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Spatial and Temporal Changes of Diurnal Temperature Range in Greece—The Urban Effect †

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Abstract: Diurnal Temperature Range (DTR), defined as the difference between the daily maximum (T_{max}) and daily minimum (T_{min}) air temperature, has received considerable attention as an important indicator of climate change. In the present study, we analyse long-term highly homogenized DTR data from 51 Greek stations and investigate their spatiotemporal changes. The long-term temporal changes of DTR revealed mixed patterns with both increasing and decreasing trends over the study period and distinct seasonal differentiations. DTR pattern in Athens has fluctuated since the beginning of the twentieth century, generally following warming and cooling air temperature trends. After the mid-1980s, DTR showed a pronounced decreasing trend at a rate of 0.47 °C/decade in summer ($p < 0.01$) due to higher warming rates of T_{min}, suggesting the combined effects of regional warming and urbanization levels.

Keywords: climate change; regional warming; diurnal temperature range; Greece; trend; urban heat island

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1. Introduction

Diurnal Temperature Range (DTR), defined as the difference between the daily maximum (T_{max}) and daily minimum (T_{min}) surface air temperature, has received considerable attention as an important indicator of climate change and variability [1–4]. Long-term changes and trends in DTR reflect asymmetrical warming or cooling rates between T_{max} and T_{min}, likely resulting from changes in cloudiness, sunshine duration, atmospheric aerosol loading, and other factors [3,5]. Besides its strong impact on ecosystems, DTR also affects human health [6,7].

Recent research studies suggest a decreasing trend in DTR globally since the beginning of the twentieth century. This pattern was more evident after the 1950s but with marked spatial differentiation [1,2]. Different regions worldwide have also reported seasonal differences in DTR as well as contrasting trends between natural and populated sites [5,8–10].

In the present study, we analysed long-term data from 1960 to 2022 of highly homogenized daily maximum and minimum air temperature in 50 Greek stations of the Hellenic National Meteorological Service (HNMS) and the National Observatory of Athens (NOA) historical climate station. We also investigated spatiotemporal DTR changes in Greece. Marked spatial and seasonal differences in mean DTR over the study period were found across the country, reflecting the specific climatic features of each Greek region. We estimated both increasing and decreasing long-term trends in DTR, considering seasonal changes and geographical area.

2. Materials and Methods

In this study, we used homogenized time series of T_{max} and T_{min} (1960–2022) from 50 weather stations of the HNMS and the NOA's historical climate station. Table 1 includes the names and altitudes of the stations. The stations' locations according to the numbering of Table 1 are indicated in the map included in Section 3.2 (below). The selected stations are distributed across Greece, representing almost all geographical areas of the country. Greece is characterized by an impressive variety of local climates. Climate conditions in Greece are modulated by numerous factors, such as topography, proximity to the sea, local circulations, and levels of urbanization. Following the procedure of Mamara et al. [11], we classified the selected stations into seven geographical areas according to their location or other features: (a) Northern Greece (stations 1–6 in Table 1); (b) semi-mountainous stations of the Greek mainland and Peloponnese (stations 7–10, 21, 29); (c) Western Greece (11–20); (d) Mainland Central Greece (22–33); (e) North and Central Aegean (34–41); (f) South Aegean (42–48); and (g) East Aegean (49–51).

Table 1. The names and altitudes of the selected stations. The numbering of the stations indicates their locations on the map included in Section 3.2.

Station Name (Altitude, m)	Station Name (Altitude, m)	Station Name (Altitude, m)	Station Name (Altitude, m)
1. Alexandroupoli (4)	14. Argostoli (22)	27. Tanagra (140)	40. Santorini (100)
2. Chryssoupoli (5)	15. Araxos (12)	28. Aliartos (110)	41. Kythira (167)
3. Drama (104)	16. Andravida (15)	29. Desfina (590)	42. Kasteli (10)
4. Serres (35)	17. Zakynthos (1)	30. Lamia (17)	43. Souda (151)
5. Macedonia (5)	18. Pyrgos (36)	31. Agxialos (15)	44. Rethymno (5)
6.Trik. Hmathias (50)	19. Kalamata (11)	32. Trikala (110)	45. Iraklio (39)
7. Florina (695)	20. Methoni (52)	33. Larissa (74)	46. Ierapetra (10)
8. Kastoria (700)	21. Tripoli (652)	34. Limnos (3)	47. Sitia (115)
9. Kozani (626)	22. Pireas (5)	35. Skyros (20)	48. Rhodes (12)
10. Ioannina (485)	23. Elefsis (31)	36. Naxos (10)	49. Samos (7)
11. Corfu (4)	24. Helleniko (15)	37. Paros (15)	50. Chios (5)
12. Aktio (4)	25. NOA (107)	38. Mykonos (50)	51. Mytilini (5)
13. Agrinio (25)	26. Tatoi (235)	39. Milos (165)	

The temperature series were homogenized using the relative homogenization method Climatol developed by the Spanish State Meteorological Agency (AEMET) [12]. In this method, stationarity tests are applied not to individual series, but to series of ratios or differences between the station under study and one or more reference stations. The R programming language is used to implement this methodology. We used Climatol 2.1 (AEMET, Balearic Islands Office, Palma, Spain) in this work. More details on the method are described in Mamara et al. [13].

Daily DTR values for each station were estimated as the difference between daily T_{max} and T_{min}, and mean monthly, mean seasonal, and mean annual DTR values over the study period were estimated from the daily DTR values. DTR values for each climate zone (area-averaged) were estimated by averaging the DTR from all stations belonging to particular climate zones.

Seasonal and annual trends in DTR were estimated by linear regression analysis. We used Student's *t*-test to determine the statistical significance of the results.

3. Results

3.1. Spatial and Intra-Annual Variability of DTR

Figure 1 illustrates the intra-annual variability of DTR for different climate zones in Greece (area-averaged) based on the mean monthly DTR values during the study period. Different DTR magnitudes and divergent patterns in intra-annual variability between climate zones confirm that DTR index accurately captures and highlights the special features and local climate conditions of each geographical area. In all cases, lower DTR values correspond to the coldest season, while higher values correspond to the warmest season. Mean DTR in the summer months exceeds 15 °C in mountainous areas (17 °C in Florina) but is close to 7 °C in the Central Aegean. However, the magnitude of the intra-annual variability (difference between the higher and lower mean monthly DTR annually) ranges between 6.8 °C (area-averaged) in mountainous stations (8.0 °C in Florina) and 2.59 °C in the Aegean islands (1.37 °C in Kythira).

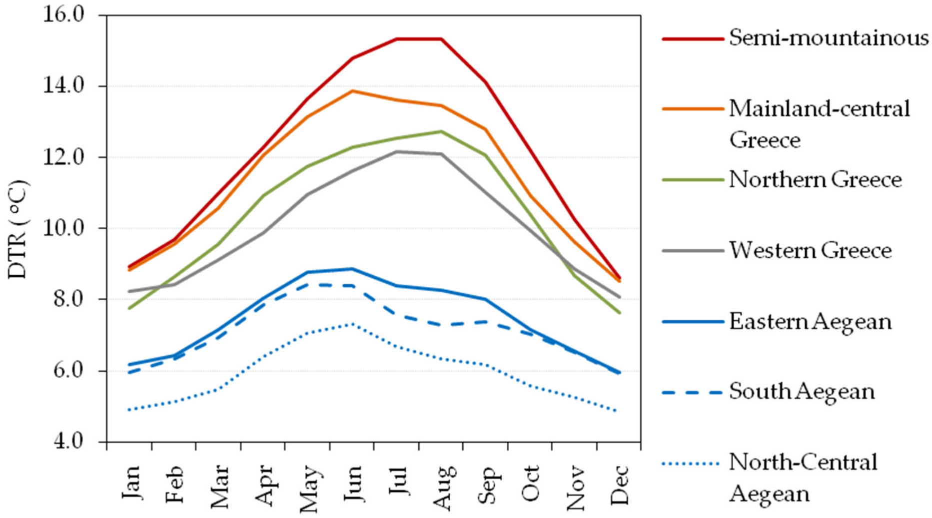
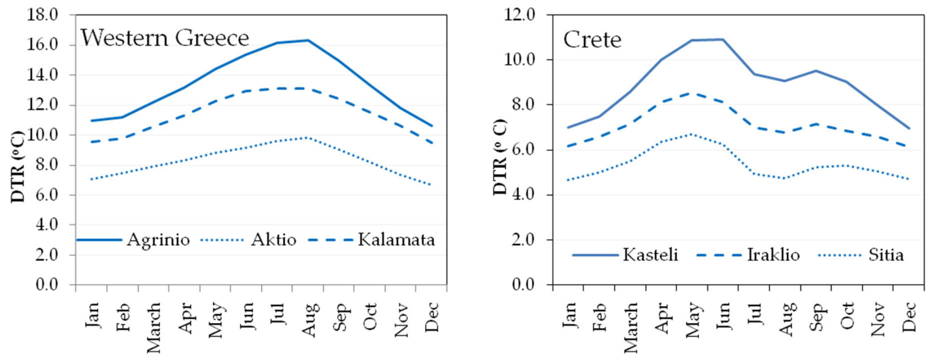


Figure 1. Area-averaged variability of mean monthly DTR in different climatic zones (1960–2022).

In addition to the observed differences in DTR magnitude between the climatic zones, monthly variability patterns present some distinct features between the different zones (Figure 1). In the mountainous areas, as well as in Northern and Western Greece, higher DTR values occur in late summer (August). By contrast, the islands' monthly variability of DTR displays a rather fluctuating pattern (consistent across the Aegean), peaking in early summer (June), followed by a sharp decline in July and August, especially in the South Aegean. This pattern is likely due to the influence of Etesian winds, which are particularly strong during daytime in the Aegean from July to August and disproportionately affect daily maximum and minimum temperatures.

Stations belonging to the same climatic zone may have different DTR values depending on their proximity to the sea and other local factors, despite having similar intra-annual variability patterns. This is for instance the case between Aktio (coastal station) and Agrinio (inland station) of Western Greece (Figure 2a), or the stations of Crete (South Aegean) where DTR decreases considerably as we move from western (Kasteli) to eastern stations (Sitia), while maintaining the same fluctuating pattern of the intra-annual variability (Figure 2b).



(**a**) (**b**)

Figure 2. Mean monthly DTR variability (1960–2022) from selected stations in (**a**) Western Greece (**b**) South Aegean (Crete).

3.2. Long-Term Trends in DTR

Our analysis of long-term DTR trends revealed a mixed pattern across Greece. Positive and negative trends during the study period were highly dependent on the season and geographical area. The annual DTR showed a negative trend at 30 stations (statistically significant at 13) and a positive trend at 24 stations. Only six of the trends were statistically significant. Nevertheless, DTR trends exhibited marked seasonal differences, with most stations experiencing increasing DTR in spring (40 stations, 14 of which were statistically significant) and winter (33 stations, seven of which were statistically significant), especially in mountainous areas, with increasing rates of up to +0.35 °C/decade. By contrast, most stations undergo decreasing DTR in summer (31 stations in total, 12 of which were statistically significant) at rates of up to −0.25 °C/decade, which was more evident in Crete. Nevertheless, the most prominent and consistent trends across the stations concern those observed in autumn. Specifically, DTR showed a decreasing trend in the vast majority of stations (43 stations in total) in autumn and was statistically significant in half (Figure 3). In most stations, decreasing DTR rates in autumn ranged between −0.23 and −0.09 °C/decade, with higher values in the South Aegean.

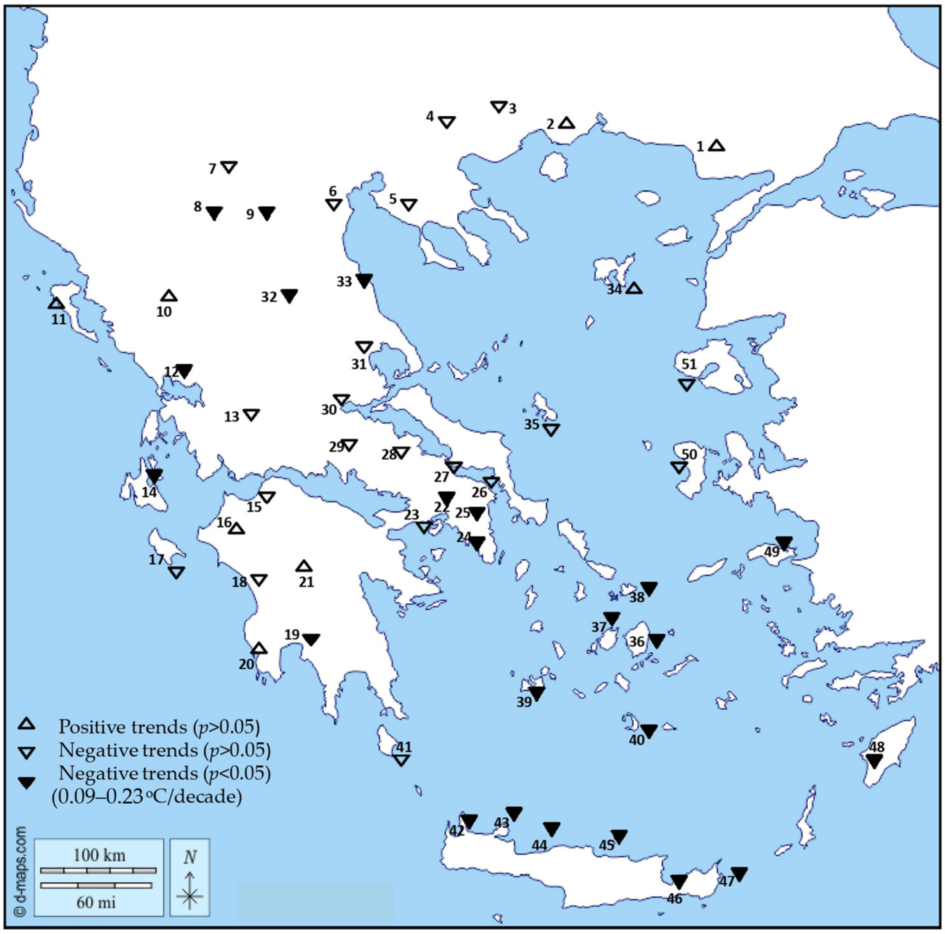


Figure 3. Long-term DTR trends during autumn (1960–2022) at selected Greek stations. Upward/downward no-fill triangles denote positive/negative trends that are not statistically significant. Downward filled triangles denote statistically significant ($p < 0.05$) negative trends. The numbers in the figure indicate the locations of the stations shown in Table 1.

In general, the South and Central Aegean experience negative trends in DTR during all seasons. However, populated areas such as Athens, Iraklio, and Larissa present higher and statistically significant trends in DTR during summer. In particular, DTR in Athens has fluctuated since the beginning of the twentieth century, following general warming and cooling trends in air temperature (not shown). After the mid-1980s, DTR had a pronounced decreasing trend at a rate of 0.47 °C/decade in summer ($p < 0.01$) due to higher warming rates in T_{min} than in T_{max}, suggesting the combined effect of regional warming, urbanization levels and urban heat island effect, and other factors.

4. Discussion and Conclusions

We analysed DTR using highly homogenized air temperature datasets from several Greek stations over a long period (1960–2022). We discovered that DTR indexes vary spatially and temporally across Greece. Striking differences in the magnitude and pattern of DTR's intra-annual variability between geographical areas demonstrate its unique reflection of each climate zone's local features.

Despite evidence of decreasing DTR globally, long-term trends on a regional scale suggest that DTR trends depend on the season and each region's geographical features (e.g., natural or urban sites) [5,8,9]. Our analysis of long-term DTR trends from Greek stations showed asymmetrical seasonal changes, with a tendency to increase in spring and winter and decrease in summer and autumn. The South and Central Aegean, as well as urban stations, had the most pronounced decreasing trends in summer and autumn, whereas mountainous areas had increasing DTR in winter, consistent with other research studies [8,9].

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

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