation $y = ax + b$, where y is the dependent variable, x is the independent variable, a is the regression coefficient, and b is the bias.

The coefficient of determination (R^2) was used to evaluate the goodness of fit, indicating both the strength and direction of the relationship. The square root of R^2 was used to derive the correlation coefficient (R). A relationship between datasets was considered meaningful when $R^2 \geq 0.25$. Boxplots were employed to summarize the distribution of sea surface temperature (SST) and to compare conditions during tropical nights (TN) with those of normal nights. These plots provide key descriptive statistics, including the median, the 25th–75th percentiles, and the minimum and maximum values.

To evaluate their statistical significance, the non-parametric Mann–Kendall test was also applied. Significance p -values were calculated to determine significance at the 95% ($p < 0.05$) and 99% ($p < 0.01$) confidence levels, and these are indicated in the relevant tables and figures. Most of the warm-season trends were found to be statistically significant at the 99% confidence level ($p < 0.01$), supporting the robustness of the linear trend results. In addition, linear regression was used to analyze sea surface temperature (SST) trends and assess the potential influence of coastal waters on extreme warm-season events—particularly on the occurrence of tropical nights, when nighttime air temperature does not fall below 20 °C.

3. Results

3.1. Air Temperature Trends

Climate change, and the accompanying accelerated warming trend observed during this century, is associated with an increased frequency of extreme weather events. It is well established that the manifestations of climatic changes vary regionally. Therefore, both global and regional research and comparisons are needed to help achieve common goals for sustainable development while ensuring that human well-being opportunities are not diminished in the future [goals] in the context of climate change and increasing extreme weather events.

For example, 2024 saw unprecedented global temperatures, following on from the remarkable warmth of 2023, and was the warmest year on record [2,26]. The global annual mean surface air temperature in 2024 reached 15.10 °C and exceeded the threshold of 1.5 °C above pre-industrial levels, as set by the Paris Agreement to significantly reduce the risks and impacts of climate change [27]. According to the World Meteorological Organization, the global mean air temperature in 2024 was 0.72 °C above the climate norm (1991–2020 average) and was approximately 1.55 °C above the pre-industrial level 1850–1900, marking the first time that a full calendar year has surpassed the 1.5 °C limit [26]. The 2024 mean annual air temperature in Europe exceeded the 1991–2020 reference period by +1.47 °C [2], reflecting a significant regional warming anomaly. In comparison, in Lithuania, 2024 was also the warmest year on record, at 2.1 °C warmer than the 1991–2020 average (climate norm) and around 2.98 °C warmer than the 1850–1990 pre-industrial average. The relative deviation of both global and Lithuanian annual air temperatures from the pre-industrial level was calculated using the estimated difference between the pre-industrial period and the recent climatological normal. According to the Copernicus Climate Change Service, the temperature difference between the pre-industrial reference period (1850–1900) and the recent climatological baseline (1991–2020) is estimated at +0.88 °C, based on a multi-dataset average (ERA5, GISTEMPv4, HadCRUT5, NOAA, Berkeley Earth) [28]. This means that Lithuania’s warming in 2024 already exceeds global averages by more than +1.43 °C, underscoring the disproportionate regional warming in the southeastern Baltic Sea region.

However, this is only a relative statistical value of the climate assessment for comparison with global changes. Indeed, the climate of mid-latitudes in the Baltic region is warming faster. In Lithuania, under current climate conditions (1991–2020, climate statistical norm period), the average annual air temperature has already risen by about ~1.2 °C higher than

under previous climate conditions (1961–1990). The average annual air temperature in Lithuania in the period 1991–2020 was 7.4 °C (in the Maritime Region 8.2 °C), and in the period 1961–1990 it was 6.2 °C (in the Maritime Region 7.0 °C). A warming climate leads to higher-than-normal air temperatures (i.e., relative to the latest 30-year climate normal) and more frequent extreme heat waves. Such findings highlight the importance of localized assessments when evaluating national climate resilience thresholds and adaptation needs in the context of global temperature targets.

Based on the analysis of historical monthly in situ air temperature data from 1981 to 2024 in Klaipeda and Nida, located on the southeastern coast of the Baltic Sea, clear seasonal and long-term warming patterns were identified (Figure 2). While the typical mid-latitude temperature seasonality persists, with low temperatures in winter and high temperatures in summer, a consistent increase in mean air temperature has been observed across all seasons in recent decades.

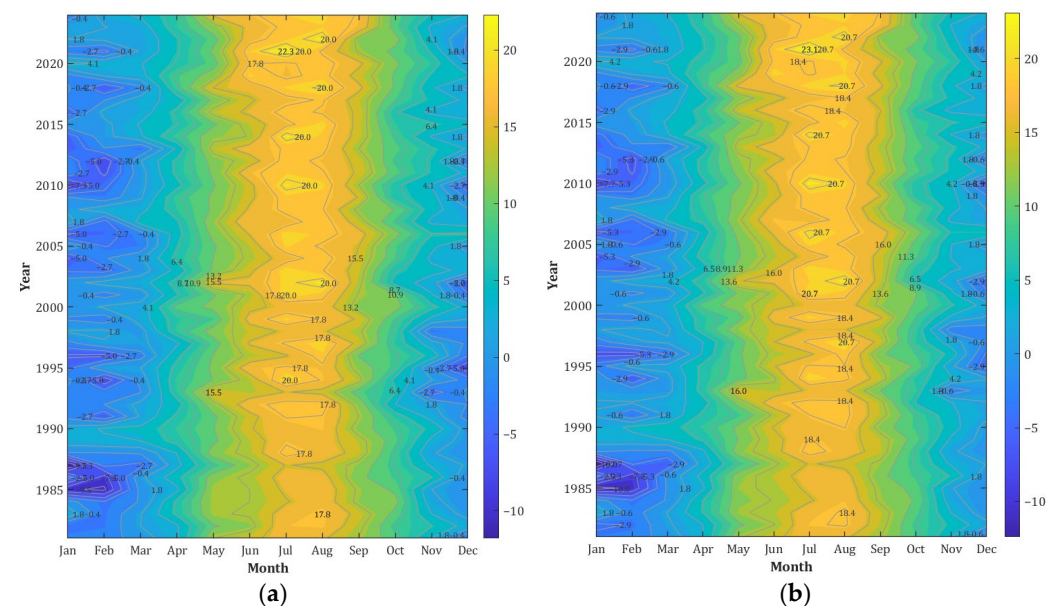


Figure 2. Long-term change in the monthly mean air temperature (1982–2024): (a) Klaipeda (meteorological station WMO No. 26509); (b) Nida (meteorological station WMO No. 26603).

The isothermal lines in the long-term monthly mean air temperature heatmap highlight the persistence of elevated temperatures during the warm season over extended periods (Figure 2). Since 1985, temperatures exceeding 18–20 °C have been occurring more frequently and over longer durations. Summers have notably warmed, particularly since the early 2000s. For instance, July and August temperatures now often surpass the 19–20 °C threshold, which was previously a rare occurrence.

The line regression trend analysis of the warm season period (May–September) revealed a clear long-term warming trend in the mean monthly air temperature in both Klaipeda and Nida (respectively, left (a) and right (b) panels, Figure 3), particularly pronounced in June (green color line). June exhibits the highest annual warming rate in Nida (+0.11 °C/year; $R^2 = 0.54$) and in Klaipeda (+0.08 °C/year; $R^2 = 0.32$), indicating that this month is experiencing the most rapid temperature increase. The coefficient of determination (R^2) suggests that the linear model explains approximately ≈ 35 –50% of the temperature variability in Nida (a resort that surrounds sea and lagoon waters) in June and August, which constitutes a statistically meaningful signal of long-term warming. All monthly warm period trends were found to be statistically significant at the 99% confidence level ($p < 0.01$) according to the Mann–Kendall test. An exception is observed in Klaipeda for the month of May (marked in blue in Figure 3a), which exhibits only a marginal warming

trend with a very low coefficient of determination ($R^2 = 0.03$), indicating that the trend is not statistically significant.

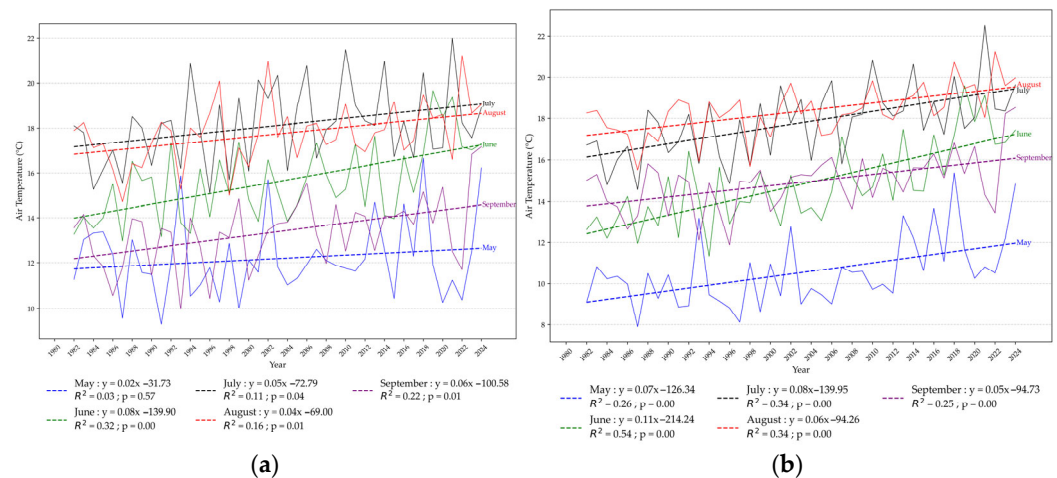


Figure 3. Long-term changes in monthly mean air temperature (1982–2024) based on Copernicus ERA5 data: (a) Klaipeda (Location No. 1); (b) Nida (Location No. 2).

The months of July and August have been warming particularly rapidly, which is associated with a higher probability of heatwaves in the region. These are also the warmest months, when heatwaves and tropical nights are most likely to occur. Data from Klaipeda and Nida show similar warming trends (Figure 3), although local differences may arise in some years due to microclimatic factors. The resort town of Nida is surrounded by both sea and lagoon water bodies, while Klaipeda's coastline is exposed to the open Baltic Sea. Overall, the signals of climate change and long-term air temperature increases appear more pronounced in Nida than in Klaipeda. It is also noteworthy that while July and August are the warmest months in Klaipeda, August remains slightly warmer than July in Nida—highlighting subtle but meaningful differences in the seasonal thermal regime between the urban port city and the more natural resort environment of the Curonian Spit.

The Comparative Analysis of Copernicus ERA5 and In Situ Air Temperature Data

The comparative analysis of Copernicus ERA5 and in situ air temperature data for Klaipeda and Nida during the warm season (May–September) reveals consistent long-term warming trends. A comparison of in situ and Copernicus long-term (1982–2024) monthly air temperature trends is presented in Table 2. Across both datasets, June demonstrates the highest warming rate (bold font in Table 2), reaching approximately $+0.11$ °C per year in Nida, with R^2 values exceeding 0.5, indicating a strong and reliable trend. Similarly, August and September show consistent positive temperature trends with moderate explanatory power. May exhibits the weakest trends and lowest R^2 values, especially in the in situ data, suggesting greater interannual variability and lower reliability in trend estimation. Overall, Copernicus data align closely with observational records, both in terms of slope and model fit, particularly during mid-to-late summer. For example, the July trend in Nida is $+0.08$ °C per year in both datasets, with comparable R^2 values (~ 0.31 – 0.34). Minor differences in trend magnitude (± 0.01 – 0.02 °C per year) are within acceptable limits. These results affirm the applicability of Copernicus data for regional climate analysis in coastal Lithuania. Their spatial completeness and temporal consistency make them a valuable resource for climate change assessments. However, in situ measurements remain essential for capturing localized microclimatic effects.

Table 2. Long-term trends in warm-season (May–September) mean air temperature in Klaipeda and Nida: comparison of in situ and Copernicus ERA5 data. K—trend slope ($^{\circ}\text{C}/\text{year}$); R^2 —coefficient of determination; KL/in—Klaipeda in situ data; NI/in—Nida in situ data; KL/Cop—Klaipeda Copernicus data; NI/Cop—Nida Copernicus data.

Month Station	KL/in K	KL/in R^2	KL/Cop K	KL/Cop R^2	NI/in K	NI/in R^2	NI/Cop K	NI/cop R^2
May	0.016	0.014	0.02	0.03	0.015	0.038	0.07	0.26
June	0.083	0.395	0.09	0.32	0.110	0.544	0.11	0.54
July	0.062	0.231	0.05	0.16	0.081	0.313	0.08	0.34
August	0.060	0.316	0.04	0.16	0.077	0.386	0.06	0.30
September	0.065	0.258	0.06	0.22	0.075	0.344	0.05	0.25

The previous results demonstrate the consistency of Copernicus data for long-term trends, considering monthly data. However, our present study focuses on extreme warm events that have a duration of a few days only. This is why the following part investigates the consistency of daily Copernicus data of air temperature in the two cities of Klaipeda and Nida by comparing it to in situ data, in order to evaluate the relevance of Copernicus data for short term trends and extremes.

The analysis investigates the correlation and linear relationship between in situ and Copernicus daily air temperature data in 2010. The high coefficient of determination ($R^2 > 0.9$) for both Klaipeda and Nida, in terms of $T_{\max}$ and $T_{\min}$ (Figures 4 and 5), indicates a strong linear agreement between the two datasets. The results of the comparison of daily air temperature ($T_{\max}$ and $T_{\min}$) between in situ and Copernicus data in Klaipeda show a very strong correlation. The correlation coefficient was $R = 0.99$ ($p < 0.01$). At the same time, it confirms that Copernicus daily air temperature data can be used for heat wave identification and research in coastal areas.

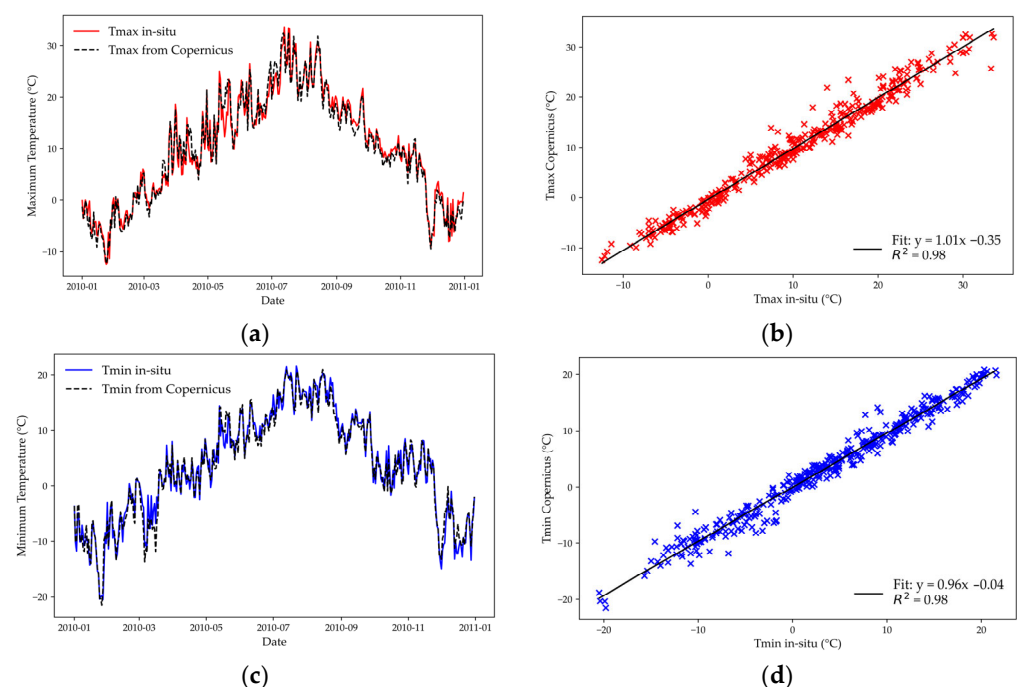


Figure 4. Comparison of daily maximum ($T_{\max}$, red) and minimum ($T_{\min}$, blue) air temperature in 2010 between in situ observations at Klaipeda and Copernicus ERA5 data (Localization No. 1): (a) Daily variations of $T_{\max}$ throughout 2010 (in situ vs. ERA5); (b) Scatterplot comparison for $T_{\max}$; (c) Daily variations of $T_{\min}$ throughout 2010 (in situ vs. ERA5); (d) Scatterplot comparison for $T_{\min}$.

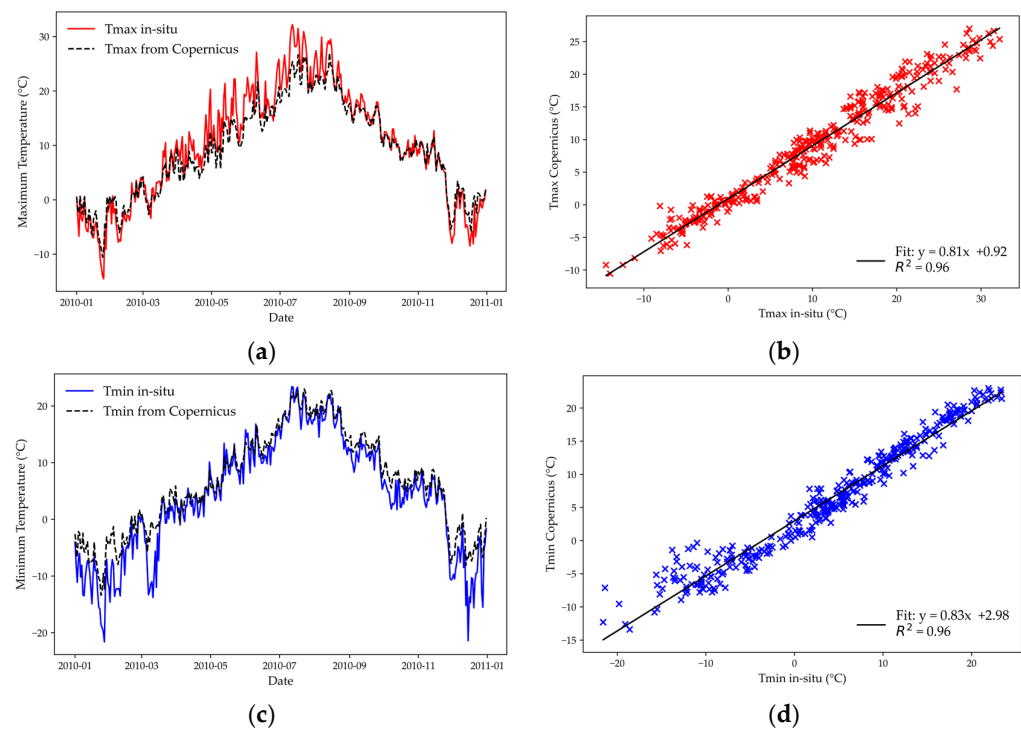


Figure 5. Comparison of daily maximum ($T_{\max}$, red) and minimum ($T_{\min}$, blue) air temperature in 2010 between in situ observations at Nida and Copernicus ERA5 data (Localization No. 2): (a) Daily variations of $T_{\max}$ throughout 2010 (in situ vs. ERA5); (b) Scatterplot comparison for $T_{\max}$; (c) Daily variations of $T_{\min}$ throughout 2010 (in situ vs. ERA5); (d) Scatterplot comparison for $T_{\min}$.

In Nida, the analysis also revealed a strong agreement between Copernicus data and in situ measurements for both daily maximum ($T_{\max}$) and minimum ($T_{\min}$) air temperatures (Figure 5). The high correlation ($R^2 = 0.96$, $R = 0.98$, $p < 0.01$) confirms that Copernicus data can be reliably used to study annual temperature variability and long-term climate trends. However, some systematic discrepancies were observed, particularly in capturing extreme values. For instance, Copernicus data did not report $T_{\max}$ values exceeding $30\text{ }^{\circ}\text{C}$, while such instances were clearly recorded by local observations. This suggests that Copernicus models tend to smooth out heat extremes. During the winter months, $T_{\min}$ values from Copernicus were generally higher than those from in situ data, indicating an underestimation of cold intensity. Differences between the two datasets are especially noticeable in Nida, where the local microclimate and specific geographic conditions (a narrow land strip between a lagoon and the sea) may cause temperature variations that are not well represented in gridded model data.

To better assess the seasonal performance of Copernicus ERA5 data, the year was divided into three climatologically relevant periods: 1 January–30 April (cold season), 1 May–30 September (warm season), and 1 October–31 December (transitional to cold season).

This comparison (Figures 6 and 7) demonstrates that Copernicus ERA5 captures daily variations in both $T_{\max}$ and $T_{\min}$ reasonably well ($R^2 > 0.8$), although seasonal differences are evident. Overall, alignment with in situ data is slightly better in Klaipeda than in Nida across all three periods. In Nida, ERA5 tends to overestimate air temperature during the cold season, resulting in a consistent positive bias. This discrepancy becomes especially pronounced during extreme cold events (e.g., below $-10\text{ }^{\circ}\text{C}$), where ERA5 proves unreliable.

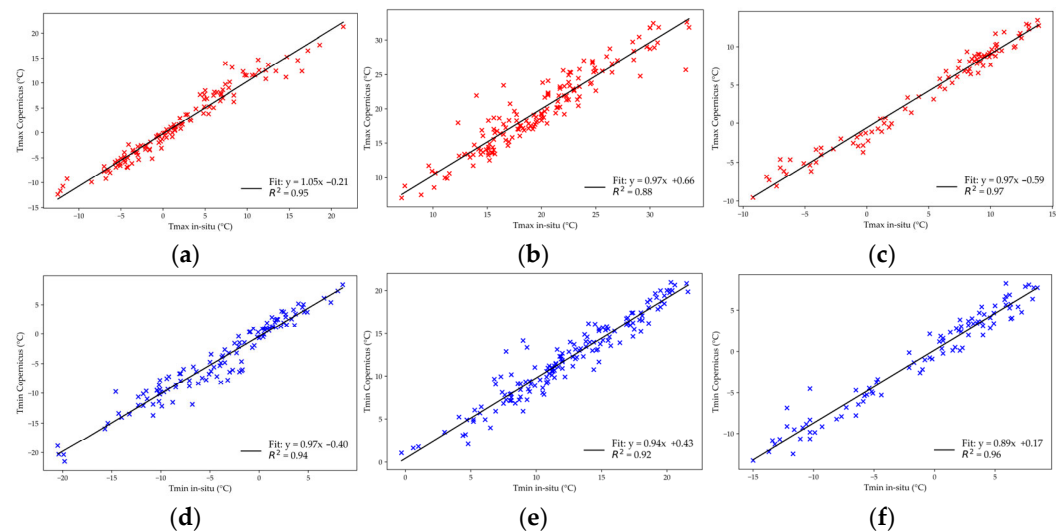


Figure 6. Scatterplots and correlation analysis of daily maximum ($T_{\max}$, red) and minimum ($T_{\min}$, blue) air temperature in 2010 between in situ (Klaipeda) and Copernicus ERA5 data (Localization No. 1), by season (a) $T_{\max}$ for January–April; (b) $T_{\max}$ for May–September; (c) $T_{\max}$ for October–December; (d) $T_{\min}$ for January–April; (e) $T_{\min}$ for May–September; (f) $T_{\min}$ for October–December.

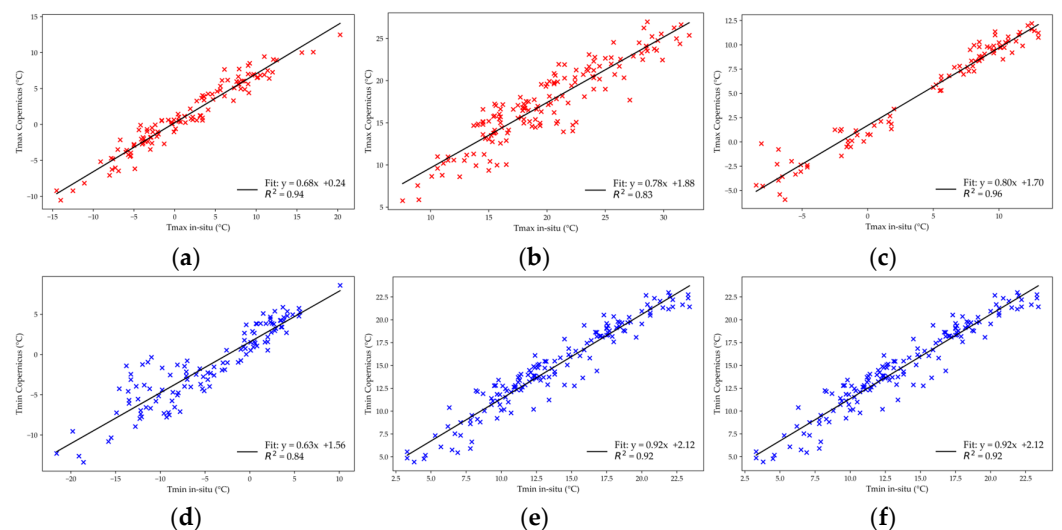


Figure 7. Line regression and correlation analysis of daily maximum ($T_{\max}$, red) and minimum ($T_{\min}$, blue) air temperature in situ (Nida) and Copernicus ERA5 data (localization No. 2) for 3 seasons: (a) $T_{\max}$ for January–April; (b) $T_{\max}$ for May–September; (c) $T_{\max}$ for October–December; (d) $T_{\min}$ for January–April; (e) $T_{\min}$ for May–September; (f) $T_{\min}$ for October–December.

In contrast, during the warm season (May–September)—when extreme heat events are most likely—the correlation between ERA5 and in situ data remains strong, with a preserved linear relationship (Figure 6b,e and Figure 7b,e), and R^2 values consistently exceeding 0.8 ($p < 0.001$). Regression slopes are closer to 1 compared to winter, indicating that ERA5 more accurately tracks temperature variability. Biases during this period are generally smaller, typically below 1 °C in Klaipeda. Nevertheless, the results reveal that in Nida, ERA5 tends to underestimate $T_{\max}$ (Figure 7b) and overestimate $T_{\min}$ (Figure 7e), leading to a reduced daily temperature range—especially on warmer days. In Klaipeda, a similar underestimation of $T_{\max}$ is observed, although the magnitude of the bias is smaller than in Nida.

The comparative analysis is explored further with a focus on extreme warm events, by comparing the number of extreme air temperature days over the whole period (1982–2024) for both datasets (Figure 8).

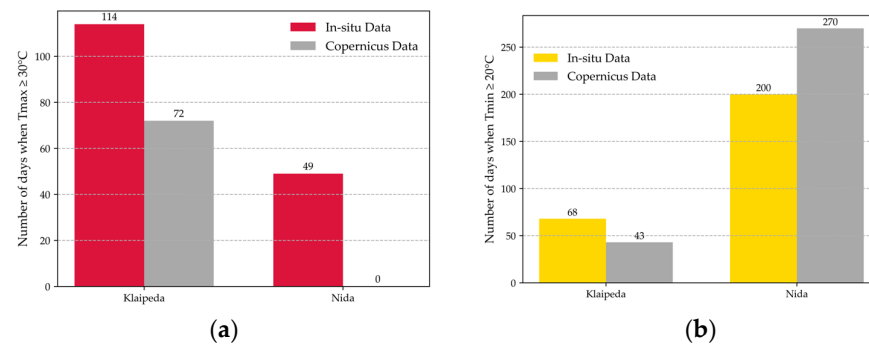


Figure 8. Comparison of extreme air temperature events between in situ observations (Klaipeda and Nida) and Copernicus ERA5 data (Localizations No. 1 and No. 2) over the period 1982–2024: (a) Number of extreme Heat (eH) days when $T_{\max} \geq 30^{\circ}\text{C}$; (b) Number of Tropical Nights (TNs) when $T_{\min} \geq 20^{\circ}\text{C}$.

These findings confirm that Copernicus ERA5 data tend to underestimate maximum air temperatures. The number of days with $T_{\max} \geq 30^{\circ}\text{C}$ (eH) is significantly higher in Klaipeda and Nida for in situ records (respectively, 114 and 49 days) compared to the ERA5 dataset (respectively, 72 and 0 days). For days with $T_{\min} \geq 20^{\circ}\text{C}$ (tropical nights), the pattern is less consistent. Copernicus ERA5 data report more tropical nights than in situ observations in Nida, while the opposite is true for Klaipeda.

Given that in situ air temperature data are available for the entire study period (1982–2024) and provide more reliable estimates of temperature extremes, only these observations were selected for the subsequent analysis of warm-season extreme events along the Lithuanian coast.

3.2. Extreme Heat Waves

The following part aims at analyzing the evolution of extreme Heat during the past 43 years in the Lithuanian Coast of the Southeastern Baltic Sea. The levels of extreme heat were distinguished according to the gradation accepted in Lithuania. A heat wave is defined as a period where the temperature reaches or exceeds 25°C for 3 consecutive days or more. An extreme Heat Wave (eHW) is defined as a period in which the maximum air temperature reaches or exceeds 30°C . Accordingly, an extreme Heat (eH) day is defined as a day when the maximum temperature reaches or exceeds 30°C . Finally, a severe Heat Wave (sHW) refers to an extreme Heat Wave lasting at least 3 consecutive days. The study focuses on the evolution of eH days and eHWs from 1982 to 2024 in Klaipeda and Nida. In situ data of daily maximum air temperature from Klaipeda's and Nida's meteorological stations are used.

A first trend analysis was done, investigating the number of eH days in Nida and Klaipeda from 1982 to 2024 (Figure 9). The average number of extremely hot (eH) days, defined as days with $T_{\max} \geq 30^{\circ}\text{C}$, during the study period was 2.65 days per year in Klaipeda and 1.14 days in Nida. The higher frequency in Klaipeda may be attributed to urbanization effects, as the city is larger and more strongly influenced by the urban heat island phenomenon. An increasing trend in the number of eH days is evident in both locations. In Klaipeda, the frequency rose from 1 to 2 days per year during 1982–2011 to > 3 days per year (3–4 days per year) during 1992–2021. A similar trend was observed in Nida, with the frequency increasing from less than < 1 day per year during 1982–2011 to 1–2 days per year during 1992–2021 period. A statistically significant increasing trend was

detected only in Klaipeda, where linear regression analysis yielded $R^2 = 0.25$ ($p < 0.04$) and an annual rate of increase of $+0.14$ eH days per year, which corresponds to approximately one additional extremely hot day every 7 years. This trend reflects the impact of ongoing climate change in the region.

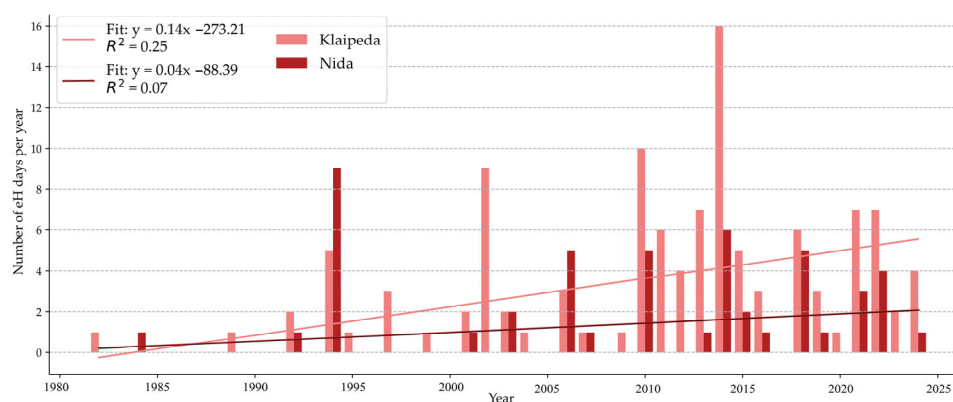


Figure 9. Annual number of extreme heat (eH) days ($T_{\max} \geq 30$ °C) in Klaipeda (WMO No. 26509) and Nida (WMO No. 26603) meteorological stations from 1982 to 2024, with line trend analysis for both stations.

As the frequency of extreme heat (eH) days increases, it becomes important to analyze not only their occurrence but also the duration of extreme heat waves (eHW), defined as periods of consecutive days with maximum air temperature $T_{\max} \geq 30$ °C (Table 1). Figure 10 shows the duration of all eHWs recorded in Klaipeda and Nida from 1982 to 2024, along with the maximum $T_{\max}$ value reached during each event. Over the study period, the mean duration of an eHW was 1.48 days in Klaipeda and 1.88 days in Nida. This indicates that although eHWs occur more frequently in Klaipeda, they are typically short-lived, often lasting only a single day. In contrast, eHWs in Nida are less frequent but tend to be more persistent, with average durations approaching two days.

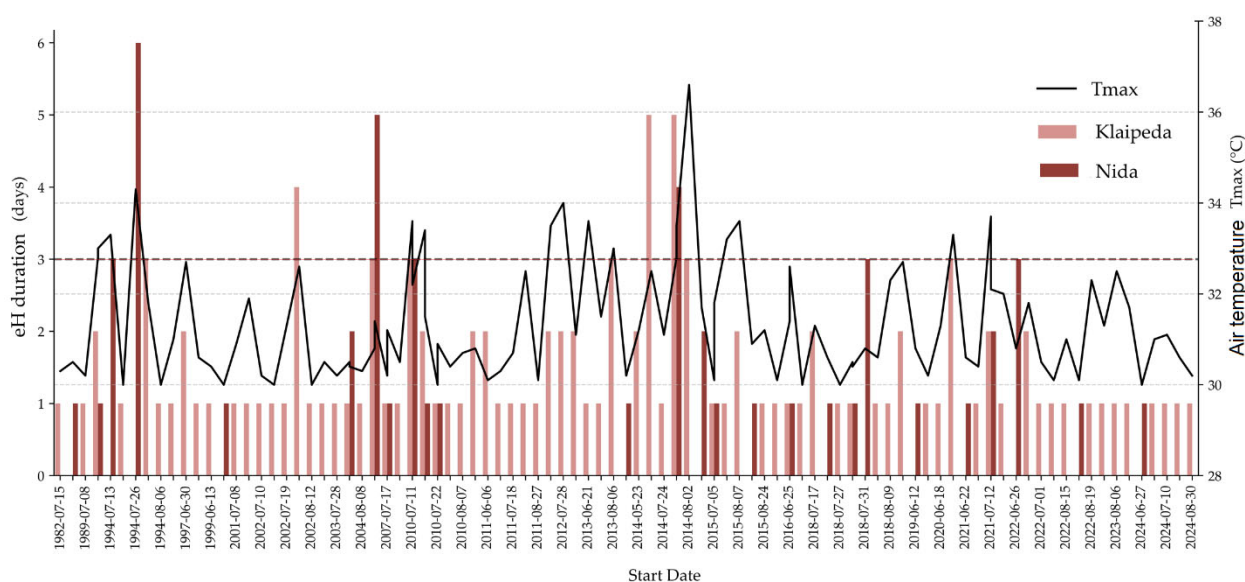


Figure 10. Duration of extreme heat (eH) events (in days, left y-axis) and maximum air temperature ($T_{\max}$, right y-axis) at Klaipeda and Nida meteorological stations from 1982 to 2024. The red dashed line indicates the threshold for an extreme heat wave (eHW), defined as more than 3 days with $T_{\max} \geq 30$ °C.

When applying the threshold for severe heat waves (sHW)—defined as periods of at least three consecutive days with $T_{\max} \geq 30\text{ }^{\circ}\text{C}$ —only a limited number of such events were identified over the 43-year study period. Specifically, 9 sHW events were recorded in Klaipeda and 7 in Nida, suggesting that prolonged heat waves remain relatively rare in both locations, despite the increasing frequency of eH days observed in previous analyses.

As illustrated in Figure 10, the maximum air temperature ($T_{\max}$) associated with each eHW event does not exhibit a consistent long-term trend. The highest $T_{\max}$ recorded during the entire study period ($36.6\text{ }^{\circ}\text{C}$) occurred in Klaipeda during the summer of 2014. However, this event was not associated with the longest-lasting heat wave, highlighting the variable relationship between the intensity and duration of extreme heat events.

After examining the duration of individual eHW events, the analysis was extended to the length of the extreme heat (eH) season, defined as the period between the first and last occurrence of an eH day in a given year. As shown in Figure 11, from 1982 to 2024, the eH season exhibits a clear tendency to extend over time, with events beginning earlier in the summer and continuing later into the season. This extension is more evident in Klaipeda than in Nida, reflecting the more rapid increase in the total number of eH days observed at the Klaipeda station. Notably, in recent years, eH days in Klaipeda have been recorded as early as mid-June and as late as the end of August. In contrast, in Nida, the onset of the eH season still tends to occur later, likely due to the moderating influence of surrounding water bodies, particularly in May and early June. The asymmetric seasonality between the two locations highlights the role of local microclimatic conditions in shaping the thermal regime along the southeastern Baltic coast. The observed shift toward a longer eH season suggests a prolonged period of heat-related risk, which is particularly relevant for public health, forest fire danger, agriculture, and energy demand planning.

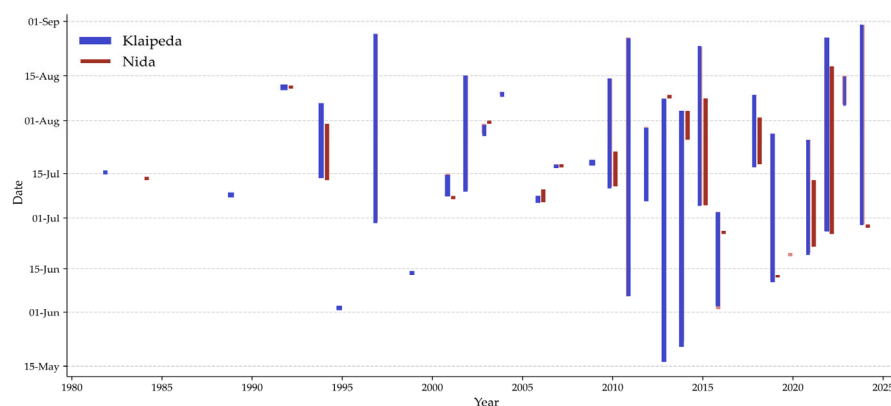


Figure 11. Duration of eH season in Klaipeda and Nida meteorological stations from 1982 to 2024, taking the first and the last day when $T_{\max} \geq 30\text{ }^{\circ}\text{C}$ per year.

Long-term trends by decade (Figure 12a) confirm a clear increase in the duration of the eH season. In Klaipeda, the average duration has risen substantially, from less than 1 day per decade in 1982–1991 to nearly 40 days in 2012–2021. The fitted regression line is highly significant ($R^2 = 0.94$) and indicates an extension of approximately 12 days per decade. In Nida, the increase is more moderate, from almost zero in 1982–1991 to about 8 days in 2012–2021. Nevertheless, the correlation remains strong ($R^2 = 0.78$), confirming an extension of around 2.5 days per decade.

The monthly distribution graph (Figure 12b) indicates that more than half of the eH days take place in July, which corresponds to the warmest month in Klaipeda climatology. The eH season begins earlier in Klaipeda than in Nida, maybe since the water in May in the Curonian Lagoon and Baltic Sea surrounding Nida is still cold and does not favor extreme heat. No eH days are recorded for the moment in September, but it may happen in the

coming years since the duration of the eH season is increasing (the last eH day recorded on 30 August in 2024).

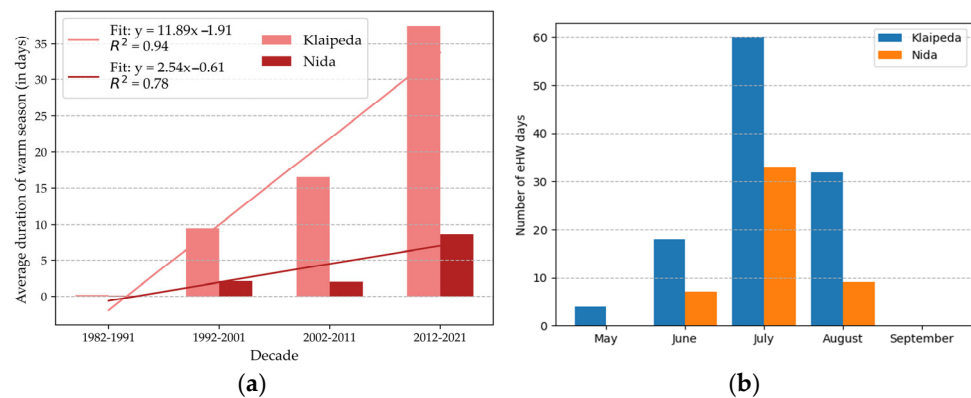


Figure 12. Extreme heat (eH) season duration in days (1982–2024): (a) comparison of changes over four decades from 1982 to 2021; (b) monthly distribution of the eH (days).

3.3. Tropical Nights

The analysis of tropical nights (TN) was conducted for the period 1982–2024 using in situ daily minimum air temperature data from the Klaipeda and Nida meteorological stations. Figure 13 presents the annual number of TN observed at both locations. Over the study period, Nida experienced nearly three times more TN than Klaipeda, with an average of 4.65 TN per year in Nida and 1.58 in Klaipeda. This discrepancy can be attributed to Nida's geographic setting—situated on the Curonian Spit between the Baltic Sea and the Curonian Lagoon—where warmer surrounding water bodies can limit nocturnal cooling of air temperatures.

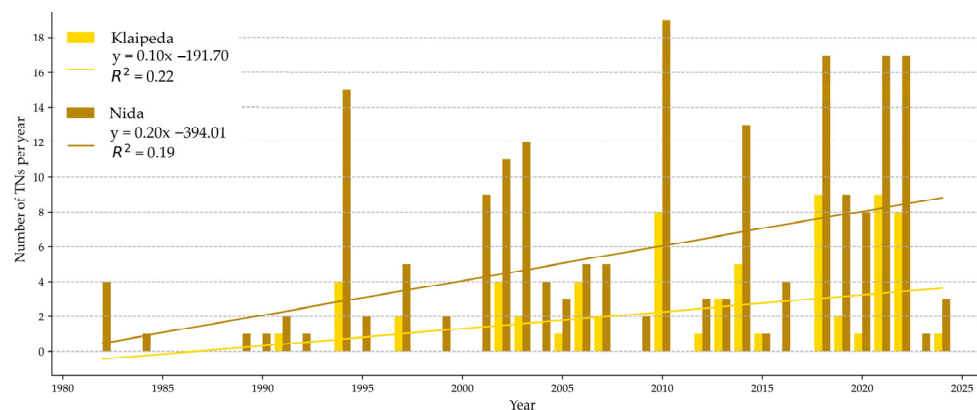


Figure 13. Number of TN ($T_{\min} \geq 20\text{ }^{\circ}\text{C}$) per year in Klaipeda and Nida meteorological stations from 1982 to 2024, and line trend analysis for both stations.

In Klaipeda, the average increased from approximately 1 TN per year during 1982–2011 to about 2 TN per year in 1992–2021. In Nida, the average rose from 3 to 4 TN to 5–6 TN per year over the same periods. However, regression analysis results ($R^2 < 0.25$) suggest that the observed increases are not statistically significant and do not follow a clear linear trend in either location. This likely reflects high interannual variability and the influence of additional factors affecting the occurrence of TN, such as local circulation patterns, land–sea interactions, and synoptic-scale conditions.

The duration of consecutive tropical nights (TNs) in Nida and Klaipeda from 1982 to 2024 is presented in Figure 14. As shown in previous results, TNs are significantly more frequent in Nida than in Klaipeda. Notably, TNs in Nida tend to last 2–3 consecutive nights

on average, compared to 1–2 nights in Klaipeda. The highest nighttime temperature during the study period was recorded in Nida in the summer of 2006, reaching 24.4 °C.

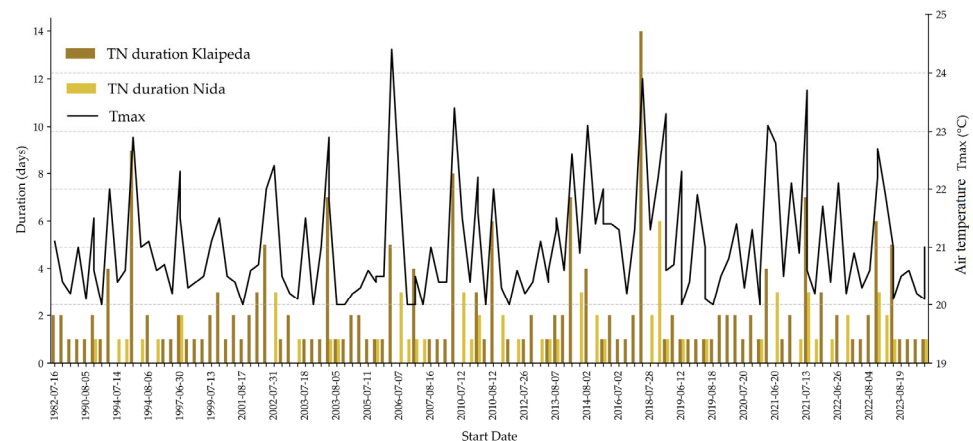


Figure 14. Duration of consecutive Tropical Nights (TN) in Nida and Klaipeda (1982–2024), along with the highest $T_{\min}$ recorded during each TN event.

The length of the TN season, defined as the number of days between the first and last TN in a given year, has increased in both Nida and Klaipeda. Figure 15 shows a more pronounced extension of the TN season in Nida, reflecting the faster increase in the total number of TNs at this location.

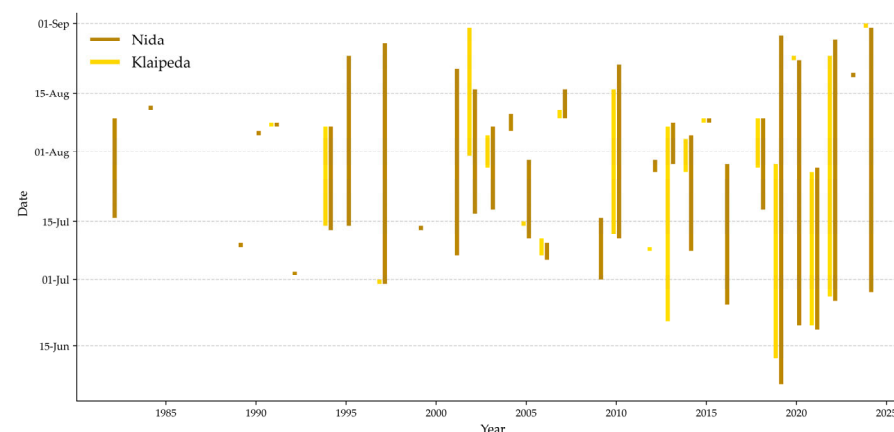


Figure 15. Duration of Tropical Night (TN) season at Klaipeda and Nida meteorological stations from 1982 to 2024, based on the first and the last day per year with $T_{\min} \geq 20$ °C.

Long-term decadal trends (Figure 16a) confirm the extension of the tropical night (TN) season. In Klaipeda, the average duration of the TN season increased from less than 1 day in 1982–1991 to over 15 days in 2012–2021. In Nida, the increase is even more pronounced—from 3 days to nearly 30 days over the same period. The fitted regression lines are statistically significant for both stations, indicating an average extension of the TN season by approximately 5 days per decade in Klaipeda and almost 10 days per decade in Nida. Most TNs occur in July and August. Compared to the extremely hot (eH) season (Figure 12b), the TN season begins later and is shorter in duration, with no TN events recorded in May (Figure 16b). This may be related to the fact that, in May, surrounding water bodies remain too cold to effectively limit nocturnal air temperature cooling.

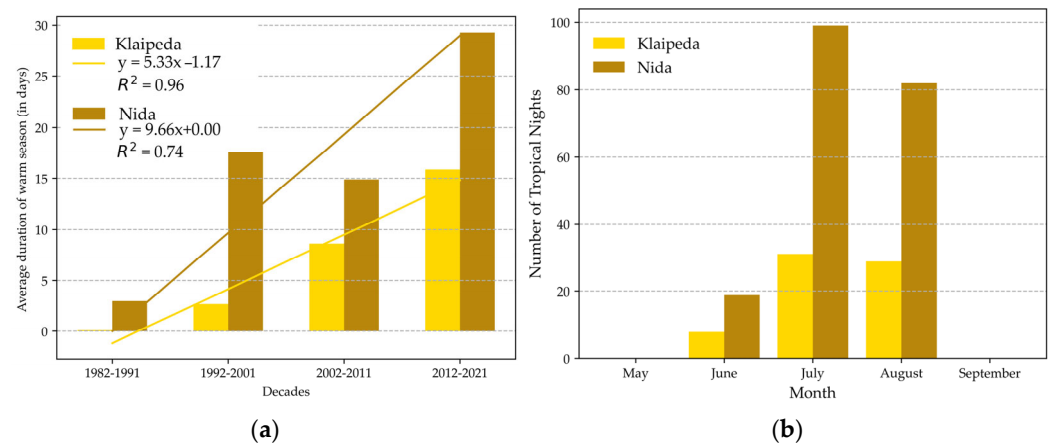


Figure 16. Analysis of tropical nights (TN) season from 1982 to 2024 in Klaipeda and Nida: (a) Average TN season duration by decade and line trend analysis; (b) Monthly distribution of TN events.

3.4. SST Effects on eHW and TN

After describing the evolution of extreme warm events—such as heatwaves and tropical nights—the analysis turns to sea surface temperature (SST) to assess whether this parameter influences the occurrence of such extreme phenomena in coastal areas. SST was examined at three locations, as previously described: in the Baltic Sea near Klaipeda and Nida, and in the Curonian Lagoon near Nida (Figure 1). Both the Baltic Sea and the Curonian Lagoon play an important role in regulating local air temperature patterns along the Lithuanian coast. Warmer SST can elevate near-surface air temperatures by acting as a thermal reservoir.

Furthermore, like many other seas, the Baltic Sea has been warming over recent decades due to climate change [16,29–31]. The average increase in SST in the Baltic Sea coastal zone was approximately 0.2 °C per decade during the period 1951–2019 [32]. Understanding the relationship between SST and the occurrence of heatwaves and tropical nights is essential for identifying and predicting changes in coastal climate extremes in Lithuania.

In this section, the primary objective is to assess whether Copernicus SST data adequately represent SST conditions in the Baltic Sea near Klaipeda and Nida, as well as in the Curonian Lagoon near Nida, based on satellite products provided by the Copernicus Marine Environment Monitoring Service (CMEMS).

A comparative study was done between Copernicus data and in situ data for 2010 in these 3 places (Figure 17). It shows that there is a linear relationship between these data that can be confirmed by a high coefficient of determination (≥ 0.9). However, SST comparison between the two datasets shows more noise than the air temperature comparison (Figures 4 and 5).

It must be noted that Copernicus marine environment SST data tends to underestimate water temperatures in spring and overestimate them in autumn. This pattern is particularly evident in the Curonian Lagoon (Figure 17e). Furthermore, Copernicus SST values for the Curonian Lagoon are very similar to those for the Baltic Sea near Nida (Figure 17c,e), suggesting that the dataset may not adequately capture local thermal variations in the shallow and enclosed waters of the lagoon. As a result, it may reflect open sea characteristics rather than the more dynamic nearshore and lagoonal conditions. In contrast, during the warm season, the agreement between Copernicus and in situ data is better, with regression slopes close to 1 and a small bias (<1 °C), indicating higher reliability in summer.

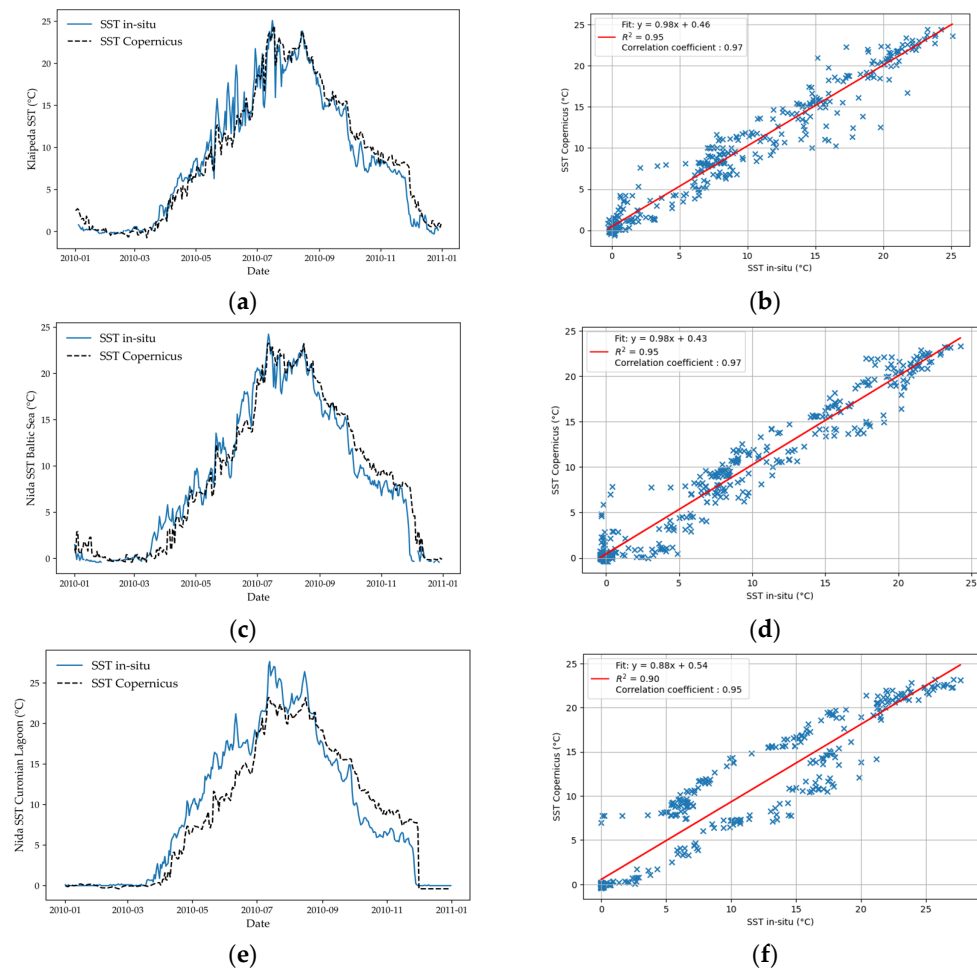


Figure 17. Comparison of 2010 daily average SST in situ measurements at coastal hydrological stations in Klaipeda and Nida with Copernicus data (Localizations No. 3, 4, and 5): (a) Annual variations in SST from both datasets in Klaipeda; (b) Scatterplot comparison of SST in Klaipeda; (c) Annual variations in SST from both datasets in the Baltic Sea near Nida; (d) Scatterplot comparison of SST in the Baltic Sea near Nida; (e) Annual variations in SST from both datasets in the Curonian Lagoon near Nida; (f) Scatterplot comparison of SST in the Curonian Lagoon near Nida.

To explore the relationship between SST and the occurrence of extreme heat waves (eHW) and tropical nights (TN), Copernicus SST data were used despite their known warm-season bias—particularly the underestimation of water temperatures in the Curonian Lagoon. These data were selected because they are consistently available for the full study period (1982–2024).

The first step in evaluating the link between sea surface temperature (SST) and extreme air temperature events was to compare daily SST values with daily air temperature measurements during the warm season, in order to assess their potential relationship. By comparing SST at three different locations—Klaipeda, Nida (Baltic Seaside), and Nida (Curonian Lagoon side)—with in situ daily maximum ($T_{\max}$) and minimum ($T_{\min}$) air temperatures recorded in Klaipeda and Nida (Figure 18), one of the main findings is that $T_{\min}$ exhibits a stronger correlation with SST than $T_{\max}$.

In Nida, a strong correlation was found between $T_{\min}$ and SST, both in the Baltic Sea ($R^2 = 0.61$; $p < 0.01$) and in the Curonian Lagoon ($R^2 = 0.59$; $p < 0.01$). In Klaipeda, the correlation between $T_{\min}$ and SST is somewhat lower but still statistically significant ($R^2 = 0.54$; $p < 0.01$). For $T_{\max}$, the linear relationship remains statistically meaningful but is weaker: $R^2 = 0.38$ in the Baltic Sea and $R^2 = 0.37$ in the Curonian Lagoon. These results suggest that SST is more closely associated with nighttime air temperatures, as a warmer

sea surface can reduce the land–sea temperature gradient during the night. This indicates that, in the context of extreme warm-season events, SST is more likely to be linked to the occurrence of tropical nights than to the occurrence of heat waves.

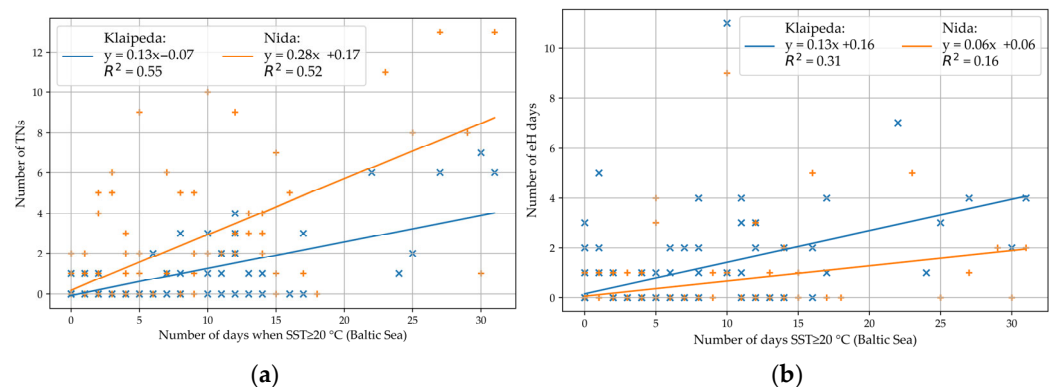


Figure 18. Comparing between the monthly number of tropical nights (TNs) and extreme heat (eH) days, and the number of Baltic Sea SST ≥ 20 °C days, based on Copernicus data (Localizations No. 3 and 4) near Klaipeda and Nida, during the warm season (1982–2024): (a) Scatterplot and regression for TNs; (b) Scatterplot and regression for eH days.

To further examine the relationship between SST and extreme warm-season events, the number of marine heat days (defined as days with SST ≥ 20 °C) was extracted for each month and year from 1982 to 2024 and compared with the monthly number of tropical nights (TNs) and extreme heat waves (eHWs). Only SST data from the Baltic Seaside near Klaipeda and Nida were used, as they exhibit less bias compared to in situ measurements than SST data from the Curonian Lagoon.

Figure 18a illustrates the relationship between the number of marine heat days and the number of TNs per month in Klaipeda and Nida. A trend line analysis reveals a moderate to strong association, with a coefficient of determination $R^2 > 0.5$ ($p < 0.01$).

When examining eH days (Figure 18b), warm SSTs may indeed contribute by enhancing local heat and promoting their occurrence, particularly in Klaipeda (where $R^2 \geq 0.25$; $p < 0.01$). However, large-scale synoptic conditions, such as persistent high-pressure systems (blocking) and the advection of warm air masses, are known to play a dominant role in controlling the frequency of extreme heat days [33].

Figure 19 highlights the long-term relationship between warm SST conditions and the occurrence of tropical nights (TNs). A high number of warm SST days (defined as SST ≥ 20 °C) per year is generally associated with the occurrence of at least one TN. These results confirm the close link between warm marine conditions and nighttime temperature extremes. However, the number of warm SST days per year consistently exceeds the number of TNs and is increasing at a faster rate. According to linear trend analysis an increase of approximately +0.7 warm SST days per year in the Baltic Sea near Klaipeda and Nida.

These findings underscore the growing influence of climate change on both marine and atmospheric conditions along the Lithuanian coast. It is also important to note that, in the case of the Curonian Lagoon, the actual number of days with SST ≥ 20 °C is likely higher than indicated in the graphs for the Baltic Sea. This is due to the negative bias observed when comparing Copernicus SST estimates with in situ measurements in the lagoon.

The distributions of daily average sea surface temperature (SST) near Klaipeda and Nida during nights with $T_{\min} < 20$ °C and tropical nights (TNs, $T_{\min} \geq 20$ °C) were compared using boxplots (Figure 20). During the warm season (May–September), SST values on nights with $T_{\min} < 20$ °C typically ranged between approximately 13 °C (25th

percentile) and 18 °C (75th percentile). In contrast, SST values during TNs were consistently higher, with median SST exceeding 20 °C at both sites. More than 75% of TNs occurred when the daily average SST was equal to or above 20 °C. Individual outlier points on the boxplots represent SST values outside the interquartile range and illustrate the variability within each group. These results indicate a strong association between elevated SST and the occurrence of tropical nights along the southeastern Baltic Sea coast.

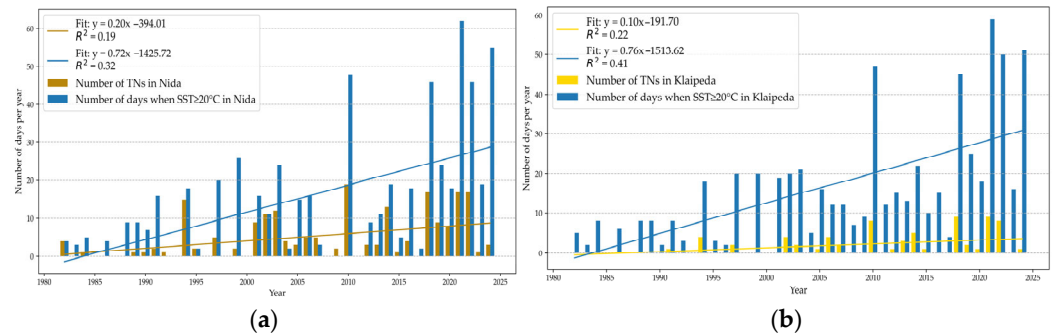


Figure 19. Comparison of tropical nights (TNs) and $SST \geq 20\text{ }^{\circ}\text{C}$ during 1982–2024: (a) Nida; (b) Klaipeda.

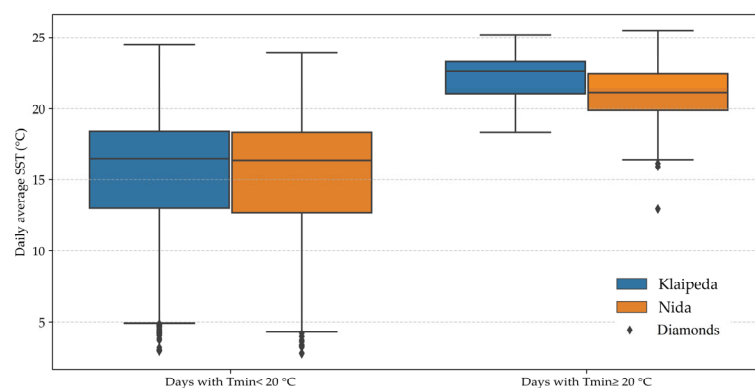


Figure 20. Boxplot of daily mean sea surface temperature (SST, °C) near Klaipeda and Nida (locations No. 3 and 4) from Copernicus data during the warm season (May–September), 1982–2024: normal nights with minimum air temperature $< 20\text{ }^{\circ}\text{C}$ (left) and tropical nights with minimum air temperature $\geq 20\text{ }^{\circ}\text{C}$ (right). Boxes represent interquartile ranges (IQR); whiskers indicate $1.5 \times \text{IQR}$; dots show outliers. Diamonds indicate statistical outliers—daily mean SST values outside the interquartile range.

Sea surface temperature (SST) is a key parameter for understanding the formation of tropical nights (TNs). Both phenomena are closely related, as warm SST is typically associated with elevated nighttime air temperatures. To examine a typical case of TN formation in more detail, the extreme heatwave (eHW) and tropical night event that occurred in July 2014 was analyzed. The corresponding synoptic situation (Figure 21) revealed that this extreme warm event was driven by the presence of a strong high-pressure system (1025 hPa) over Northern Europe. As the system moved eastward, it induced a southerly airflow over Lithuania, advecting warm air from the south and thereby intensifying the heat event.

This heat wave was particularly intense, marked by exceptionally high daytime and nighttime air temperatures. Maximum daytime temperatures reached 33.5 °C in Klaipeda (26 July 2014) and 32.8 °C in Nida (29 July 2014), while nighttime minimum temperatures peaked at 20.9 °C in Klaipeda (28 July) and 22.6 °C in Nida (29 July). The event was also remarkable in terms of duration: Klaipeda recorded five consecutive days with maximum

temperatures equal to or exceeding 30 °C, and Nida recorded four such days. In terms of tropical nights (TN), Nida experienced six consecutive TN, while Klaipeda registered three.

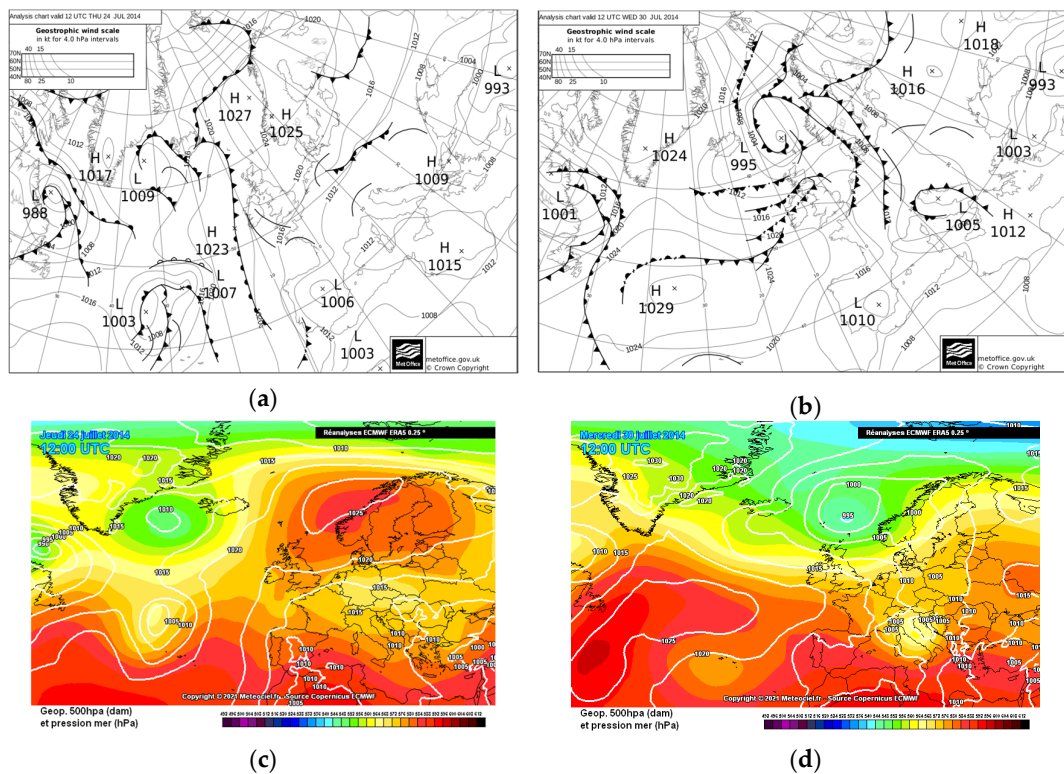


Figure 21. Synoptic situation over Europe in July 2014: (a,c) before a tropical night and extreme heatwave event (24 July 2014); (b,d) after a tropical night and extreme heatwave event (30 July 2014). ((a,b) source: <https://digital.nmla.metoffice.gov.uk> [accessed 21 November 2025]; and (c,d) source: <https://www.meteociel.fr/modeles/archives/archives.php> [accessed 21 November 2025]).

A significant increase in sea surface temperature (SST) was observed during the event, with differences reaching up to +4 °C in certain coastal areas, rising from 18 °C to 22 °C. These relatively large SST anomalies may be attributed to an upwelling event that occurred along the Lithuanian Baltic Sea coast shortly before the heatwave (Figure 22). Upwelling—a process driven by persistent northeasterly winds that push warmer surface waters offshore, allowing colder deep waters to rise to the surface—was clearly visible in MODIS Aqua satellite SST imagery on 24 July 2014 (Figure 22a). This event temporarily cooled coastal waters and contributed to slightly lower air temperatures. However, by 30 July, both sea and lagoon SSTs had risen significantly. Upwelling events can substantially reduce SST in coastal zones and consequently influence local meteorological conditions. The associated cooling effect can lower near-surface air temperatures by approximately 2–4 °C during such episodes [29]. Therefore, the presence or absence of upwelling may play a critical role in modulating the onset, intensity, and spatial distribution of extreme heat events in coastal areas.

The findings of this study highlight that the analysis and forecasting of extreme heatwaves and tropical nights, particularly in coastal environments, require detailed information on the thermal state of adjacent water bodies. The interplay between atmospheric and oceanographic processes can significantly influence the dynamics of extreme temperature events. Improving the understanding and prediction of such extreme phenomena demands the integration of comprehensive environmental data sources. Although this study focused mainly on the influence of sea surface temperature (SST) variability on coastal heat extremes and tropical nights, further research should investigate the role of at-

atmospheric circulation patterns and land–sea thermal gradients in modulating these events. Integrating circulation-based classifications and high-resolution SST data could help to disentangle the relative contributions of marine and atmospheric drivers to extreme temperature formation in coastal regions. Such analyses would enhance predictive capabilities and improve deep understanding of local-scale responses to large-scale climate dynamics. This is essential not only for enhancing early warning systems, but also for supporting climate adaptation strategies, advancing sustainability goals, and mitigating the impacts of increasingly frequent extreme heat events in the 21st century.

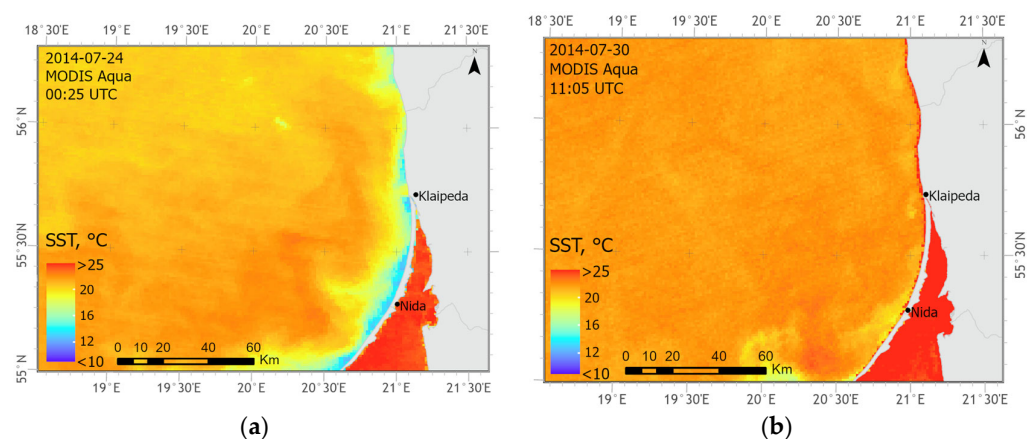


Figure 22. Maps of MODIS Aqua SST data in the southeastern Baltic Sea and the Curonian Lagoon in July 2014: (a) before a tropical night and extreme heatwave event (24 July 2014); (b) after a tropical night and extreme heatwave event (30 July 2014).

4. Discussion

Recent advances in satellite-based remote sensing and high-resolution reanalysis datasets (e.g., Copernicus ERA5, ERA5-HEAT, and Sentinel missions) have significantly enhanced the capacity to monitor and investigate changes in extreme heat events, complementing in situ observations. Copernicus ERA5 data provide spatially and temporally consistent records suitable for analyzing both long-term climate trends and short-lived extremes. This makes ERA5 particularly valuable for studying heatwaves and tropical nights in regions such as the southeastern Baltic Sea, where the density of in situ meteorological stations is limited. A key limitation in the study of extreme weather events is the insufficient spatial coverage of ground-based meteorological stations, especially in coastal and sparsely populated areas. This constraint also affects hydrological observation networks, where the limited number and uneven distribution of monitoring sites hinder a comprehensive assessment of the role of sea surface warming in the formation of tropical nights.

The comparison and integration of in situ and Copernicus datasets in coastal zones is essential for improving the future applicability of remote sensing products in such environments. This combined methodology allows for improved detection of local-scale extremes, validation of reanalysis products, and better understanding of coastal thermal variability—particularly in underrepresented regions such as the southeastern Baltic Sea coast.

The results of this study indicate that Copernicus data should be complemented with local in situ measurements. Copernicus datasets may not fully capture all extreme temperature values in coastal areas due to temporal or spatial mismatches, particularly when land grid cells are surrounded by water. The ERA5 dataset is provided at a spatial resolution of $0.25^\circ \times 0.25^\circ$ (approximately ~ 31 km) and an hourly temporal step, ensuring high detail for regional-scale analysis. Nevertheless, in coastal zones, each grid cell typically includes both land and adjacent water surfaces, which leads to temperature smoothing. Therefore, while Copernicus data are well suited for analyzing general air temperature

trends, they may underestimate the intensity or frequency of extreme heat events in specific coastal zones, small islands, or narrow landforms like spits, where sharp land–sea contrasts dominate local climate conditions.

In this work, the integration of both data resources, in situ and Copernicus ERA5 data, provides new insights into long-term temperature dynamics and the trends of extreme heat events. Based on the results of the study, in the Southeastern part of the Baltic Sea coast, heat waves (HW) and tropical nights (TN) phenomena were historically rare, but recent observations indicate a clear upward trajectory. A coastal-Lithuania study (1982–2024) found that seaside resorts experienced annual heat waves characterized by daytime maxima above 30 °C and an increasing number of tropical nights influenced by Baltic Sea and Curonian Lagoon microclimates. Warming coastal sea-surface waters above 20 °C during the warm season can promote the occurrence of a greater number of tropical nights. Under marine heatwave (MHW) conditions, minimum nighttime air temperatures exceeding 20 °C may be recorded more frequently.

The results are consistent with previous research, which indicates that many of the world's most severe heatwave seasons, as measured by cumulative heat, have occurred since 2000, with the majority taking place since the 1980s [4]. In Lithuania's coastal zone, a pronounced upward trend in the frequency and duration of heatwaves has been observed over the period 1982–2024, particularly in the urban port city of Klaipeda and the resort town of Nida. The number of extreme heat days—defined as days with maximum air temperature exceeding 30 °C—has steadily increased, accompanied by a clear temporal expansion of the heatwave season. These events are now recorded as early as May and extend into late August, reflecting a shift toward a longer and more intense period of thermal stress in the region.

From a tourism and regional development perspective, the coastal areas of Palanga and Nida may be considered more climatically suitable for sustainable tourism expansion, as they experience fewer occurrences of extreme heat compared to the more urbanized Klaipeda. However, recent observations indicate a rising frequency of tropical nights (minimum air temperature ≥ 20 °C) in the Curonian Spit, particularly in Nida, where such events have been recorded almost annually since 2018. This emerging trend suggests growing nocturnal thermal stress, which may have implications for human health, ecosystem functioning, and the long-term viability of the resort sector, changing traditions of the coastal marine tourism.

These terrestrial phenomena are closely interconnected with warming patterns in the marine environment. The spatial extent of marine heatwaves (MHWs) has expanded significantly in the Baltic Sea, including the Lithuanian coast, over recent decades, with SSTs ≥ 20 °C persisting longer and becoming more frequent in shallow coastal zones—leading to notable ecosystem stress [29–31,34]. Under such marine heatwave conditions, minimum nighttime air temperatures ($T_{\min}$) exceeding 20 °C have become increasingly likely, indicating that marine thermal anomalies can exacerbate nocturnal heat stress in adjacent coastal areas. This suggests that marine thermal anomalies can modulate nighttime heat stress on land and must be considered in any integrated climate impact assessment for coastal regions. Recognizing these linkages is essential for developing sustainable coastal adaptation strategies and enhancing community resilience to climate-induced thermal extremes.

At the broader European level, these patterns mirror a continent-wide escalation in thermal extremes. The European Environment Agency reports [35] that Europe is experiencing hotter days, elevated nighttime temperatures, and more frequent humid heatwaves—trends that are increasingly affecting human health and well-being. Notably, the number of tropical nights has risen across Europe, and under high-emission scenarios,

Southern Europe may face up to 100 tropical nights annually by the century's end. Additionally, hot days exceeding 30 °C are projected to increase up to fourfold by the same timeframe, especially in southern regions. For example, in Cyprus, extreme temperatures are projected to intensify under climate change. The number of tropical nights has been rising significantly since the 1980s and is expected to continue increasing throughout the 21st century, and could exceed 100 tropical nights per year at the end of the century. Similarly, the frequency of summer days (maximum temperature > 25 °C) has also shown a marked upward trend, particularly after the 2000s, and more extreme heat of more than 40 °C is expected in the future [36].

Overall, understanding and forecasting heatwaves and tropical nights is vital not only for climate science but also for the development of sustainable adaptation policies that protect ecosystems, human health, and coastal resilience. The concept of sustainability increasingly extends beyond efficient resource use to encompass climate system stability, societal resilience, and the need for sustainable adaptation measures.

Therefore, the study and prevention of extreme natural phenomena is an important part of sustainable development, contributing to the United Nations Sustainable (SDG) Development Goals (DG) [37]. SDG DG13 (Climate Action), which calls for reducing greenhouse gas emissions in order to stop not only the increase in global air temperature but also the intensification and frequency of extreme phenomena. Thus, it is associated with the need not only to mitigate climate change (mitigation), but also to take adaptation measures to solve the problems posed by heat waves. Heat waves affect vulnerable social groups the most—the elderly, children, the sick, and the poor. Thus, this is related not only to the SDG3 (Good health and well-being) goal, but also to the SDG10 (Reduce inequality) goal. Therefore, knowledge of heat waves and timely forecasts can contribute to preserving health or even lives. The study shows that the number of heat waves and heat waves is increasing. Cities can become heat islands (especially the central parts of cities) during heat waves. Therefore, it is important to keep cities as green as possible, as this can reduce the number of heat waves and contribute to the implementation of DG 11 (Sustainable urban planning), e.g., green spaces, and cooling infrastructure is an adaptation tools.

The increasing frequency of extreme heatwaves and tropical nights directly affects sustainability by disrupting the ability of natural and social systems to maintain balance and function. Therefore, a faster transition toward a sustainable economy and safer environment can be achieved through the use of advanced technologies, remote sensing systems, artificial intelligence tools, and the development of digital twins that support policymakers and society in implementing sustainable management practices. Therefore, future research should integrate new observational datasets and modeling approaches to improve the prediction of extreme heat events and their effects on sustainable development. Continued interdisciplinary research is required to more accurately assess the implications of heatwaves and tropical nights for sustainability and coastal resilience.

In summary, the integration of Copernicus data in this study provides new insights into the changing frequency, duration, and intensity of extreme heat events, heatwaves, and tropical nights in the southeastern Baltic Sea region. This is particularly relevant considering that nearly 15 million people live within 10 km of the Baltic Sea coastline [38], making coastal zones among the most densely populated and climate-sensitive areas in Northern Europe. During the warm season, these areas, especially urban centers and recreational beaches, experience intensified human activity and increased exposure to heat-related risks. Therefore, understanding the formation processes and dynamics of local coastal extreme heat events is essential for developing climate-resilient urban planning measures, protecting public health, and ensuring sustainable cooling and adaptation strategies in both residential and tourism-heavy environments.

5. Conclusions

The increasing frequency of extreme heat waves and tropical nights is an indicator of the unsustainability of the climate system. Lithuania's warming exceeds global averages, underscoring the disproportionate regional warming in the southeastern Baltic Sea region. A warming climate leads to increasingly above-normal air temperatures and more frequent extreme heat events. Such findings highlight the importance of localized assessments when evaluating national climate resilience thresholds, sustainability goals, and long-term adaptation strategies.

As climate warming limits are surpassed, the frequency and severity of extreme heat events become critical indicators of climate vulnerability and a key challenge for achieving sustainability and resilience objectives. Based on a long-term analysis of meteorological data using historical in situ observations and Copernicus ERA5 datasets for the period 1981–2024 in the southeastern Baltic Sea region, clear long-term trends of air temperature increase, and the growing frequency of extreme heat events (eH), heatwaves (eHW), and tropical nights (TN) were identified. These findings indicate that average monthly air temperatures in summer months higher than 18–20 °C have been increasing since 1985. June exhibits the highest annual warming rate (≈ 0.08 °C/year near Klaipeda, and ≈ 0.11 °C/year near Nida). In the study period, the extreme hot season was getting longer and was recorded every year for the last decade.

In the Southeastern part of the Baltic Sea coast, heat waves and tropical nights phenomena were historically rare, but recent observations from the 9th decade of the 20th century indicate a clear increasing trend. As the average air temperature warms, the recurrence of extreme weather events with air temperatures above 30 °C is increasing. The frequency of extremely hot days eH in Klaipeda has more than doubled over recent decades, increasing from 1 to 2 days per year (1982–2011) to >3 days per year (1992–2021). The average number of extremely hot (eH) days, defined as days with $T_{\max} \geq 30$ °C, during the study 1982–2024 period was 3 days per year. A significant increasing trend was observed in the Lithuanian coastal zone (Klaipeda), with an average rise of +0.14 eH days per year, equivalent to approximately one additional extremely hot day every 7 years. In Nida, the number of eH days also increased (from <1 day to 1–2 days per year), although the trend was not statistically significant.

Despite the increasing frequency of extremely hot (eH) days, the occurrence of severe heat waves (sHW), defined as periods of three or more consecutive days with $T_{\max} \geq 30$ °C, remains relatively rare along the Lithuanian Baltic Sea coast. Over the 43-year study period, only a few such events were identified (9 in Klaipeda and 7 in Nida), indicating that prolonged heatwave episodes have not yet become a dominant feature of the regional climate. The mean annual number of TNs also rose, from around 1 to 2 TNs per year in Klaipeda and from 3 to 4 to 5–6 TNs per year in Nida between the periods 1982–2011 and 1992–2021. The duration of the tropical night (TN) season has significantly lengthened in recent decades, with an average increase of approximately 5 days per decade in Klaipeda and nearly 10 days per decade in Nida, indicating a clear seasonal shift in nighttime heat extremes.

Copernicus ERA5 data demonstrate strong consistency with in situ station records in Klaipeda and Nida, particularly during the core summer months. The warmest season (June–August) exhibits clear and statistically significant warming trends in both datasets, supporting the reliability of reanalysis products for long-term climate studies. Minor discrepancies observed in spring months highlight the continued importance of local observations for capturing finer-scale variability. Larger differences are recorded when comparing the number of eH (days with $T_{\max} > 30$ °C) cases. These findings indicate that Copernicus data are suitable for long-term climatological analyses but should be used

with caution when assessing short-term temperature extremes, particularly in coastal or microclimatic regions. Further investigation of extreme temperature events and application of correction methods is recommended where necessary.

The study demonstrated that for extreme heat events, formations in the Southeastern Baltic Sea coastal zone are strongly influenced by the thermal dynamics of adjacent water bodies. This study underscores the importance of integrating marine and atmospheric datasets—particularly in situ observations, Copernicus ERA5 reanalysis, and MODIS Aqua SST—in assessing local and regional heat-related risks. The incorporation of higher-resolution satellite SST data helped reveal potential links between marine heatwaves (MHWs) and the occurrence of tropical nights (TNs). A better understanding of these interactions could contribute to improved early-warning systems, more effective urban heat mitigation strategies, and informed decision-making for sustainable coastal tourism development in the context of a warming climate.

Coastal areas influenced by maritime climate conditions are traditionally considered less prone to extreme temperature events. However, the observed intensification of warming in southeastern Baltic coastal settlements, such as Klaipeda and Nida, challenges this assumption. Due to their exposure to both marine and anthropogenic influences, these regions face unique climate-related risks. The growing frequency and persistence of extreme heat events in coastal zones not only threaten local ecosystems and public health but also undermine regional sustainability and climate resilience. Therefore, assessing heat extremes in these areas is essential for developing place-based adaptation strategies and informing future urban and coastal planning.

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Data Availability Statement: Lithuanian meteorological and hydrological data used in this study were obtained from the archives of the Lithuanian Hydrometeorological Service (LHMT): <https://archyvas.meteo.lt/> (accessed on 15 July 2025). ERA5 post-processed daily statistics on single levels were retrieved from the Copernicus Climate Data Store (CDS): <https://cds.climate.copernicus.eu/datasets/derived-era5-single-levels-daily-statistics> (accessed on 30 July 2025). No new data were created in this study. All datasets used are publicly available from the sources indicated above. The sea surface temperature (SST) data for the Baltic Sea used in this study were sourced from the Copernicus Marine Environment Monitoring Service (CMEMS) ocean reanalysis products: https://data.marine.copernicus.eu/product/SST_BAL_SST_L4_REP_OBSERVATIONS_010_016/description (accessed on 1 September 2025).

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