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SPATIAL COHERENCE OF MEAN ANNUAL AIR TEMPERATURE AND LOCAL DAY-TO-DAY TEMPERATURE VARIABILITY ACROSS CONTRASTING ENVIRONMENTAL SETTINGS

PROSTORSKA SKLADNOST POVPREČNE LETNE TEMPERATURE ZRAKA IN LOKALNA MEDDNEVNA TEMPERATURN A SPREMENLJIVOST V RAZLIČNIH OKOLJSKIH OBMOČJIH

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Abstract

This study investigates the long-term behavior of mean annual air temperature and Day-to-Day (DTD) temperature variability across nine climatological stations representing three contrasting environmental settings: continental urban environments, the Istrian Peninsula, and Adriatic islands. The objective was to evaluate the spatial coherence of long-term temperature change while examining the extent to which local environmental characteristics influence short-term temperature variability. Mean annual air temperature exhibits a statistically significant increase at all stations and exceptionally strong inter-station correlations within each environmental setting, indicating a dominant regional-scale climate signal. In contrast, DTD variability displays considerably weaker spatial coherence and generally lacks statistically significant long-term trends, reflecting a stronger influence of local climatic and environmental factors. Urban stations exhibit relatively stable DTD behavior despite pronounced warming, whereas smaller urban centers demonstrate greater variability. Within the Istrian Peninsula, marked contrasts are observed between coastal and inland locations, while the Adriatic islands display remarkably homogeneous mean annual air temperature trends but locally distinct DTD characteristics despite their common maritime setting. These findings indicate that mean annual air temperature primarily reflects regional-scale climatic forcing, whereas DTD variability provides insight into local climatic stability and short-term atmospheric processes. The study demonstrates that analyses based solely on mean annual air temperature may overlook important aspects of local climate variability and highlights the value of DTD variability as a complementary metric for understanding climate change across contrasting environmental settings.

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Keywords: air temperature, Day-to-Day temperature variability, urban environmental setting, small island setting, the Istrian Peninsula.

Izvleček

V raziskavi je obravnavano dolgoročno spreminjanje povprečne letne temperature zraka in meddnevne (Day-to-Day, DTD) temperature spremenljivosti na devetih klimatoloških postajah, ki predstavljajo tri različna okoljska območja: celinska urbana okolja, Istrski polotok in jadranske otoke. Namen raziskave je bil ovrednotiti prostorsko skladnost dolgoročnih sprememb temperature ter preučiti, v kolikšni meri lokalne okoljske značilnosti vplivajo na kratkoročno temperaturno spremenljivost. Povprečna letna temperatura zraka na vseh postajah kaže statistično značilno naraščanje in izjemno močne korelacije med postajami znotraj posameznega okoljskega območja, kar kaže na prevladujoči podnebni signal regionalnega merila. Po drugi strani pa je prostorska skladnost DTD-spremenljivosti bistveno manjša, dolgoročni trendi pa večinoma niso statistično značilni, kar odraža močnejši vpliv lokalnih podnebnih in okoljskih dejavnikov. Na urbanih postajah je DTD-spremenljivost kljub izrazitemu segrevanju razmeroma stabilna, medtem ko manjša urbana središča izkazujejo večjo spremenljivost. Na Istrskem polotoku so opazne izrazite razlike med obalnimi in celinskimi lokacijami, medtem ko jadranski otoki kljub skupnemu maritimnemu okolju izkazujejo izjemno homogene trende povprečne letne temperature zraka, vendar lokalno različne značilnosti DTD-spremenljivosti. Rezultati kažejo, da povprečna letna temperatura zraka predvsem odraža podnebne vplive regionalnega merila, medtem ko DTD-spremenljivost omogoča vpogled v lokalno podnebno stabilnost in kratkotrajne atmosferske procese. Raziskava dokazuje, da lahko analize, ki temeljijo izključno na povprečni letni temperaturi zraka, spregledajo pomembne vidike lokalne podnebne spremenljivosti, ter poudarja pomen DTD-spremenljivosti kot dopolnilnega kazalnika za razumevanje podnebnih sprememb v različnih okoljskih območjih.

Ključne besede: temperatura zraka, meddnevna temperaturna spremenljivost, urbano okolje, okolje majhnih otokov, Istrski polotok.

1. Introduction

The analysis of air temperature time series allows for a more reliable understanding of numerous complex interactive processes, thereby facilitating more effective preparation for an uncertain climatic future. It is therefore important to recognize that climate change manifests in markedly different ways across distinct environmental contexts. To this end, the present study employs the Day-to-Day (DTD) method applied to mean daily air temperatures.

This method has been used as a sensitive indicator of climate change, urbanization, and land-atmosphere interactions. DTD fluctuations are defined as the absolute differences in mean daily air temperatures between two consecutive days. The method constitutes an analytical approach in climatology and meteorology in which changes in mean daily air temperature are examined as a continuous time series, without initial aggregation to monthly, seasonal, or annual averages. As such,

it serves as an important complementary tool to traditional climatological analysis, as it enables the assessment not only of warming magnitude but also of changes in daily temperature dynamics that may not be evident from analyses based solely on aggregated temperature statistics.

While conventional trend analyses describe long-term increases or decreases in annual, seasonal, or monthly mean air temperatures, the DTD method focuses on the dynamic stability of the atmosphere and the intensity of daily temperature oscillations, thereby providing insight into changes in climate variability that are not necessarily evident from analyses of long-term mean temperatures alone. In the context of global warming, this method has particular scientific and applied relevance. Global warming is not manifested exclusively through rising mean temperatures, but also through changes in temperature variability. Increased DTD variability may reflect a more frequent occurrence of abrupt temperature changes, with potential

implications for environmental and socio-economic systems.

Because DTD analysis is based on day-to-day changes, it also allows comparisons of temperature variability across different geographical regions irrespective of their long-term climatic means.

DTD has been increasingly applied to characterize local and regional temperature variability and to investigate the influence of climatic setting, geographic location, and land-surface characteristics on day-to-day thermal behavior. The DTD variability framework was first introduced by Karl et al. (1995) and subsequently applied by numerous authors, including Moberg et al. (2000), Rebetez (2001), Gough (2008), Tam and Gough (2012), Gough and Hu (2016), Wu et al. (2017), and Wang et al. (2025b), among others.

Factors influencing DTD variability over time are numerous and vary substantially between locations, even among geographically proximate sites. Moreover, multiple factors may simultaneously influence DTD variability at any given location. The key drivers include synoptic circulation, particularly changes in air masses and associated weather conditions (Krauskopf and Huth 2024; Hamal and Pfahl 2025), and seasonality and insolation, which influence the annual cycle of surface heating (Kotz et al. 2021; Krauskopf and Huth 2025). Continentality and maritime influence affect DTD variability through differences in the thermal response of land and water and the resulting moderation of temperature fluctuations (Gough and Shi 2020; Dailidienė et al. 2023; Gough 2024; Gough and Li 2024b; England et al. 2025; Zhang et al. 2025). Local environmental and anthropogenic factors, such as topography, elevation, vegetation cover, soil properties, and urbanization, further modify temperature variability at individual locations (Anderson et al. 2018; Bonacci and Roje-Bonacci 2020; Bonacci et al. 2022b; Bonacci and Đurin 2023; Fernández 2024; Krsnik 2024; Gough 2025; Reek et al. 2025; Shi and Wu 2025; Spencer et al. 2025). At broader spatial and temporal scales, DTD variability may be influenced by large-scale climate trends and modes, including global warming, the North Atlantic Oscillation (NAO), and the El Niño–Southern Oscillation (ENSO)

(Kotz et al. 2021; Krauskopf and Huth 2024; Stuecker et al. 2025; Wang et al. 2025a). Finally, local and regional meteorological conditions, such as cloud cover, humidity, precipitation regimes, and snow cover, can substantially modify day-to-day temperature fluctuations (Bonacci et al. 2023; Deng et al. 2023; Gough and Li 2024a; Tyystjärvi et al. 2024; Fernández-Castillo et al. 2025; Shih et al. 2025). The relative importance and interaction of these drivers vary spatially and temporally, contributing to the distinct patterns of DTD variability observed among locations.

Although mean air temperature is the metric most commonly used to characterize long-term climatic change, it does not fully capture temporal variability in temperature. Evaluating DTD temperature variability alongside mean air temperature across contrasting environmental settings provides a broader perspective on long-term temperature behavior and facilitates comparison of temperature characteristics among differing climatic and geographic conditions.

The objective of this study was to characterize and compare the long-term behavior of mean air temperature and DTD temperature variability at climatological stations representing contrasting continental and Adriatic environments, including urban areas, the Istrian Peninsula, and Adriatic islands. A further objective is to investigate the relationship between these two temperature metrics and evaluate whether DTD variability provides information complementary to conventional analyses based solely on mean air temperature. Such a comparative approach can reveal fine-scale spatial differences in temperature dynamics that may not be apparent from mean annual air temperature alone, thereby providing a more comprehensive understanding of climate variability across contrasting environmental settings.

2. Materials and methods

This study is based on long-term mean daily air temperature records from nine climatological stations representing three contrasting environmental settings: continental urban environments, the Istrian Peninsula, and Adriatic

Islands. The following sections describe the study locations and their main climatic and environmental characteristics, followed by the methods used to analyze mean annual air temperature and annual DTD variability.

2.1 Description of the study locations

The study encompasses nine long-term climatological stations representing a broad range of climatic, geographic, and environmental conditions in the northern and eastern Adriatic region and the adjacent Pannonian Basin (Figure 1, Table 1).



Figure 1: Map of the study area showing the locations of the nine climatological stations: (1) Belgrade, (2) Zagreb, (3) Varaždin, (4) Pula, (5) Pula Airport, (6) Pazin, (7) Lastovo, (8) Hvar, and (9) Lošinj.

Slika 1: Karta obravnavanega območja s prikazom lokacij devetih klimatoloških postaj: (1) Beograd, (2) Zagreb, (3) Varaždin, (4) Pulj, (5) Letališče Pulj, (6) Pazin, (7) Lastovo, (8) Hvar in (9) Lošinj.

Table 1: Main characteristics of the climatological stations.

Preglednica 1: Glavne značilnosti klimatoloških postaj.

Station	Geographic coordinates	Elevation (m a.s.l.)	Available period	Mean annual air T (°C), average (min–max)	Observed T (°C) min–max
Belgrade	44° 48' 47" N, 20° 27' 09" E	132	1946–2019	12.5 (10.6–15.1)	–21.0–43.6
Varaždin	46° 16' 58" N, 16° 21' 50" E	167	1969–2019	10.6 (9.0–12.3)	–28.0–39.4
Zagreb Grič	45° 48' 52" N, 15° 58' 19" E	157	1946–2019	12.1 (10.3–14.3)	–22.2–40.3
Pula	44° 51' 56" N, 13° 50' 46" E	29	1963–2024 Missing: 2012–2013	14.5 (13.1–16.5)	–9.8–38.5
Pula Airport	44° 53' 51" N, 13° 55' 13" E	63	1978–2024 Missing: 1991–1992	14.0 (12.2–15.8)	–14.0–38.2
Pazin	45° 14' 27" N, 13° 56' 43" E	291	1961–2024	11.6 (10.4–13.6)	–26.7–39.5
Lastovo	42° 46' 06" N, 16° 54' 00" E	186	1948–2024	15.9 (14.7–18.0)	–6.8–38.3
Hvar	43° 10' 16" N, 16° 26' 13" E	20	1946–2024	16.8 (15.5–18.8)	–6.2–33.0
Lošinj	44° 31' 57" N, 14° 28' 19" E	53	1961–2024	15.7 (14.5–18.2)	–7.5–37.5

The selected stations span pronounced gradients in continentality, maritime influence, topographic complexity, and urbanization, providing an appropriate framework for investigating spatial differences in mean annual air temperature and diurnal temperature difference (DTD) variability. The stations were grouped into three contrasting environmental settings: (1) continental urban environments (Belgrade, Zagreb, Varaždin), (2) the Istrian Peninsula representing a transition from coastal Mediterranean to inland continental conditions (Pula, Pula Airport, Pazin), and (3) Adriatic island environments (Lastovo, Hvar, Lošinj). Together, these locations capture a wide spectrum of climatic controls operating across southeastern Europe, ranging from highly continental lowland climates to Mediterranean island climates strongly moderated by the Adriatic Sea.

The continental group includes Belgrade, Zagreb, and Varaždin, three urban centers situated within the Pannonian climatic domain. Belgrade is located at the confluence of the Sava and Danube Rivers, at the transition between the Pannonian Plain and the Balkan Peninsula (Bonacci et al., 2024a). The city is classified as having a temperate humid climate with hot summers (Cfa) according to the Köppen–Geiger climate classification (Köppen and Geiger, 1936; Peel et al., 2007), with mild to cold winters and precipitation occurring throughout the year, with higher amounts generally occurring during the warmer part of the year. Owing to its geographical position at the interface between continental and subtropical air masses, Belgrade is frequently exposed to pronounced weather variability and occasional extreme events.

Zagreb, Croatia's capital, occupies the southern margin of the Pannonian Plain along the Sava River, immediately south of the Medvednica Mountains. The city has a temperate humid climate with warm summers (Cfb) (Filipčić, 1998; Šegota and Filipčić, 2003), characterized by cold winters and year-round precipitation with a late spring maximum. Besides large-scale atmospheric circulation over the Pannonian Basin, local climatic conditions are strongly modified by the Medvednica massif, which enhances orographic precipitation and influences

airflow patterns over the urban area (Nimac et al., 2022).

Varaždin, located in northern Croatia near the Drava River (Bonacci et al., 2022), also belongs to the temperate humid climate with warm summers (Cfb) climatic zone (Filipčić, 1998; Šegota and Filipčić, 2003). Although considerably smaller than Belgrade and Zagreb, it experiences a similar moderately continental climate characterized by cold winters, frequent frost, and precipitation throughout the year, with a seasonal maximum during the warmer part of the year. The surrounding low-relief agricultural landscape, interspersed with forests and urban green areas, provides a representative example of the continental environments of northern Croatia.

The second group comprises three stations on the Istrian Peninsula, one of the most climatically heterogeneous regions of the eastern Adriatic. Covering approximately 3,558 km², Istria is shared between Croatia (3,132 km²), Slovenia (385 km²), and Italy (38 km²). The peninsula lies at the northernmost extension of the Mediterranean Sea into continental Europe, where Mediterranean and continental atmospheric influences converge. Atlantic air masses entering from the northwest provide moisture throughout the year, while the Adriatic Sea moderates seasonal temperature extremes. In winter, cold continental outbreaks frequently generate the bora, a strong northeasterly downslope wind, whereas during summer the region is characterized by warm, dry Mediterranean conditions. Moving inland, Mediterranean climatic characteristics rapidly transition toward a more continental regime due to increasing elevation, greater distance from the sea, and the influence of the Dinaric Mountains and the Alps (Gluhčić and Dotlić, 2007; Zoldaš et al., 2025).

Pula, situated at the southern tip of the peninsula within a sheltered Adriatic Bay, represents the coastal environment. Its climate is transitional between a temperate humid climate with hot summers (Cfa) and a Mediterranean climate with hot summers (Csa), with mild winters, relatively dry summer months, and more abundant precipitation during the cooler part of the year. The city receives more than 2,300 hours of sunshine annually.

Pula Airport, located approximately 6 km inland from the coast, provides an important comparison with the nearby urban coastal station. The airport surroundings consist primarily of open grassland and low vegetation, minimizing local urban influences on temperature observations. A recent climatological analysis documented declining frequencies of fog and mist at the airport between 2001 and 2020, with increasing air and sea-surface temperatures identified as important contributing factors (Zoldaš et al., 2025).

Pazin, situated in central Istria, represents the inland climatic environment of the peninsula. Unlike the coastal stations, Pazin is surrounded by hilly terrain that promotes cold-air drainage and nocturnal temperature inversions, particularly during winter. Consequently, its temperate humid climate with hot summers (Cfa) exhibits more pronounced continental characteristics, including larger annual temperature amplitudes and reduced maritime moderation.

The third group comprises three Croatian Adriatic islands differing substantially in size, relief, and geographical position but sharing strong maritime climatic influences. Maritime environments generally experience reduced seasonal and diurnal temperature variability owing to the high heat capacity of seawater, making these stations particularly suitable for examining the influence of the sea on DTD.

Lastovo is the southernmost inhabited Croatian Adriatic island (Bonacci, 2019; Bonacci et al., 2024b). Covering 40.82 km² (Duplančić-Leder et al., 2004), the island reaches a maximum elevation of 417 m above sea level and is characterized by a highly indented coastline and relatively isolated position within the southern Adriatic. According to the Köppen–Geiger classification, Lastovo has a Mediterranean climate with hot summers (Csa) (Köppen and Geiger, 1936; Filipčić, 1998; Šegota and Filipčić, 2003).

Hvar, located in central Dalmatia approximately 9 km offshore from the mainland, is among the largest Croatian islands, covering 297.38 km² with elevations reaching 628 m. Its Mediterranean climate with hot summers (Csa) (Filipčić, 1998;

Šegota and Filipčić, 2003), together with its elongated east-west orientation and complex topography, produces considerable local climatic variability despite the dominant maritime influence (Bonacci et al., 2021).

Lošinj covers 74.36 km² and consists predominantly of carbonate rocks (Bonacci et al., 2024b). Although also strongly influenced by the Adriatic Sea, its northern position results in a temperate humid climate with hot summers (Cfa) (Filipčić, 1998; Šegota and Filipčić, 2003), representing a transitional climatic setting between the Mediterranean and the northern Adriatic. The aerial distances between the islands are approximately 95 km between Lastovo and Hvar, 187 km between Hvar and Lošinj, and 277 km between Lastovo and Lošinj.

Mean daily air temperature data for Belgrade were obtained from the Republic Hydrometeorological Service of Serbia, whereas observations from the remaining eight stations were provided by the Croatian Meteorological and Hydrological Service.

2.2 Methods

Linear regression (McGhee 1985) was used to analyze the relationships between mean annual air temperatures at the climatological stations. The method was applied to examine the relationships between annual DTD values at these stations. Additionally, trends in the time series of mean annual air temperatures and annual DTD values at the nine stations were analyzed using this approach. The linear regression equation is expressed by equation (1):

$$Y = A + (B \times X) \quad (1),$$

where Y represents the dependent variable and X the independent variable. For the temporal trend analyses presented in Figures 2–7, X represents time (calendar year), while Y represents the mean annual temperature or annual DTD value at respective stations. For the inter-station relationships presented in the corresponding tables, X and Y represent the same variables measured at the respective pair of stations.

For each analyzed regression case, the coefficient of determination (R^2) was calculated. The coefficient of determination represents the square of the Pearson correlation coefficient (R). Both coefficients indicate how well one variable explains the variation of the other in a linear regression, or how well the regression line fits the data. For example, a coefficient of determination of $R^2=0.70$ ($R=0.837$) indicates that 70% of the total variation in the dependent variable Y can be explained by its linear dependence on the independent variable X , while the remaining 30% cannot be explained linearly. The DTD equation is expressed by equation (2):

$$DTD = \frac{\sum |T_i - T_{i-1}|}{n - 1} \quad (2),$$

where n is the number of elements in the time series, i is the counter running through the days of the year, T_i is the mean daily temperature on day i , T_{i-1} is the mean daily temperature on the previous day, and $|$ denotes the absolute value of the difference.

For each year, the annual DTD value was calculated by computing the absolute difference in mean daily air temperature between each pair of consecutive days throughout the year. These daily differences were then averaged over the total number of day-to-day transitions within that year to obtain a single annual DTD value.

The statistical significance of monotonic increases or decreases in the linear trends of the time series of mean annual air temperatures and annual DTD values was assessed using the nonparametric Mann–Kendall (M–K) test (Mann 1945; Kendall 1975). The null hypothesis states that there is no statistically significant monotonic trend in the analyzed time series, whereas the alternative hypothesis asserts the presence of a statistically significant trend. A significance level of $p < 0.01$ was used as the criterion for accepting the alternative hypothesis.

The DTD method has several methodological limitations that should be considered when interpreting the results. As an aggregated measure of absolute daily temperature changes, DTD does not retain information on the direction of

temperature change (Gross et al. 2018; Kotz et al. 2021; Krauskopf and Huth 2024). DTD is also sensitive to the quality and homogeneity of input data, and changes in station location, instruments, or measurement protocols may affect the estimated daily variability (Squintu et al. 2019; Coscarelli et al. 2021; Dijkstra et al., 2022). In addition, the method is sensitive to temporal scaling, and the resulting DTD values may depend on the method used to calculate mean daily air temperature (Bonacci et al. 2013; Gross et al. 2018; Krauskopf and Huth 2025).

3. Results

3.1. Three Cities: Belgrade, Zagreb, Varaždin

Figure 2 presents the time series of mean annual air temperatures observed at the climatological stations Belgrade (1946–2019), Zagreb (1946–2019), and Varaždin (1969–2019).

The warming trend at all three stations is statistically significant, as indicated by Mann–Kendall test results ($p < 0.01$). It is also evident that the rapid temperature increase began toward the end of the 20th century. At the Belgrade station, this process began in 1998 (Bonacci et al. 2024a), while at the Zagreb station it started in 1988 (Bonacci and Đurin 2023). At the Varaždin station, the rapid increase in mean annual air temperature began in 1982 (Bonacci et al. 2022a).

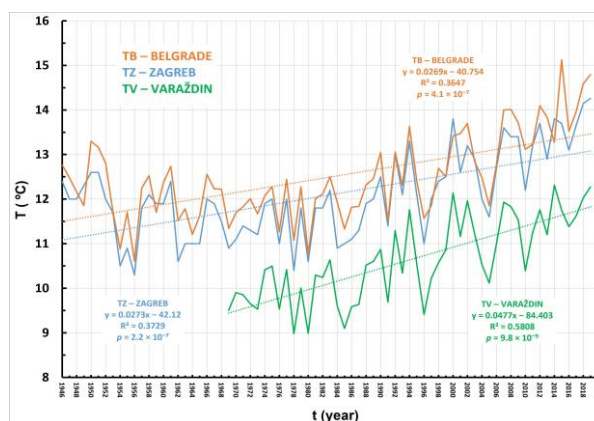


Figure 2: Time series of mean annual air temperatures for Belgrade (1946–2019), Zagreb (1946–2019), and Varaždin (1969–2019).

Slika 2: Časovni nizi povprečnih letnih temperatur zraka za Beograd (1946–2019), Zagreb (1946–2019) in Varaždin (1969–2019).

During the 1969–2019 period, Belgrade recorded the highest average annual air temperature (12.65 °C) as well as the largest range of mean annual air temperatures (4.35 °C). The average annual air temperature in Zagreb was 12.27 °C, with a range of 3.86 °C. Varaždin recorded the lowest average annual air temperature (10.64 °C) and the smallest range (3.33 °C).

Table 2 presents the coefficients of determination (R^2) between the mean annual air temperatures and annual DTD values at the three analyzed climatological stations. For mean annual air temperatures, the R^2 values are very high, ranging from 0.861 for the Belgrade–Varaždin relationship to 0.965 for the Zagreb–Varaždin relationship. In comparison, the R^2 values for the annual DTD are considerably lower, ranging from 0.528 for the Belgrade–Zagreb relationship to 0.721 for the Zagreb–Varaždin relationship.

Figure 3 presents the time series of annual DTD values at the climatological stations Belgrade (1946–2019), Zagreb (1946–2019), and Varaždin (1969–2019).

During the 1969–2019 period, Belgrade exhibited the highest average annual DTD value (2.08 °C) with a range of 0.549 °C. Varaždin recorded an average annual DTD value of 1.95 °C and exhibited the largest range (0.729 °C), while Zagreb had the lowest average annual DTD value (1.79 °C) and the smallest range (0.456 °C).

An increasing trend in annual DTD values was observed only at the Varaždin station; however, this trend is not statistically significant ($p = 0.341$). Decreasing trends in DTD were identified at the Belgrade and Zagreb stations, but these trends are also not statistically significant (Table 3). In contrast, mean annual air temperatures show statistically significant increasing trends at all three stations. The Mann–Kendall test results and Sen’s slope estimates for annual DTD and mean annual air temperature at all three stations are summarized in Table 3.

A clear distinction is observed between the behavior of mean annual air temperatures and annual DTD

values in Belgrade, Zagreb, and Varaždin. While mean annual air temperatures at all three stations exhibit strong and statistically significant increasing trends and are highly correlated with one another, annual DTD values show no statistically significant trends and are considerably less interrelated. This contrast arises because mean air temperature reflects the long-term energy balance of the climate system, whereas DTD represents a measure of short-term atmospheric dynamic stability.

Table 2: Coefficients of determination (R^2) between mean annual air temperatures and annual DTD values at Zagreb, Belgrade, and Varaždin.

Preglednica 2: Koeficienti determinacije (R^2) med povprečnimi letnimi temperaturami zraka in letnimi vrednostmi DTD v Zagrebu, Beogradu in Varaždinu.

Station pair	Mean Annual Temperature R^2	Annual Day-to-Day R^2
Belgrade – Zagreb	0.885	0.528
Belgrade – Varaždin	0.861	0.551
Zagreb – Varaždin	0.965	0.721

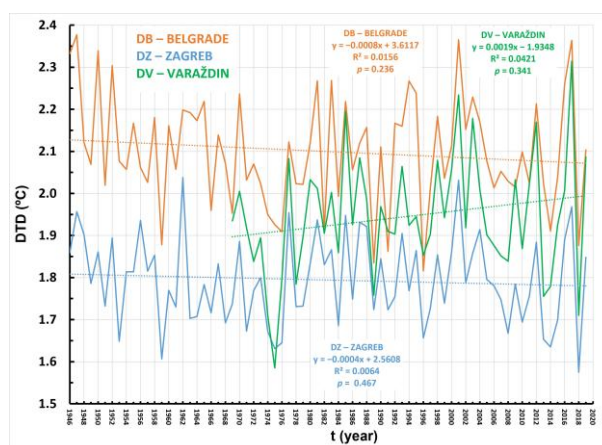


Figure 3: Time series of annual DTD for Belgrade (1946–2019), Zagreb (1946–2019), and Varaždin (1969–2019).

Slika 3: Časovni nizi letnih vrednosti DTD za Beograd (1946–2019), Zagreb (1946–2019) in Varaždin (1969–2019).

Table 3: Mann–Kendall trend test and Sen’s slope estimates for annual DTD and mean annual air temperature at Zagreb, Belgrade, and Varaždin.

Preglednica 3: Rezultati Mann–Kendallovega testa in Senovega naklona za povprečne letne temperature zraka in letne vrednosti DTD v Zagrebu, Beogradu in Varaždinu.

Series	Sen’s slope (Q)	M–K Z	p-value	Significance
DZ	-0.000500	-0.7187	0.467	NS
TZ	0.028571	5.1804	<0.001	S
DB	-0.000726	-1.714	0.236	NS
TB	0.027209	5.0266	<0.001	S
DV	0.001250	0.9513	0.341	NS
TV	0.047351	5.7343	<0.001	S

Note: DZ, DTD Zagreb; TZ, mean annual air temperature Zagreb; DB, DTD Belgrade; TB, mean annual temperature Belgrade; DV, DTD Varaždin; TV, mean annual air temperature Varaždin; M–K, Mann–Kendall; S, statistically significant; NS, not statistically significant. Trends are considered statistically significant at $p < 0.01$.

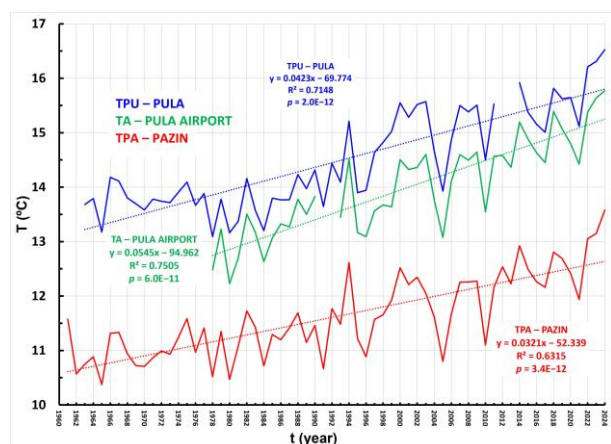


Figure 4: Time series of mean annual air temperatures for Pula (1963–2024, missing 2012–2013), Pula Airport (1978–2024, missing 1991–1992), and Pazin (1961–2024).

Slika 4: Časovni nizi povprečnih letnih temperatur zraka za Pulj (1963–2024, manjkajo podatki za obdobje 2012–2013), Letališče Pulj (1978–2024, manjkajo podatki za obdobje 1991–1992) in Pazin (1961–2024).

An increase in mean annual air temperature does not necessarily imply an increase in daily temperature variability, particularly in urban environments where high thermal inertia and anthropogenic influences tend to dampen daily temperature fluctuations. In Belgrade and Zagreb, this is reflected in weak, statistically insignificant decreasing trends in DTD despite rising temperatures. In contrast, Varaždin, as a smaller and less urbanized city situated in a more distinctly continental setting, exhibits higher DTD variability and a slight increasing trend, indicating greater sensitivity to synoptic-scale atmospheric changes. Lower coefficients of determination among the DTD time series further indicate that daily temperature variability is primarily governed by local, process-based controls. These results emphasize that climate change manifests not only through shifts in temperature magnitude but also through changes in daily temperature dynamics, which do not necessarily evolve synchronously.

3.2. Istrian Peninsula: Pula, Pula Airport, Pazin

Figure 4 presents the time series of mean annual air temperatures observed at the climatological stations Pula (1963–2024), Pula Airport (1978–2024), and Pazin (1961–2024). The warming trends at all three stations are statistically significant, as the trend probabilities calculated using the Mann–Kendall (M–K) test yield $p \ll 0.01$. A pronounced intensification of warming is evident from the late 20th century onward.

During the 1978–2024 period, Pula recorded the highest mean annual air temperature, averaging 14.71 °C, with a range of 3.44 °C. The Pula Airport station had an average annual temperature of 14.02 °C and a range of 3.54 °C. Pazin had the lowest average annual temperature, averaging 11.85 °C, and the smallest range of 3.11 °C.

Table 4 presents the coefficients of determination (R^2) between mean annual air temperatures and annual DTD values at the three analyzed climatological stations on the Istrian Peninsula. For mean annual air temperatures, the R^2 values are very high, ranging from 0.908 for the Pula–Pazin relationship to 0.939 for the Pula–Pula Airport

relationship. In comparison, the R^2 values for annual DTD are considerably lower, ranging from 0.265 for the Pula–Pazin relationship to 0.427 for the Pula–Pula Airport relationship. The warming trends at the Pula and Pula Airport stations are nearly parallel and notably stronger than at the Pazin station, which is located in the central, more continental part of the peninsula.

Figure 5 presents the time series of annual DTD observed values at the climatological stations Pula (1963–2024), Pula Airport (1978–2024), and Pazin (1961–2024).

Slight, statistically non-significant increasing trends in DTD were detected at the Pazin and Pula Airport stations, while a weak, statistically non-significant decreasing trend was observed at the Pula station.

During the 1978–2024 period, the Pula Airport station recorded the highest average annual DTD value, averaging 1.63 °C, with a range of 0.367 °C. Pula exhibited an average annual DTD of 1.40 °C and the largest range, amounting to 0.415 °C. Pazin had the lowest average annual DTD value, averaging 1.59 °C, as well as the smallest range of 0.341 °C.

At the Istrian stations, a clear divergence is observed between the behavior of mean annual air temperatures and DTD variability, arising from the opposing maritime and continental controls operating within the peninsula's relatively small spatial extent.

Pula and Pula Airport station exhibit nearly parallel and strongly correlated warming trends due to the dominant influence of the Adriatic Sea, whose high thermal capacity dampens short-term thermal oscillations but does not prevent a long-term increase in the energy state of the system.

Pazin, located inland and at a higher elevation, records lower mean temperatures and a weaker warming trend reflecting a more continental regime, frequent nocturnal cold-air accumulation, and a stronger dependence on local topography. In contrast to the high mutual correlation of mean temperatures, the DTD time series show weak interdependence, as daily temperature variability

responds primarily to local processes rather than to regional-scale energy forcing.

Table 4: Coefficients of determination (R^2) between mean annual air temperatures and annual DTD values at Pula, Pula Airport, and Pazin.

Preglednica 4: Koeficienti determinacije (R^2) med povprečnimi letnimi temperaturami zraka in letnimi vrednostmi DTD v Pulju, na Letališču Pulj in v Pazinu.

Station pair	Mean Annual Temperature R^2	Annual Day-to-Day R^2
Pula – Pula Airport	0.939	0.288
Pula – Pazin	0.908	0.265
Pula Airport – Pazin	0.931	0.427

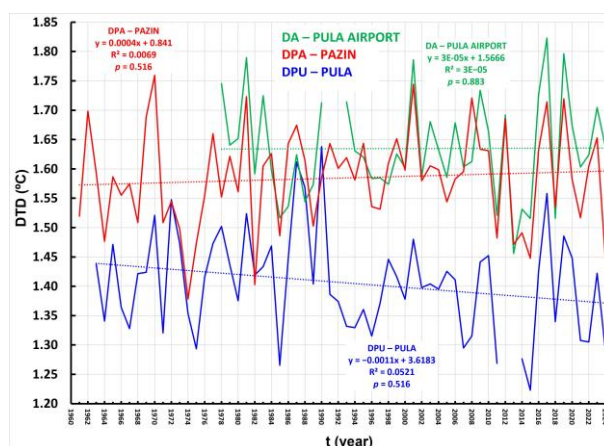


Figure 5: Time series of annual DTD for Pula (1963–2024, missing 2012–2013), Pula Airport (1978–2024, missing 1991–1992), and Pazin (1961–2024).

Slika 5: Časovni nizi letnih vrednosti DTD za Pulj (1963–2024, manjkajo podatki za obdobje 2012–2013), Letališče Pulj (1978–2024, manjkajo podatki za obdobje 1991–1992) in Pazin (1961–2024).

Table 5: Mann–Kendall trend test and Sen’s slope estimates for annual DTD and mean annual air temperature at Pula, Pula Airport, and Pazin.

Preglednica 5: Koeficienti determinacije (R^2) med povprečnimi letnimi temperaturami zraka in letnimi vrednostmi DTD v Pulju, na Letališču Pulj in v Pazinu.

Series	Sen’s slope (Q)	M–K Z	p-value	Significance
DPU	-0.001302	-2.0225	0.516	NS
TPU	0.044240	7.4257	<0.001	S
DA	0.000339	0.3742	0.883	NS
TA	0.055417	6.4832	<0.001	S
DPA	0.000457	0.6489	0.516	NS
TPA	0.032649	6.9581	<0.001	S

Note: DPU, DTD Pula; TPU, mean annual air temperature Pula; DA, DTD Pula Airport; TA, mean annual temperature Pula Airport; DPA, DTD Pazin; TPA, mean annual air temperature Pazin; M–K, Mann–Kendall; S, statistically significant; NS, not statistically significant. Trends are considered statistically significant at $p < 0.01$.

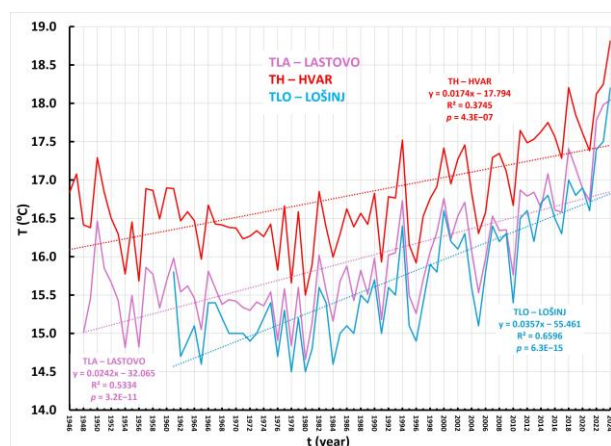


Figure 6: Time series of mean annual air temperatures for Lastovo (1948–2024), Hvar (1946–2024), and Lošinj (1961–2024).

Slika 6: Časovni nizi povprečnih letnih temperatur zraka za Lastovo (1948–2024), Hvar (1946–2024) in Lošinj (1961–2024).

The highest mean DTD values at the Pula Airport station indicate an open, weakly urbanized environment lacking both maritime moderation and

significant orographic barriers, which facilitates rapid synoptic transitions. Lower and more stable DTD values in Pula result from the combined effects of maritime influence and urban thermal inertia, whereas Pazin exhibits moderate DTD values constrained by topographic enclosure and frequent temperature inversions. These results confirm that global warming in Istria manifests more uniformly in the mean temperature magnitude than in its daily dynamics, with DTD remaining a sensitive indicator of local climatic stability and surface-atmosphere coupling processes.

3.3. Three Islands: Lastovo, Hvar, Lošinj

Figure 6 presents the time series of mean annual air temperatures observed at the climatological stations on the islands of Lastovo (1948–2024), Hvar (1946–2024), and Lošinj (1961–2024). Warming trends at all three stations are statistically significant, with M–K test probabilities of the trends $p \ll 0.01$. A pronounced intensification of warming is evident from the late 20th century onward. At the Lastovo station, this acceleration began in 1992 (Bonacci 2019, Bonacci et al. 2024b), while at Hvar it started somewhat later, in 1998 (Bonacci et al. 2021). At the Lošinj station, a sharp increase in mean annual air temperatures also commenced in 1992 (Bonacci et al. 2024b).

Table 6 presents the coefficients of determination (R^2) between mean annual air temperatures and annual DTD values at the three analyzed island climatological stations. For mean annual air temperatures, the R^2 values are very high, ranging from 0.935 for the Hvar–Lošinj relationship to 0.974 for the Hvar–Lastovo relationship. In comparison, the R^2 values for annual DTD are considerably lower, ranging from 0.484 for the Lastovo–Lošinj relationship to 0.566 for the Lastovo–Hvar relationship.

Table 6: Coefficients of determination (R^2) between mean annual air temperatures measured and annual DTD values at the three analyzed island climatological stations.

Preglednica 6: Koeficienti determinacije (R^2) med povprečnimi letnimi temperaturami zraka in letnimi vrednostmi DTD na Lastovu, Hvaru in Lošinj.

Station pair	Mean Annual Temperature R^2	Annual Day-to-Day R^2
Lastovo – Hvar	0.974	0.566
Lastovo – Lošinj	0.948	0.484
Hvar – Lošinj	0.935	0.562

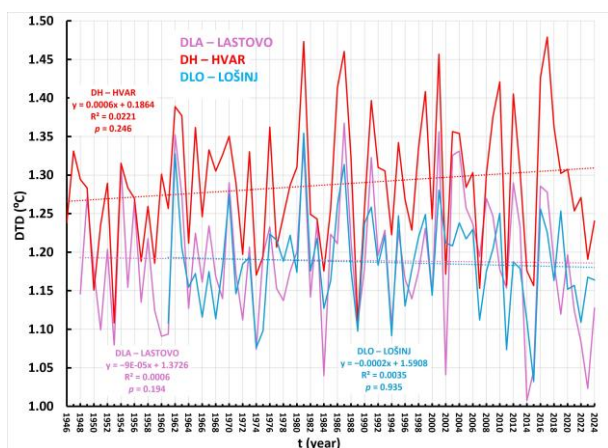


Figure 7: Time series of annual DTD values for Lastovo (1948–2024), Hvar (1946–2024), and Lošinj (1961–2024).

Slika 7: Časovni nizi letnih vrednosti DTD za Lastovo (1948–2024), Hvar (1946–2024) in Lošinj (1961–2024).

Figure 7 presents the time series of annual DTD values observed at the climatological stations Lastovo (1948–2024), Hvar (1946–2024), and Lošinj (1961–2024). Nearly identical, statistically non-significant decreasing trends in DTD were observed at the Lošinj and Lastovo stations, while a statistically non-significant increasing trend was detected at the Hvar station. During the 1961–2024 period, Hvar recorded the highest average annual DTD value of 1.30 °C and the largest range of 0.371

°C. The average annual DTD at Lastovo was 1.192 °C, with a range of 0.359 °C. Lošinj exhibited an average annual DTD nearly identical to that of Lastovo, at 1.187 °C, but with the lowest range of 0.322 °C.

In contrast to the absence of statistically significant trends in annual DTD, mean annual air temperatures show statistically significant increasing trends at all three stations. The Mann–Kendall test results and Sen’s slope estimates for annual DTD and mean annual air temperature at Lastovo, Hvar, and Lošinj are summarized in Table 7.

On the Adriatic islands of Lastovo, Hvar, and Lošinj, mean annual air temperatures exhibit a strong, statistically significant, and highly correlated increase, indicating the dominance of regional energy forcing associated with global warming and rising Adriatic Sea surface temperatures (Bonacci 2023). Hvar records the highest mean annual air temperatures due to its location in the central Adriatic, where higher and more persistent sea surface temperatures than in the northern Adriatic produce a stronger regional thermal signal in the near-surface atmosphere. Compared with Lastovo, despite being located further south, Hvar lies closer to the mainland and is therefore more strongly influenced by secondary heating of the air from land surfaces, particularly during the summer season. In addition, local orographic features and sheltered settings reduce nocturnal heat loss and the intensity of radiative cooling. Together, these factors result in higher mean annual air temperatures on Hvar compared with both Lastovo and Lošinj.

The pronounced maritime character of all three locations leads to relatively uniform temperature trends, as the sea, owing to its large heat capacity, effectively integrates long-term changes in the atmospheric energy balance. In contrast, annual DTD values exhibit substantially weaker inter-station correlations and lack statistically significant trends, confirming that daily temperature variability is primarily controlled by local and short-term processes. Higher DTD values on Hvar reflect greater exposure to the open sea and synoptic-scale variability, combined with weaker orographic and continental influences. Lošinj, being closer to the

mainland and under stronger influence from the northern Adriatic, exhibits lower and more stable DTD values, indicating more effective attenuation of daily temperature fluctuations. Higher DTD values on Hvar result from greater exposure to synoptic-scale variability in the central Adriatic, whereas the nearly identical and lower DTD values on Lastovo and Lošinj arise from different but equally effective stabilizing mechanisms: extreme maritime influence in the case of Lastovo and regional homogenization of air masses in the northern Adriatic. Differences in DTD are further modulated by local circulation patterns, coastline complexity, and interactions with the atmospheric boundary layer. These results confirm that on small Adriatic islands, climate change manifests more uniformly in temperature magnitude than in daily temperature dynamics, with DTD remaining a sensitive indicator of local climatic stability and process-level variability.

Table 7: Mann–Kendall trend test and Sen’s slope estimates for annual DTD and mean annual air temperature at Lastovo, Hvar, and Lošinj.

Preglednica 7: Rezultati Mann–Kendallovega testa in Senovega naklona za povprečne letne temperature zraka in letne vrednosti DTD na Lastovu, Hvaru in Lošinju.

Series	Sen’s slope (Q)	M–K Z	p-value	Significance
DLA	0.000113	0.1935	0.194	NS
TLA	0.023939	6.6463	<0.001	S
DH	0.000490	1.1600	0.246	NS
TH	0.016915	5.0758	<0.001	S
DLO	-0.000064	-0.0811	0.935	NS
TLO	0.035635	7.1940	<0.001	S

Note: DLA, DTD Lastovo; TLA, mean annual air temperature Lastovo; DH, DTD Hvar; TH, mean annual temperature Hvar; DLO, DTD Lošinj; TLO, mean annual air temperature Lošinj; M–K, Mann–Kendall; S, statistically significant; NS, not statistically significant. Trends are considered statistically significant at $p < 0.01$.

Comparison of the three environmental settings further emphasizes the complementary information provided by DTD. The consistently high inter-station relationships for mean annual air temperature indicate the importance of regional-scale forcing, whereas the substantially lower relationships for annual DTD demonstrate greater sensitivity to environmental setting and local processes. Geographic proximity therefore does not necessarily imply similar day-to-day temperature behavior. The results highlight the limitations of relying solely on mean annual air temperature as an indicator of climate change, as such an approach may obscure changes and spatial differences in short-term temperature dynamics that may also have implications for ecosystems, human health, and risk management.

Despite its high sensitivity to short-term temperature dynamics, the DTD method has several methodological limitations that must be considered when interpreting the present results. As an aggregated measure of absolute daily temperature changes, DTD does not retain information on the direction of temperature change and therefore cannot distinguish between gradual changes and oscillations of opposite sign (Gross et al. 2018; Kotz et al. 2021; Krauskopf and Huth 2024). This limitation is particularly relevant to the present study, in which pronounced and statistically significant increases in mean annual air temperature occur at all nine stations without corresponding statistically significant trends in annual DTD.

DTD is also sensitive to the quality and homogeneity of the underlying temperature series. Inhomogeneities associated with changes in station location, instrumentation, or measurement protocols may artificially increase or decrease estimated daily variability and therefore need to be considered when interpreting long-term DTD behavior (Squintu et al. 2019; Coscarelli et al. 2021; Dijkstra et al., 2022). In addition, the method is sensitive to temporal scaling and requires a multi-scale approach, particularly when seasonal variability and extreme events are considered. DTD values may also depend on the method used to calculate mean daily temperature (Bonacci et al. 2013; Gross et al. 2018; Krauskopf and Huth 2025).

A further limitation, particularly relevant to the interpretation of the differences observed among the nine stations, is that DTD cannot directly separate the contributions of individual physical processes. DTD integrates the effects of synoptic circulation, local orography, surface properties, humidity, cloud cover, and anthropogenic influences into a single metric. Consequently, the absence of a statistically significant DTD trend should not be interpreted as evidence of climatic stability but may instead reflect the combined influence of competing processes acting in different directions (Röthlisberger and Papritz 2023; Krauskopf and Huth 2024; Hamal and Pfahl 2025; Liu et al. 2025; Wang et al. 2025a).

Despite these limitations, DTD remains a valuable complementary tool to conventional climatological indicators because it provides information on daily temperature dynamics that is not captured by analyses of mean annual air temperature alone. The contrasting DTD behavior observed among the urban, peninsular, and insular stations demonstrates its value for identifying location-specific climatic characteristics, including differences occurring over relatively short distances. Considered together, mean annual air temperature and DTD therefore provide a more comprehensive representation of temperature behavior and its spatial variability under ongoing climate change.

4. Discussion

The results reveal a consistent distinction between the behavior of mean annual air temperature and annual DTD variability across the three environmental settings. Mean annual air temperatures exhibit statistically significant increasing trends and strong inter-station relationships, indicating a coherent regional warming signal. In contrast, annual DTD values show no statistically significant trends and considerably weaker relationships among stations. This indicates that long-term changes in temperature magnitude and changes in day-to-day temperature variability represent different aspects of the climate system and do not necessarily evolve synchronously. Previous studies have similarly demonstrated that DTD variability responds to a

range of controls, including synoptic circulation, seasonality, continentality and maritime influence, and local environmental and anthropogenic factors (Gough and Shi 2020; Kotz et al. 2021; Krauskopf and Huth 2024; Gough and Li 2024b; Gough 2025; Hamal and Pfahl 2025).

Comparison of the three environmental settings further emphasizes the complementary information provided by DTD. The consistently high inter-station relationships for mean annual air temperature indicate the importance of regional-scale forcing, whereas the substantially lower relationships for annual DTD demonstrate greater sensitivity to environmental setting and local processes. Geographic proximity therefore does not necessarily imply similar day-to-day temperature behavior. The results highlight the limitations of relying solely on mean annual air temperature as an indicator of climate change, as such an approach may obscure changes and spatial differences in short-term temperature dynamics that may also have implications for ecosystems, human health, and risk management.

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Despite these limitations, DTD remains a valuable complementary tool to conventional climatological indicators because it provides information on daily temperature dynamics that is not captured by analyses of mean annual air temperature alone. The contrasting DTD behavior observed among the urban, peninsular, and insular stations demonstrates its value for identifying location-specific climatic characteristics, including differences occurring over relatively short distances. Considered together, mean annual air temperature and DTD therefore provide a more comprehensive representation of temperature behavior and its spatial variability under ongoing climate change.

5. Conclusions and Future Research Directions

The analysis of mean annual air temperatures and annual DTD variability at nine climatological stations demonstrates that climate change in the studied region does not manifest uniformly but strongly depends on the environmental context – urban, peninsular, or insular. Across all three analyzed environmental settings, mean annual temperatures exhibit statistically significant increasing trends and strong inter-station

relationships. In contrast, annual DTD values show no statistically significant trends and considerably weaker relationships among stations, indicating that daily temperature dynamics are more strongly influenced by local and short-term processes and do not necessarily evolve synchronously with long-term warming. The contrast between coherent mean-temperature behavior and weaker DTD coherence is central to the results of the study.

In the urban environments of Belgrade, Zagreb, and Varaždin, strong increases in mean annual air temperature occur without statistically significant trends in annual DTD. Cities with higher levels of urbanization and greater thermal capacity exhibit a more stable daily temperature regime, reflecting the buffering effect of urban fabric and anthropogenic heat sources. Varaždin, as the smaller and less urbanized city in a more distinctly continental setting, exhibits greater DTD variability than the two larger urban centers, indicating greater sensitivity to synoptic changes and a weaker effect of urban stabilization.

On the Istrian Peninsula, the contrast among Pula, Pula Airport, and Pazin demonstrates that maritime influence, continentality, urbanization, and topography can produce substantial differences in daily temperature dynamics over relatively short distances. On the Adriatic islands of Lastovo, Hvar, and Lošinj, mean annual air temperatures exhibit the strongest spatial coherence, while annual DTD remains less synchronized despite the common maritime influence. These findings demonstrate that local environmental characteristics have a considerably stronger expression in day-to-day temperature variability than the regional long-term signal.

Overall, the results highlight the importance of not relying solely on mean annual air temperatures when characterizing climate change. DTD provides complementary information on short-term temperature dynamics and reveals spatial differences that may remain obscured when only long-term changes in mean annual air temperature are considered. The combined analysis of the two metrics therefore provides a more comprehensive representation of temperature behavior across contrasting environmental settings.

Future research should focus on identifying the relative contributions of the processes controlling DTD variability. Analyses at seasonal and other temporal scales, combined with examination of synoptic circulation, maritime influence, topography, surface characteristics, urbanization, cloud cover, humidity, and other meteorological controls, could help distinguish the mechanisms responsible for the observed differences among stations. Such analyses would further clarify how long-term warming and short-term temperature variability interact across different environmental settings and strengthen the application of DTD as a complementary climatological indicator.

CRediT authorship contribution statement

Author Contributions: Conceptualization, O.B.; methodology, O.B. and T.R.B.; software, O.B. and A.Z.C.; validation, A.Z.C. and T.R.B.; formal analysis, O.B. and T.R.B.; investigation, O.B. and A.Z.C.; data curation, O.B. and A.Z.C.; writing—original draft preparation, O.B.; writing—review and editing, A.Z.C.; visualization, O.B. and A.Z.C.; supervision, T.R.B.; project administration, T.R.B.

Data availability

The meteorological data used in this study were provided by the Croatian Meteorological and Hydrological Service (DHMZ) upon request for scientific research purposes. The original data are available directly from DHMZ upon request through its data request service: https://meteo.hr/proizvodi.php?param=zahtjev_podaci_usluge§ion=katalog_zahjtevi&utm.

Declaration of interest

The authors declare no conflict of interest.

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