environmental sciences proceedings

Proceeding Paper

Analysis of Current and Future Heating and Cooling Degree Days over Greece Using Observations and Regional Climate Model Simulations †

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† Presented at the 16th International Conference on Meteorology, Climatology and Atmospheric Physics—COMECAP 2023, Athens, Greece, 25–29 September 2023.

Abstract: Heating and Cooling Degree Days (HDD, CDD) are indicative of the energy needs of buildings and also are associated with agriculturalism, tourism and other outdoor activities. Under the changing climate, future modifications of HDD and CDD are of primary importance. In the present work, monthly and annual HDD and CDD are computed and analyzed for the present and near future climate conditions. Elevation and sea proximity were found to be crucial in the formulation of energy requirements. Summer energy needs for cooling are expected to increase due to global warming while winter needs for heating are expected to decrease.

Keywords: HDD; CDD; weather stations; EURO-CORDEX; climate change; energy

Citation: Karagiannids, A.; Lagouvardos, K.; Kotroni, V.; Galanaki, E. Analysis of Current and Future Heating and Cooling Degree Days over Greece Using Observations and Regional Climate Model Simulations. *Environ. Sci. Proc.* **2023**, *26*, 149. https://doi.org/10.3390/environsciproc2023026149

Academic Editors: Konstantinos Moustris and Panagiotis Nastos

Published: 1 September 2023

1. Introduction

Heating and Cooling Degree Days (HDD and CDD respectively) are indicators of the energy needs of buildings, if comfortable conditions for humans are to be achieved inside the buildings. They can also be considered as associated with deviations from the optimum conditions for outdoor activities like agriculture and tourism. Monthly and annual HDD and CDD for the present and near-future climate conditions have been computed and analyzed.

Various studies exist on the computation and analysis of HDD and CDD in Greece. For example, Matzarakis and Balafoutis [1] studied the geographical distribution of HDD in Greece using weather station data and showed that the heating needs are higher in Northern Greece, while they decrease from north to south and from the mainland to the islands. Psiloglou et al. [2] compared the characteristics of electricity demand for London, UK and Athens, Greece and also explored its relationship to climate- and non-climate-related factors. They used electrical energy consumption data, weather stations data and also gross annual product data. Regarding the electrical energy needs, they showed that these peak during winter, due to the increased need for heating while for Athens, a second peak during summer exists, which is related to the increased needs for cooling. They also showed that the relationship between electricity demand and air temperature is not linear. To assess the HDD and CDD and the related influence of urbanization within the greatest Athens area, Moustris et al. [3] used weather station temperature data. They concluded that the annual number of CDD is almost sevenfold higher in the city center compared peripheral areas and also that the annual number of HDDs at the peripheral areas is about threefold higher than the number of HDDs in the city center. Kyriakopoulos et al. [4], using temperature data from urban and rural weather stations in the Patras and Kalamata cities (both in Southwestern Greece), identified the influence of the urban heat island in the heating and cooling energy needs of these cities.

The aim of the present study is to identify (i) topographical features that influence HDD and CDD and (ii) the changes in HDDs and CDDs in the near future under the changing climate. Section 2 presents the data and methods used while Section 3 illustrates the main results of the study. Finally, Section 4 summarizes the main conclusions.

2. Data and Methods

2.1. Data

Daily minimum and maximum temperature data from 5 automated weather stations in the Athens area and 1 in the Trikala area were used to compute daily and subsequently monthly HDD and CDD values. The weather stations are part of the National Observatory of Athens network of automated weather stations [5] and the data used here are presented in the Table 1, while their locations are shown in Figure 1.

Table 1. Weather stations and period of data.

Weather	Period of Data
Athens center	January 2010–December 2021
Maroussi	February 2010–December 2021
Faliro	April 2012–December 2021
Peristeri	December 2012–December 2021
Kantza	January 2010–December 2021
Trikala	January 2010–December 2021

Figure 1. Locations of Athens and Trikala area weather stations.

For the analysis of future variations of HDD and CDD over the Greek area, daily minimum and maximum temperature data derived from the EURO-CORDEX database [6] are used. 11 km horizontal resolution data, corrected using the MESAN data package [7] covering the 2023–2030 period were extracted and analyzed. Initially, 5 Global Climate Models (GCMs) and 6 Regional Climate Models (RCMs) data were downloaded. After comparing them to weather stations data for consistency, it was decided to include in the analysis only the data derived from the Global / Regional model combinations HadGEM2-ES/RC4A, HadGEM2-ES/RACMO22E and MPI-ESM-LR/RCA4.

Climate models provide estimates for different climate scenarios. They simulate the complex processes and interactions that affect climate and also use data of anthropogenic effects on climate. Different anthropogenic activities such as socio-economic, technological and environmental development are described in climate models as equivalent changes in greenhouse gas concentrations but also as changes in land use. For the present study, data from 2 Representative Concentration Pathways (RCPs) were used, which differed in the flow of energy in the atmosphere caused by natural or anthropogenic factors (Radiative Forcing-RF): (a) RCP4.5 is a stabilization scenario that assumes global annual greenhouse gas emissions peaking around 2040 and then decline due to emissions mitigation policies, leading to RF = 4.5 W/m^2 in 2100. (b) RCP8.5 is a scenario that does not include a specific mitigation target for greenhouse gas emissions leading to an RF increase to 8.5 W/m^2 in 2100.

Average annual values of HDD and CDD were calculated for the period 2023–2030 and also for the Reference Period (RP) 1991–2020. Deviations from RP were finally computed in order to estimate the future trends of HDD and CDD for both emission RCPs.

2.2. Methods

The definition of degree-days was based on the hypothesis that if the ambient temperature is equal to a base temperature (T_{base}) there is no need for heating or cooling of the buildings. One degree-day suggests that the average ambient temperature is one degree higher or lower than T_{base}. The monthly or annual sum of degree-days (HDD or CDD) is proportional to the energy required to heat or cool a building [8] for a month or a year respectively.

Certain variations in HDD and CDD computation can be found in the literature. The formulae presented by Spinoni et al. ([9,10]) and the Met Office and were adopted by the European Environmental Agency were applied here. Maximum and minimum daily temperature (T_{max} and T_{min} respectively) and also the average daily temperature (T_{aver} = (T_{min} + T_{max})/2) were needed for their computation. The base temperature (T_{base}) was set to 18 °C. Tables 2 and 3 illustrate the formulae of computation of daily HDDs and CDDs. Monthly and annual values can be produced using a simple summation of daily values.

Table 2. Computation formulae of daily HDD.

Temperature Criterion	HDD
$T_{max} \leq T_{base}$	HDD = $T_{base} - T_{aver}$
$T_{aver} \leq T_{base} \leq T_{max}$	HDD = $[(T_{base} - T_{min})/2] - [(T_{max}\text{-}T_{base})/4]$
$T_{min} \leq T_{base} \leq T_{aver}$	HDD = $(T_{base} - T_{min})/4$
$T_{min} \geq T_{base}$	HDD = 0

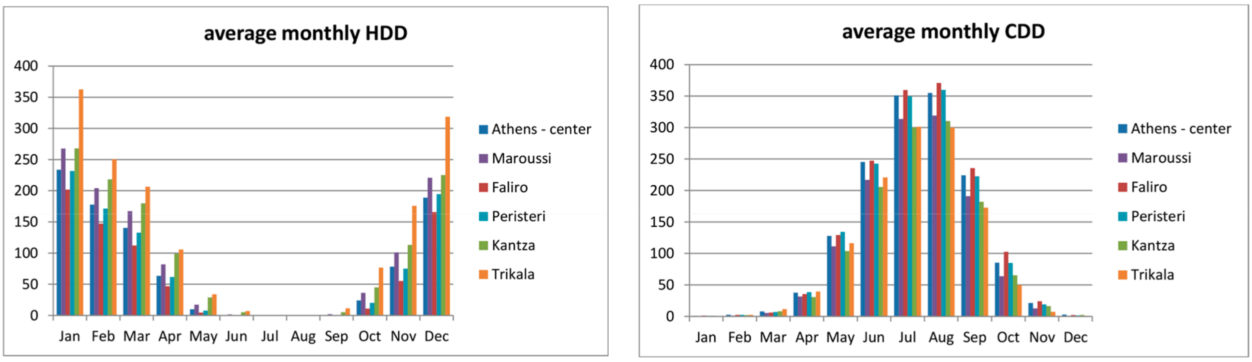
Table 3. Computation formulae of daily CDD.

Temperature Criterion	CDD
$T_{max} \leq T_{base}$	CDD = 0
$T_{aver} \leq T_{base} \leq T_{max}$	CDD = $(T_{max} - T_{base})/4$
$T_{min} \leq T_{base} \leq T_{aver}$	CDD = $[(T_{max} - T_{base})/2] - [(T_{base} - T_{min})/4]$
$T_{min} \geq T_{base}$	CDD = $T_{aver} - T_{base}$

3. Results

3.1. Current Conditions

The average monthly HDD and CDD that are computed for each of the weather stations are illustrated in Figure 2. Their number is zero or close to zero for the three summer months (June–August) and September, so no heating is required, while in May and October it is particularly low. The heating needs are maximized from December to March when colder conditions prevail, while the months of April and November can be characterized as transitional since the heating needs are relatively limited. The highest average monthly number of heating degree days is found in Trikala for January and is equal to 362.6, while for the Athens area, the higher average monthly number of heating degree days is found in Kantza for January and it is equal to 268.0.



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

Figure 2. Average monthly (**a**) HDD and (**b**) CDD for the Athens and Trikala weather stations.

Regarding the differences in energy requirements between the five Athens area stations, (a) the smallest requirements exist in the area of Faliro, probably due to the effect of the sea that maintains the minimum temperatures at higher levels compared to the rest of the areas that are further away from the sea (b) the highest requirements exist in the regions of Kantza and Maroussi, a fact that can be attributed to the higher altitude of these regions, which results in the prevalence of generally colder conditions. The Trikala station presents higher HDD values than those of the Athens area throughout the year, a fact associated to (a) the weaker urban heat island effect and (b) the practically non-existent influence of the sea on the temperature conditions of the city.

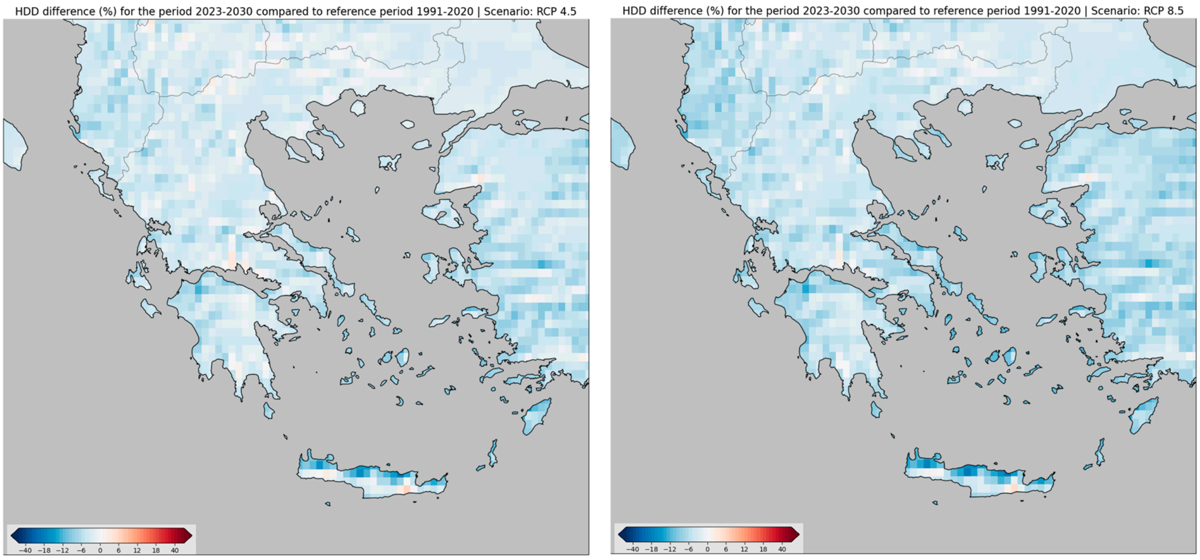
This number of average monthly CDD is zero or close to zero during the period December–March due to the low temperatures that prevail, while during November and April it is very low. Cooling needs are maximized in July and August, while in June and September they are also quite high. During October and May, there is a need for cooling, but it is relatively limited. The maximum monthly number of cooling degree days was recorded in Faliro in August and was equal to 370.7.

Regarding the differences between the five Athens stations, the cooling energy requirements seem to be partially reversed compared to the heating energy requirements. The smallest cooling requirements are found in Kantza and Maroussi, where the higher altitude leads to generally lower temperatures. Trikala cooling needs are comparable to the two higher-altitude Athens stations, namely Kantza and Marousi.

3.2. Future Conditions

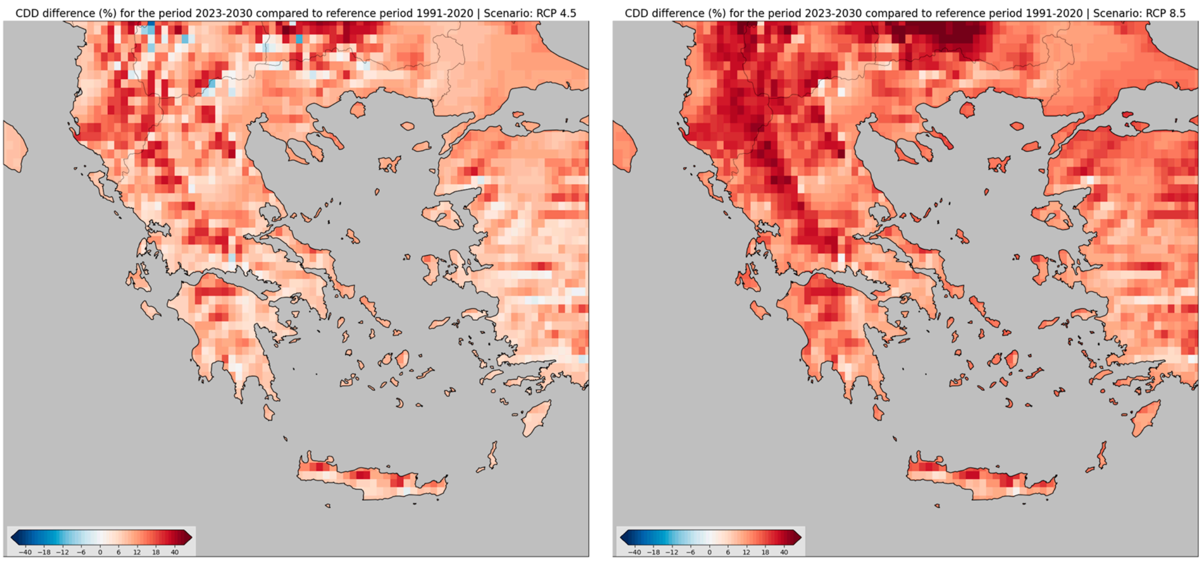
Figure 3 presents maps of average annual HDD deviations under RCP4.5 and RCP8.5 for the period 2023–2030 compared to the RP. Figure 4 is similar except for CDD. The prevailing trend for the period 2023–2020 is the reduction of HDD which, of course, fluctuates between scenarios and regions. The largest relative decrease for both RCPs is found at the northern parts of Crete (16.6% and 18.3% for RCP4.5 and RCP8.5 respectively). A few areas of relative increase are noted, distributed all over the country.

Regarding CDD, the prevailing trend is an increase which fluctuates between scenarios and regions. The largest relative increases are found in regions of high elevation. The absolute maximum increase is 37.4% and 52.6% for RCP4.5 and RCP8.5, respectively. A few areas of relative decrease are noted for RCP4.5, distributed all over the country.



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

Figure 3. Average annual HDD difference for the period 2023–2030 compared to the reference period 1991–2020 for (**a**) RCP4.5 and (**b**) RCP8.5.



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

Figure 4. Average annual CDD difference for the period 2023–2030 compared to the reference period 1991–2020 for (**a**) RCP4.5 and (**b**) RCP8.5.

4. Conclusions

The analysis of the current conditions revealed that

- Heating needs are higher during the period November–March and peak in January, while cooling needs are higher during the period June–September and peak in July and August;
- Higher heating needs and lower cooling needs are found in higher altitudes areas and less intense urban heat islands;
- Proximity to sea results in lower heating needs.

Regarding the future energy needs, according to the analyzed models and scenarios

- HDDs (CDDs) are expected to decrease (increase) in general, in agreement with the expected ambient temperature increase due to climate change. Thus, cooling energy needs are expected to increase while heating energy needs are expected to decrease;
- The higher relative HDD decrease is expected in North Crete while the higher relative CDD increase is expected in high-elevation areas;
- The CDD relative increase appears to be greater than the relative decrease in HDD.

Author Contributions: Conceptualization, A.K., K.L. and V.K.; methodology, A.K., K.L. and V.K.; software, A.K. and E.G.; validation, A.K., K.L. and V.K.; formal analysis, A.K., K.L. and V.K.; investigation, A.K.; resources, K.L. and V.K.; data curation, A.K. and E.G.; writing—original draft preparation, A.K.; writing—review and editing, A.K., K.L., V.K. and E.G.; visualization, A.K.; supervision, K.L. and E.G.; project administration, K.L. and V.K.; funding acquisition, K.L. and V.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Energy Competence Center (ECC).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Restrictions apply to the availability of some data. Data were obtained from the Institute of Environmental Research and Sustainable Development, National Observatory of Athens and the Coordinated Regional Climate Downscaling Experiment-WCRP CORDEX. Available online: https://esgf-node.ipsl.upmc.fr/search/cordex-ipsl/ (accessed on 28 April 2023).

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

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