INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **24**: 1817–1828 (2004)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/joc.1107

HEATING DEGREE-DAYS OVER GREECE AS AN INDEX OF ENERGY CONSUMPTION

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Received 27 January 2003
Accepted 13 May 2004

ABSTRACT

The geographical distribution of heating degree-days (HDDs) in Greece is studied by means of special maps. HDDs are calculated by using daily thermal parameters (daily maximum and minimum air temperature) and then compared with an experimentally determined basic air temperature equal to 14 °C, according to our estimations. These calculations are based on daily weather data of 40 meteorological stations of the Hellenic National Weather Service published in the *Monthly Climatic Bulletin*.

The regionalization of the 40-point stations' data was achieved using the multiple regression analysis technique and a digital terrain model. For the statistical analysis, the calculated HDDs provide the dependent variables, and geographical data of latitude and longitude, elevation, nearest grid distance from the sea and the land/sea ratio were the independent variables. The resultant statistical correlation was very high.

The final outcome of this study was the drawing up of 10 HDD maps, eight for the eight coldest months (October to May) in Greece, one for the entire cold period and one for the number of days demanding heating. The geographical distribution of HDDs is consistent with the great variety of Greek climates arising from the influence of the country's variable relief.

The distribution of the HDDs presented in the maps shows that the calculated values were close to the measured ones, which confirms the accuracy of the statistical model used. Possible small deviations were deemed to be acceptable, as the net of the stations used is sparse and it is limited to the elevations below 700 m above sea level. The high accuracy of the HDD maps will be useful for various energy projects and other environmental applications. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: heat degree-days; Greece; energy consumption

1. INTRODUCTION

The use of diesel or electric energy for indoor heating and the amounts of consumption depend on the prevailing weather conditions in the area of investigation and also on the season of the year. The term degree-days in its different expressions, i.e. heating degree-day (HDD) or growing degree-day, can be used for many investigations and assessments in applied climatology (Hargy, 1982; Yang *et al*., 1995; McMaster and Wilhelm, 1997; Roltsch *et al*., 1999; Cesaraccio *et al*., 2001).

Generally, a degree-day fixes the value that expresses the added temperature of the environment. It gives the value of quantity and duration when the air temperature becomes lower or higher than a determined threshold value, which is known as its basic temperature (Hitchen, 1981). In order to estimate heating costs, this value is given as the total deficit of outdoor air temperature in relation to the basic temperature.

The basic temperature, for the determination of HDDs, depends on the constructional specifications of buildings and their application in research (Allen, 1976; Hitchen, 1981; Hargy, 1982; Snyder, 1985; Driva,

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1998; Roltsch *et al*., 1999) and is expressed by means of the relationship

$$\text{Basic temperature} = \text{Desirable indoor temperature} - \frac{\text{Mean energy profit}}{\text{Total conductivity of building}}$$

In this study, the parameter of building conductivity is not taken into consideration, because the estimates reported concern all the Greek territory, where the architecture and the constructional techniques differ considerably from region to region.

The objective of this work is to determine with high precision the time periods where cheaper diesel is sold for heating purposes within the entire Greek area. A further objective is to define the energy requirements for heating in the various regions of the country.

In Greece, the duration of the heating systems' operation and the total amount of the HDDs varies from one location to the other, as the air temperature (apart from the prevailing atmospheric circulation conditions) depends strongly on geographical factors, such as latitude and longitude, altitude, distance from the sea, etc. Using the meteorological station data, the HDDs were calculated and regionalized by means of statistical methods. The main and final aim of the data processing was to construct HDD maps for Greece. This material is very useful for the calculation of energy demands and fuel consumption for heating purposes.

The aims of this paper are the description of the database, the methods applied and the analysis of the heating degree conditions according to the relevant maps, which have been constructed for this purpose.

2. MATERIALS AND METHODS

In order to calculate the energy requirements for indoor heating, we used a basic thermal unit called an HDD.

Daily values of HDDs can be obtained only by means of calculations. The HDD amount, for each day, expresses the differences between the air temperature and the basic temperature, when the basic temperature is higher than the air temperature. Many approaches and techniques to calculating HDDs can be found in the literature (e.g. Baskerville and Emin, 1969; Floyd and Braddock, 1984; Yang *et al*., 1995; McMaster and Wilhelm, 1997; Martinaitis, 1998). Simpler approaches use the mean daily air temperature compared with the basic temperature. A relatively more complicated way of determination, which was applied in the present study, is based on the comparison of the daily pattern of air temperature with the basic temperature.

The HDDs were calculated (Table I; HNWS, 1983–1987) based on the daily data of the maximum and minimum air temperatures collected from the 40 main stations of the Greek climate network (Figure 1) for the colder eight months (October–May). The short time periods used may lead to misleading data, though according to Court (1974) short time periods regarding daily air temperature data generate representative information for the patterns of an area. With experimental and empirical methods of trial and error, a value of 14 °C was fixed as the basic temperature T_b, which corresponds realistically to the requirements of the Greek territory. This value confirms the answers on a questionnaire that was filled in by householders in the most populated Greek cities regarding the starting and ending dates of the use of central heating units.

The calculation of HDDs has been carried out by means of different equations, depending on the relationship between the basic temperature T_b and the mean T_{mean}, minimum T_{min} and the maximum T_{max} daily air temperatures. These relations are given below.

If $T_b > T_{max}$, then the estimation is obtained from the relation

$$\text{HDD} = T_b - T_{mean} \tag{1}$$

where $T_{mean} = (T_{max} + T_{min})/2$ (this relation means that heating is required during the whole 24 h period).

If $T_b < T_{max}$, then three cases of calculation of HHD need to be specified, depending on the relation between T_b and T_{mean} Thus:

$$\text{HDD} = \frac{T_b - T_{min}}{2} - \frac{T_{max} - T_b}{4} \qquad \text{if } T_{mean} < T_b \tag{2a}$$

Table I. Latitude, longitude, elevation, total HDDs, length of the heating period and Julian days (start and end date) of the heating period at Greek stations for period 1983–87

Station	Code	Longitude (°)	Latitude (°)	Elevation (m)	HDD (°C/year)	Length (days)	End (Julian day)	Start (Julian day)
Agrinio		38.37	21.23	46	809	186	295	120
Alexandroupolis	2	40.51	25.57	3	1218	206	284	125
Argostolion		38.11	20.29	2	326	149	307	95
Arta		39.1	21	39	571	170	301	110
Athina		37.58	23.43	74	477	167	301	105
Chalkida		38.28	23.36	4	632	164	305	105
Chania		35.3	24.02	62	318	153	305	95
Chios	12	38.2	26.08	3	591	164	305	105
Florina	5	40.47	21.24	650	1748	217	274	125
Helliniko		37.54	23.44	10	488	166	303	105
Heraklio		35.2	25.11	38	300	152	307	95
Ierapetra		35	25.45	16	228	146	308	90
Ioannina	8	39.4	20.51	483	1337	206	284	125
Kalamata		37.04	22.06	6	573	170	305	110
Kavala	3	40.56	24.23	60	1197	191	287	115
Kerkyra		39.37	19.55	2	575	172	305	115
Korinthos		37.56	22.57	4	612	170	305	110
Kozani	6	40.18	21.47	625	1629	217	274	125
Kymi	11	38.38	24.06	222	851	179	298	115
Kythira		36.09	23	167	381	160	307	105
Larisa	9	39.38	22.25	73	1182	187	293	115
Limnos	7	39.53	25.04	13	873	178	301	115
Methoni		36.5	21.42	33	417	164	305	105
Milos		36.43	24.27	182	401	149	305	90
Mytilini		39.06	24.03	2	563	171	305	115
N. Philadelphia		38.03	23.4	136	669	170	301	110
Naxos		37.06	25.23	9	285	145	308	90
Orestias	1	41.49	26.31	43	1481	211	274	120
Patras		38.15	21.44	1	433	159	305	100
Rhodes	15	36.23	28.07	35	195	125	319	90
Samos		37.42	26.55	48	499	169	305	110
Serres	4	41.04	23.34	32	1166	196	284	115
Sitia		35.12	26.06	25	309	149	305	90
Skyros		38.54	24.33	4	530	159	305	100
Thera	14	36.25	25.26	213	288	146	308	90
Thessaloniki		40.31	22.58	4	1057	185	293	115
Trikala	10	39.33	21.46	112	992	188	291	115
Tripolis	13	37.31	22.24	661	1300	194	287	120
Volos		39.22	22.57	3	670	175	301	115
Zakynthos		37.47	20.53	3	504	165	305	105

$$\mathrm{HDD} = \frac{T_b - T_{min}}{2} \quad \text{if } T_{mean} > T_b \tag{2b}$$

$$\mathrm{HDD} = 0.0\,^{\circ}\mathrm{C} \quad \text{if } T_{mean} = T_b \tag{2c}$$

Values of HDDs obtained from these HDD relations were used for the construction of maps presenting the geographic distribution of the HDDs over the entire Greek area up to elevations of 2000 m. There was an issue of how to fit special statistical models in order to transfer specific information from point

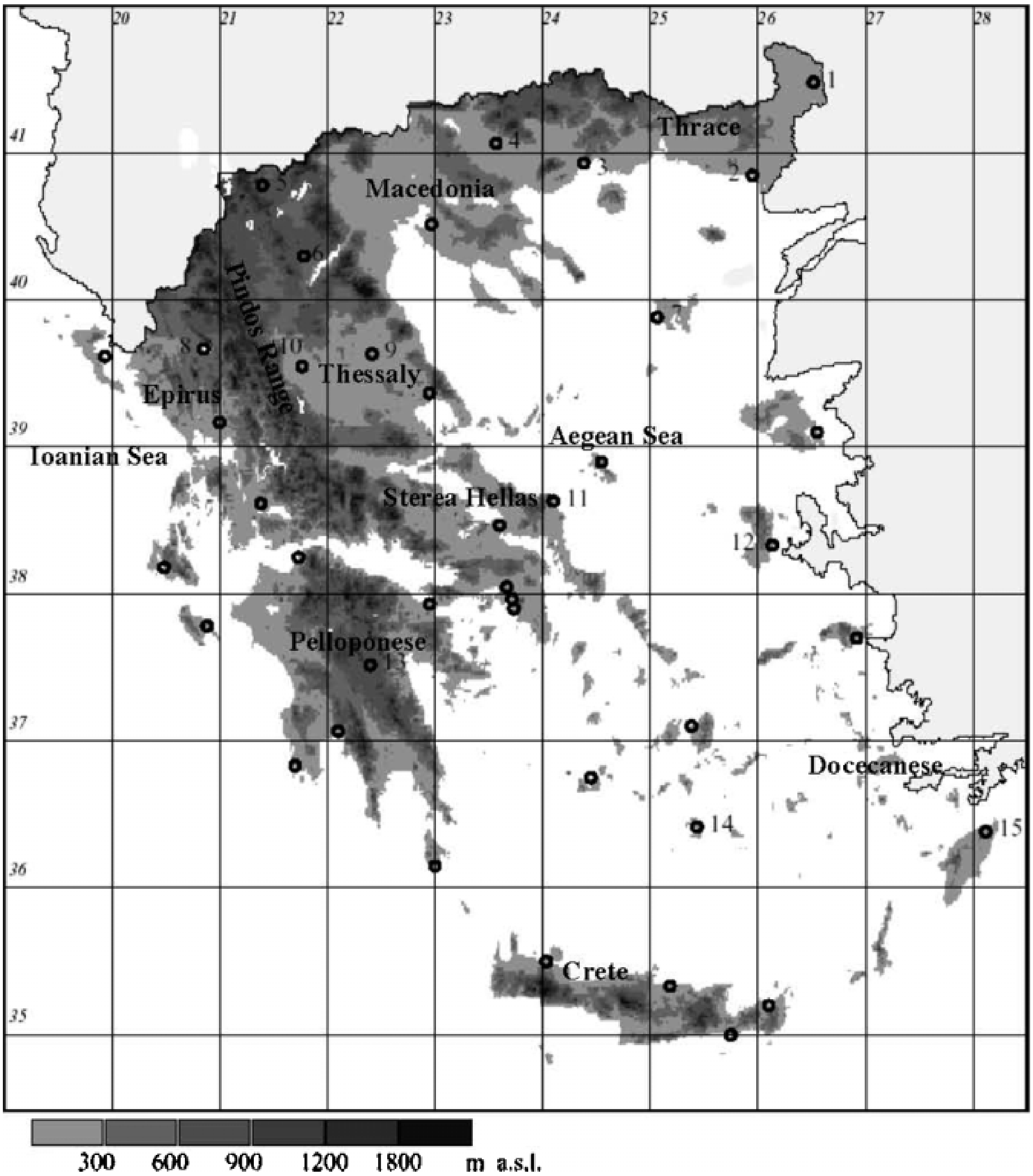

Figure 1. Topography and location of the climatic stations used (note: the numbers denote the stations referred to in the discussion)

observations (40 stations) in space. This was solved by using the method of multiple regression with the data of a topographic model of the Greek area (Figure 1), which was created in a previous study (Matzarakis, 1995) and applied in various climatic and bioclimatic studies in Greece (Matzarakis *et al*., 1998).

For the subsequent statistical analysis the calculated HDDs were regarded as the dependent variable. The independent variables were (Matzarakis, 1995; Matzarakis and Mayer, 1997) the magnitudes of:

- longitude
- latitude
- elevation above mean sea level

- shortest distance of each grid from the sea (as an indicator for continentality)
- a special factor of land/sea coverage (%) for an area around the grid point, within a diameter of approximately 40 km.

The resulting statistical correlation is very high, with a coefficient of determination R^2 oscillating from a low of 0.74, in May, to a high of 0.95, in December. The mean value of the period is 0.93.

3. RESULTS AND DISCUSSION

Analysing the calculated data from the previously reported relationships, we establish that the mean value of HDDs varies considerably from region to region. The highest value of HDDs (1748.4 °C) for the whole period is recorded in the mountainous city of Florina, located in northwest Greece (Figure 1, station no. 5). This value is almost nine times higher than the corresponding value of 195.4 °C observed on the island of Rhodes (station no. 15, in the southeastern Aegean Sea), where the minimal thermal requirements of the country are observed. This large difference in HDD values between Florina and Rhodes shows the intense contrast in the climatic characteristics between these two extreme geographic points; and it gives an idea about the energy demands, as a resident living in Florina should spend, roughly, nine times more on fuel in order to enjoy the same heating comfort as a resident living on the island of Rhodes.

High values were observed mainly in the stations of the northern hinterland, as in Kozani (no. 6, 1629.4 °C), Orestias (no. 1, 1481.1 °C), Ioannina (no. 8, 1336.5 °C) and Serres (no. 4, 1165.7 °C). Also, coastal stations, in northern Greece, e.g. Kavala (no. 3, 1197.3 °C) and Alexandroupolis (no. 2, 1217.7 °C), have high values of HDDs, denoting that the northern Aegean Sea does not act beneficially with regard to air temperature along the northern shores, as cold invasions from the Balkans are common in this area during the cold period. Larisa (no. 9, 1182.3 °C) and neighbouring Trikala (no. 10, 992.1 °C), both located in the centre of the low mainland, have considerably increased energy requirements, due to the intense topography of the Thessalian basin, which isolates the area from the sea's benefits. South, in Peloponnese, Tripolis (no. 13, 1300.3 °C) is considered as a very cold spot due to its high elevation and long distance from the sea.

As far the Greek islands are concerned, the highest energy requirements are estimated in Limnos (no. 7, 872.7 °C), where cold air masses coming from the Black Sea and the Balkans are frequent. South, in Kymi (no. 11, 851.5 °C), high energy consumption is required due to the northeasterly cold air current coming from the Black Sea. In Santorini (no. 14) and the coastal sites of Crete, low values were recorded, ranging between 200 and 300 °C. These values are slightly higher than those recorded on the island of Rhodes.

Based on the mean period values, as well as on the mean monthly values of each station, we constructed maps of the geographic distribution of the HDDs, and some of them are analysed below.

From Figure 2, in which the geographic distribution of the HDDs for the entire study period is given, we conclude the following. Regions with smaller heating demands are the lowland areas of the island of Crete, the Dodecanese islands, the Cyclades, the coastal regions of Peloponnese, central Greece, the southern Ionian Islands, as well as many parts of the low-altitude hinterland. A slightly higher consumption of energy is observed in the other Greek islands. A high energy requirement (HDD $>$ 1000 °C) is needed in the highlands of Peloponnese, the mountainous western mainland, the Thessaly basin (except the coastal regions), the lowlands of Macedonia, and Thrace. The coasts of the Thermaikos Gulf demand less heating energy consumption. The most energy-consuming region, with HDD $>$ 1600 °C, is western Macedonia, which is noted as being the cold pole of Greece. Also, very high energy requirements are recorded in the mountainous central and eastern Macedonia and in Thrace. This analysis yields a comprehensive description of the differences in thermal needs in the various regions of Greece.

However, of more practical interest is the annual variability of the seasonal march of HDDs in the various parts of Greece (these graphs are not included). Values of HDDs higher than 50 °C appear first in October (especially at the end of October) in the mainland. High values in the mountainous areas can be greater than 100 °C. In November, values lower than 50 °C are common in the southern mainland and the southern islands. In the rest of Greece heating is necessary, as the HDDs exceed 200 °C.

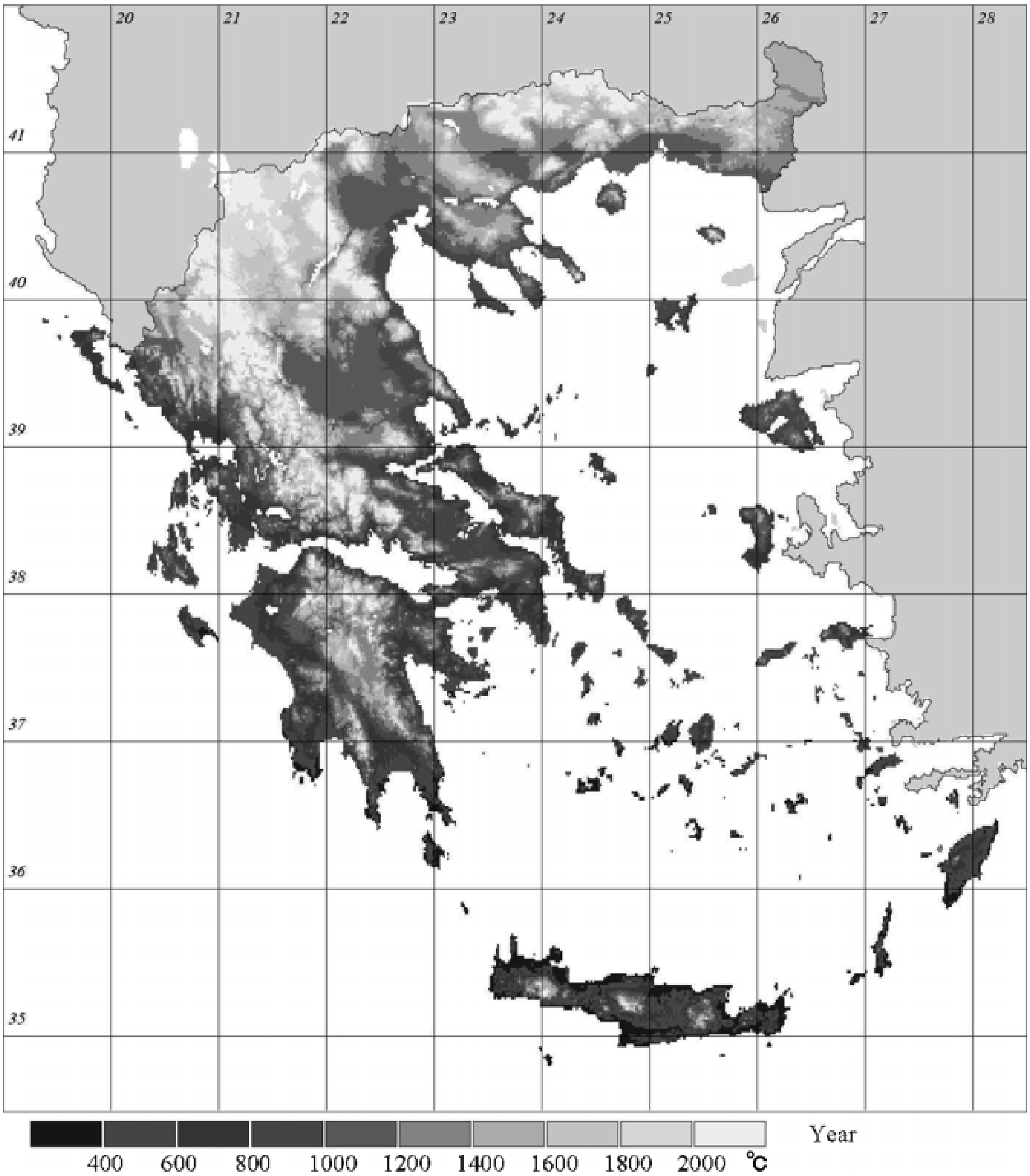

Figure 2. Geographical distribution of HDDs for the cold period of the year

During the coldest winter months (December to February) the geographic distribution of the HDD values is very similar, and thus the analysis of the geographical distribution for January (Figure 3) represents, with high precision, all the winter period. In January (and in the other two winter months) high energy requirements for heating (>300 °C) are observed over all western Macedonia, in the mountainous areas of central and eastern Macedonia and in Thrace, in the mountain range of Pindos, and to a smaller extent in the centre of the Peloponnese. The interior lowlands of northern Greece and Epirus, parts of the Thessalian plain, at the fringes of the mountains and elevated areas of the Peloponnese have relatively lower energy requirements, where the total amount of the HDDs ranges between 250 and 300 °C. The coastal regions of the mainland are characterized by milder conditions, and the monthly totals of the HDDs are limited to 200 or 250 °C.

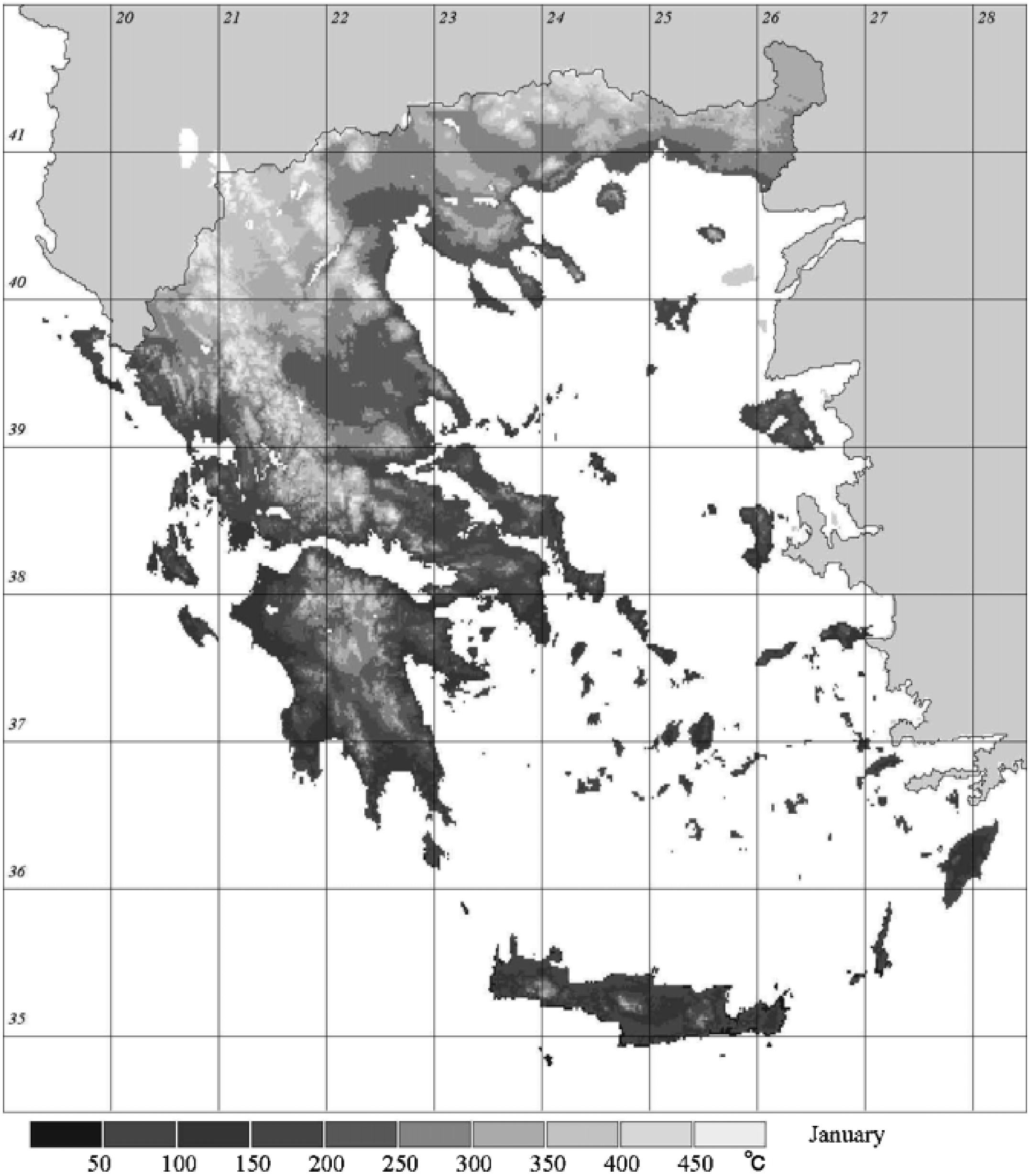

Figure 3. Distribution of the HDDs during January

Conditions that allow lower consumption of fuel are present, of course, in the island cluster of the southern Aegean Sea. Economic profit from the reduction of energy consumption is also enjoyed by all low-altitude regions of the Peloponnese, western Greece, the eastern coasts of central Greece, until the 39 °N parallel and, moving north, the peninsula of Kassandra. In March (map not presented) the geographic distribution of the HDDs is similar to that of January, but with a reduction in the absolute values of HDDs by at least of 50 °C in most of the country. In April the HDDs' values are lower than 200 °C in the entire country, except the higher mountain regions. Concerning the May pattern, the HDD values are lower than 50 °C in the regions where people live.

We propose an arbitrary monthly limit of 50 °C for HDDs below when heating is not required. The analysis of the maps in Figures 4 and 5, which present the beginning and the end dates (Julian days) of the heating period, reveals which regions have reduced requirements for heating and which regions continue consuming considerable fuel quantities. These estimations will help the authorities to identify those areas of the country where the distribution of cheaper heating diesel will continue to be needed.

Further analysis of these two relative maps (Figures 4 and 5) shows that the starting dates for heating demand appear first in the northern territory, close to the Bulgarian borders and especially in western Macedonia. In this part of the country the heating demands appear early in autumn, at Julian day 263 (20 September). In the mountainous range, crossing the country from north to south, the Julian day 275 (2 October) marks the start of the heating period. In the main plains of the country, located in north and central Greece, the heating demands appear after Julian day 285 (12 October). In the shores lying north of the 39 °N

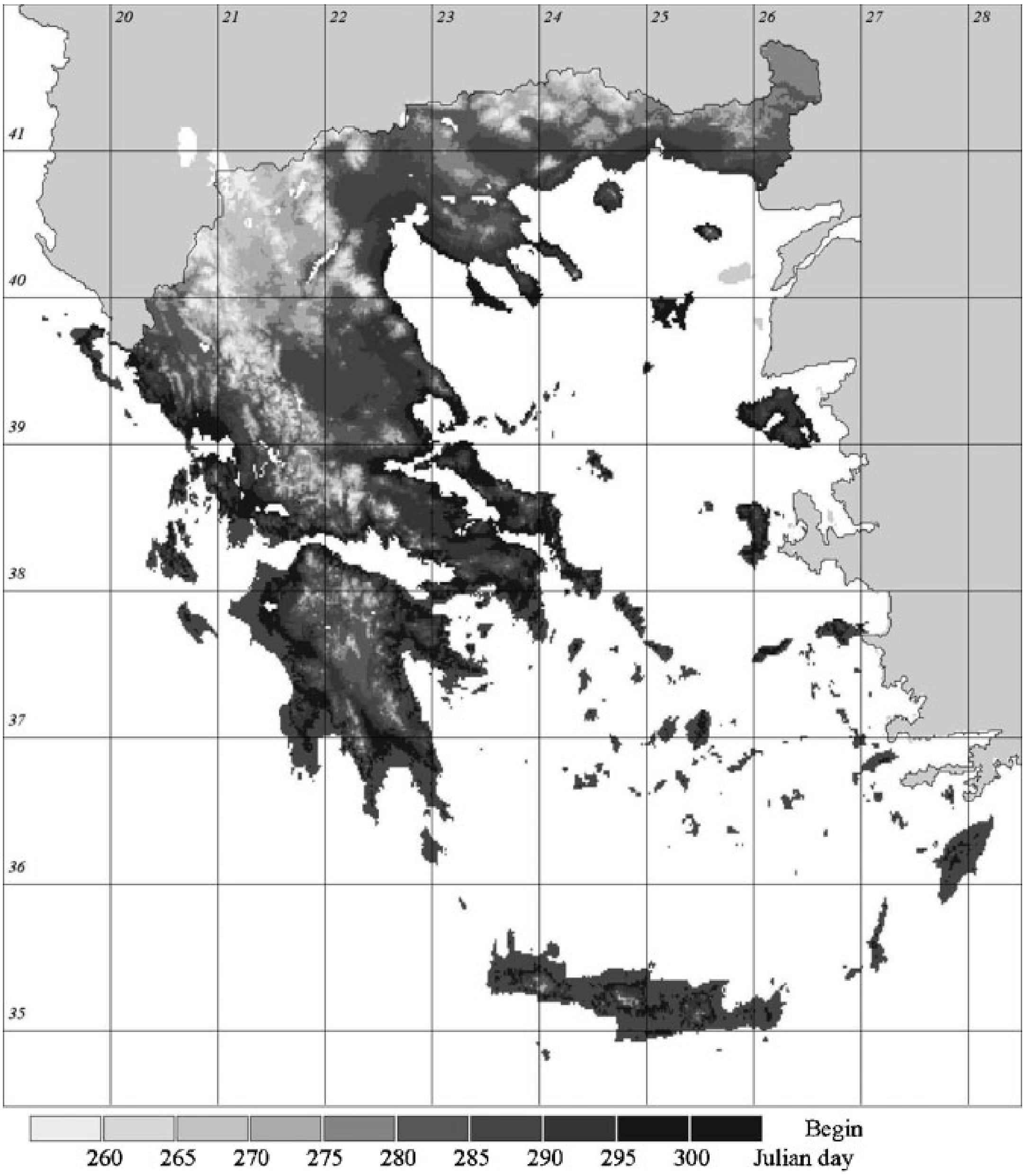

Figure 4. Start of heating period (in Julian days) over Greece

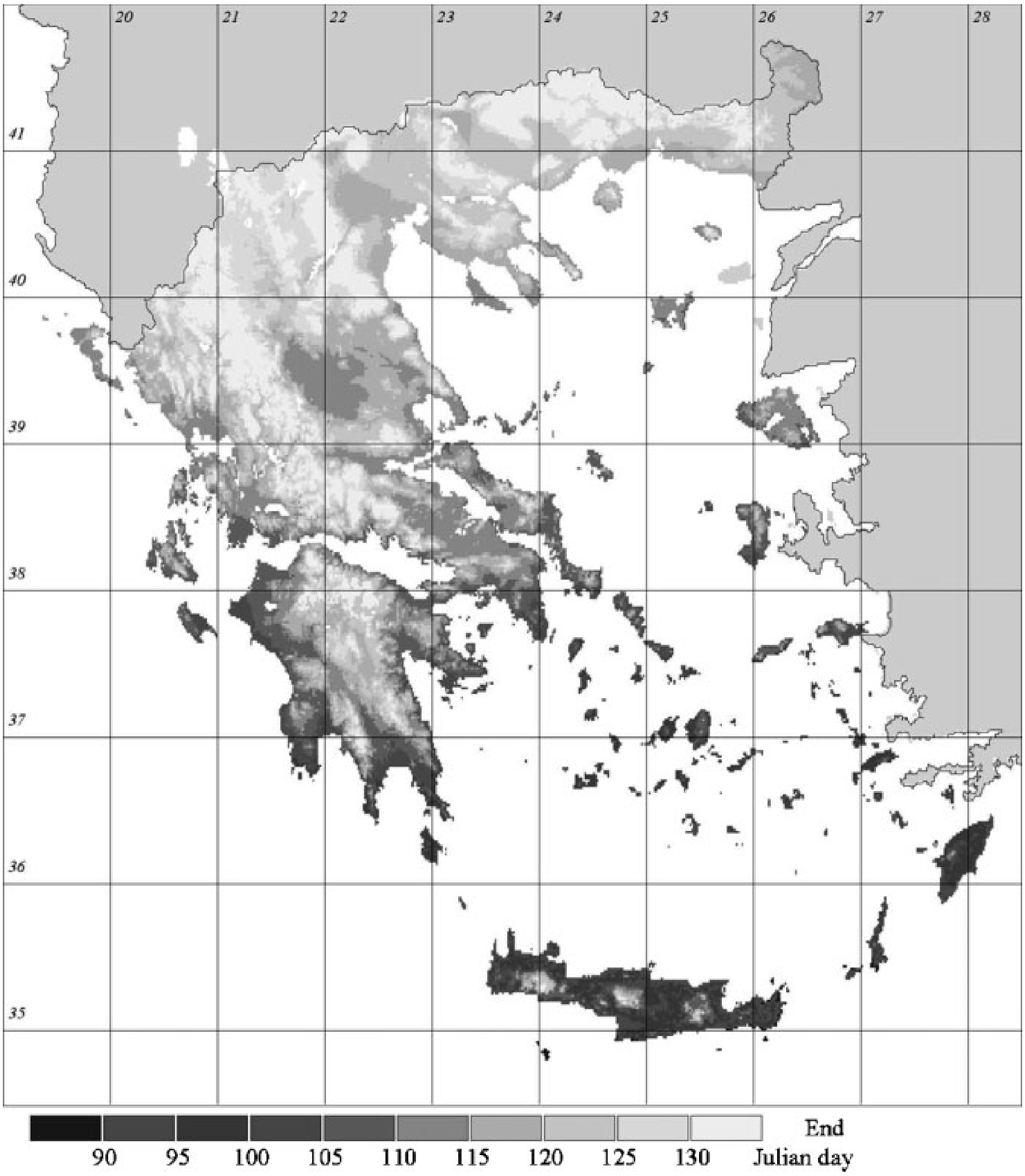

Figure 5. End of heating period (in Julian days) over Greece

parallel and in the northern Aegean Islands, the first heating date appears at Julian day 290 (17 October). Finally, Julian day 300 (27 October) marks the starting date of the heating period for the Ionian Islands, the southern shores of central Greece, the coastal area of the Peloponnese, the central and south Aegean Islands, the Dodecanese islands and the island of Crete.

Regarding the finishing time of heating, it is observed that, in southern Greece, Julian day 85 (26 March) marks the latest date for terminating heating, a value that exceeds Julian day 130 (10 May) in mountainous northern Greece. In the coastal areas, the Greek plains and the northern islands the heating period ends at around Julian days 110–115 (20–25 April).

Figure 6 gives the geographical distribution of the mean length in days when heating is required in Greece. The analysis of this map shows that the regions with the highest demand period for heating, greater than

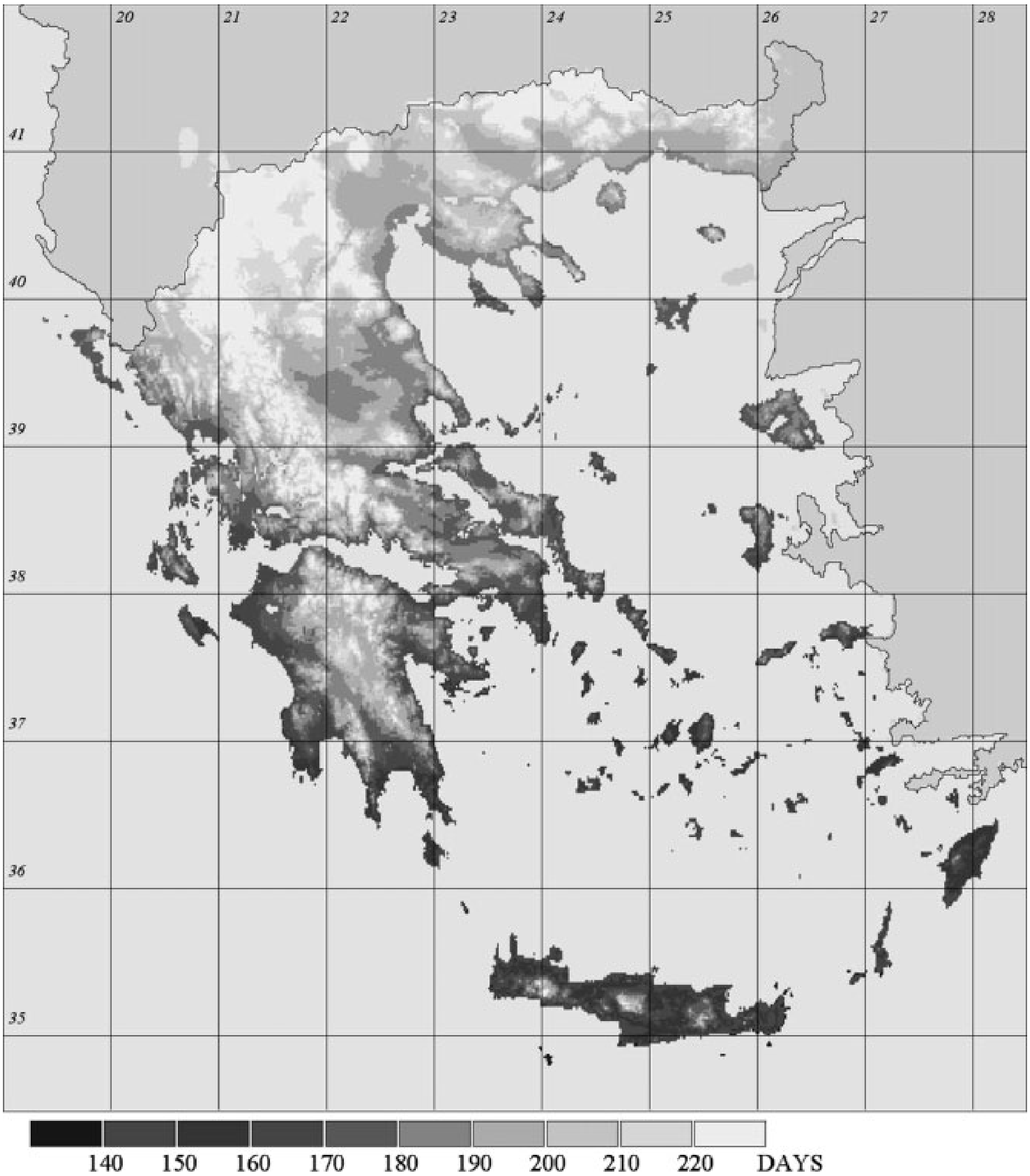

Figure 6. Total length, in days, of heating period over Greece

220 days, are located in northern Greece. Still, scattered spots with the same length were observed in the main part of Pindos range and the mountainous Peloponnese. The plains of Macedonia and Thrace present a period of 190–210 days for continuous heating. In the coastal regions and the plain of Thessaly, as well as in the northern islands in the Ionian and Aegean Seas, the length of the heating period varies from 170 to 190 days. A period of 150–160 days is observed along the northern Peloponnese coasts, on some of the Cyclades islands, in the Dodecanese islands and at Zakynthos Island. Reduced demand for continuous heating in the day is observed in the majority of the Cyclades islands, the coastal parts of Crete and the island of Rhodes, where the duration ranges from 130 to 150 days.

Generally, investigations in this field are rare. Some results from colder or arid climates are known from Şen and Kadioĝlou (1998). The paper of Büyükalaca *et al*. (2001) is also interesting, where the heating conditions in Turkey are analysed and their results are partly comparable with ours. They have found that the energy requirements for heating, in northeastern Turkey at an elevation of 1829 m, is 7.4 times higher in comparison with values recorded at Iskenderun, a place located in southeastern Turkey. The range of our results is also similar in value (nine times higher). Taking into account the geographical coordinates of two neighbouring stations at the same latitude, Chios (in Greece) and Izmir (in Turkey), both with the same latitude of 38.2 °N, the HDD amounts are 591 °C and 562 °C respectively. The small differences can be explained by the different period of estimation (in Turkey 15 years and in Greece only 5 years) and also due to the different method applied.

In northeastern Greece, in Orestias, a town very close to the Turkish border, the mean annual value of the HDDs was 1481 °C and in the town of Edirne (in Turkey), just a short distance from Orestias, the HDD value was 1403 °C, denoting that the results are again similar to ours.

5. CONCLUSIONS

HDDs provide an excellent tool regarding the quantity of energy demand in any region. We conclude from an analysis of the maps constructed that higher fuel consumption appears in northern Greece, with much higher HDD amounts and for a longer period of time. In the rest of Greece the HDD amounts decrease, declining from north to south and from the mainland to the islands. The absolute HDD range is estimated to be 1553.0 °C between Florina and Rhodes.

The state authorities should take into consideration the estimates of this study in order to determine the exact time period for cheaper fuel distribution. Just as there are differences in the HDDs over the country, it is obvious that the distribution of fuels can also be at different time intervals in the various regions of Greece. This is a method to support a better service for residents and for energy saving in the private and public sectors.

The geographical distribution of the HDDs, as they are represented on the maps, show a significant statistical relation, as the estimated values are very close to the measured ones, verifying the reliability of the models applied. Small divergences should be acceptable, because the network of the stations used is sparse and limited only to areas up to 700 m above sea level.

HDDs can be a useful tool to engineers, in estimating the domestic heating energy consumption, as well as in applied climate studies and urban air pollution, offering relevant information and support.

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