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Changes of temperature data for energy studies over time and their impact on energy consumption and CO_2 emissions. The case of Athens and Thessaloniki – Greece

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Abstract
In steady-state methods for estimating energy consumption of buildings, the commonly used data include the monthly average dry bulb temperatures, the heating and cooling degree-days and the dry bulb temperature bin data. This work presents average values of these data for the 1983-1992 and 1993-2002 decades, calculated for Athens and Thessaloniki, determined from hourly dry bulb temperature records of meteorological stations (National Observatory of Athens and Aristotle University of Thessaloniki). The results show that the monthly average dry bulb temperatures and the annual average cooling degree-days of the 1993-2002 decade are increased, compared to those of the 1983-1992 decade, while the corresponding annual average heating degree-days are reduced. Also, the low temperature bins frequency results decreased in the 1993-2002 decade while the high temperature ones increased, compared to the 1983-1992 decade. The effect of temperature data variations on the energy consumption and on CO_2 emissions of buildings was examined by calculating the energy demands for heating and cooling and the CO_2 emissions from diesel-oil and electricity use of a typical residential building-model. From the study it is concluded that the heating energy requirements during the decade 1993-2002 were decreased, as compared to the energy demands of the decade 1983-1992, while the cooling energy requirements were increased. The variations of CO_2 emissions from diesel oil and electricity use were analog to the energy requirements alterations. The results indicate a warming trend, at least for the two regions examined, which affect the estimation of heating and cooling demands of buildings. It, therefore, seems obvious that periodic adaptation of the temperature data used for building energy studies is required.

Keywords: Climate change; Cooling; CO_2 emissions; Degree-days; Energy consumption in buildings; Heating; Steady-state methods; Temperature data.

1. Introduction
A climate change seems to be in progress and there is strong evidence that it will continue in the forthcoming decades. Obviously, this change affects the temperature data used both in designing HVAC systems and for estimating the energy behavior of buildings.
The temperature data commonly used for simulating the energy behavior of buildings under steady-state conditions are the monthly average temperatures, according to the ISO 13790 method [1], or the heating

and cooling degree-days at various base temperatures, according to the variable-base degree-days method [2, 3, 5-7] or, finally, the ambient temperature occurrence frequency according to the bin method [4, 7].
In the present study, these data were determined for the 1983-1992 and 1993-2002 decades and for the two major cities of Greece. The determination is based on statistical evaluation of hourly measurements of ambient air dry-bulb temperature over the period 1983 – 2002. The raw data were obtained from the meteorological stations of the National Observatory of Athens (NOA) [8] and of the Aristotle University of Thessaloniki (AUTh) [9]. The results for the two decades are compared and the existing differences are discussed.

2. Temperature data analysis

2.1 Air temperature

Average temperature is a prime climate indicator and the basis for calculations of heating and cooling energy demand [1] or for estimating bin data and heating and cooling degree-days at any base [2, 10, 11].
Table 1 shows the monthly and yearly average ambient dry-bulb temperatures for the two cities and for the two decades, as well as for the twenty year period of 1983-2002. The values of the two decades for the two cities are plotted in Figure 1. As it can be clearly seen, the values of the 1993-2002 decade are increased, compared to the corresponding values of the 1983-1993 decade, in both cities.
During summer, the increase ranges from 0.66 K (2.82%) in September to 1.92 K (7.85%) in June for Athens and from 0.61 K (2.36%) in July to 0.91 K (3.91%) in June for Thessaloniki. Only in Thessaloniki in September the average temperature is reduced by 0.23 K (1.04%).
During winter, the increase ranges from 0.29 K (3.08%) in January to 1.17 K (12.52%) in February for Athens and from 0.21 K (3.43%) in January to 0.98 K (14.21%) in February for Thessaloniki. Only in April and for both cities, a slight decrease of the average temperature is observed (0.02 K or 0.15% in Athens and 0.41 K or 2.84% in Thessaloniki).
The summer time temperature increase in the second decade is supported by the warming trends in the daily temperature data of these two stations reported in previous research [12]. The warming trends initiated in 1996 in Thessaloniki and 1998 in Helliniko (Athens). This study linked the observed positive trends during summer in Greece to a significant positive pressure trend in the eastern and south-eastern parts of the Mediterranean, indicating a less frequent expansion of the low pressure over the area and therefore a weakening of the Etesian winds and a subsequent summer temperature rise.
Between the two decades, the annual average temperature of the two cities results increased by 1 K (5.4%) in Athens and by 0.6 K (3.1%) in Thessaloniki (Table 1).
The above findings clearly suggest a climate change trend, the last decade being characterized by milder winters and hotter summers, already reported elsewhere [13, 23]. Although these results are consistent with general warming of the world climate system, there are also other effects that undoubtedly contribute, such as increased urbanization of large cities. In the present analysis it is not attempted to determine the reasons for the changes.

Table 1. Mean monthly ambient temperature for Athens and Thessaloniki

	Athens			Thessaloniki		
Period	1983-1992	1993-2002	1983-2002	1983-1992	1993-2002	1983-2002
Jan.	9.44	9.73	9.58	6.13	6.34	6.23
Feb.	9.32	10.48	9.90	6.86	7.84	7.35
Mar.	11.47	11.97	11.72	9.83	10.06	9.95
Apr.	15.77	15.74	15.75	14.58	14.17	14.38
May	19.93	21.34	20.63	18.86	19.62	19.24
Jun.	24.42	26.34	25.38	23.31	24.22	23.76
Jul.	27.13	28.79	27.96	25.93	26.54	26.23
Aug.	26.77	28.30	27.53	25.53	26.17	25.85
Sep.	23.50	24.16	23.83	21.92	21.69	21.80
Oct.	18.32	19.43	18.87	16.16	16.85	16.50
Nov.	13.88	14.64	14.26	10.91	11.58	11.24
Dec.	10.13	11.18	10.65	6.60	7.47	7.03
Annual	17.50	18.50	18.00	15.55	16.05	15.80

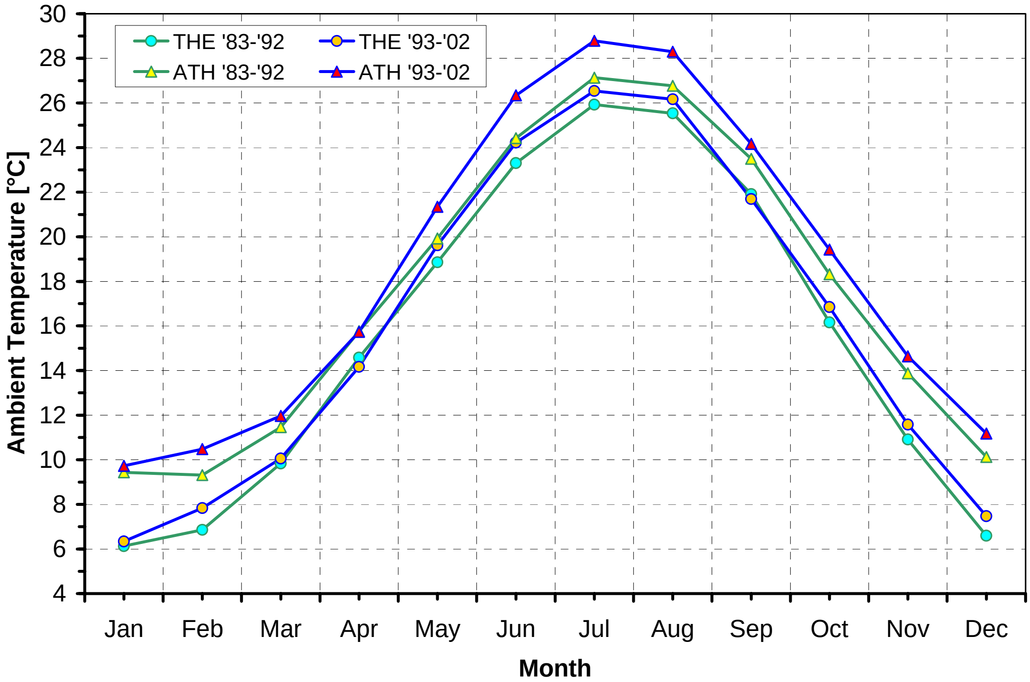

Figure 1. Mean average temperature of 1983-1992 and 1993-2002 decades for Athens and Thessaloniki

It is reminded at this point that the results of this work are based on actual continuous temperature measurements over the last 20 years in both cities, a period sufficiently long to ensure representativeness, including also the recent changes in climate and/or local conditions. It can therefore safely be suggested that the average temperature values of the twenty-year period 1983-2002 should be used for energy studies in the two cities.

2.2 Degree-days

Using outdoor air temperature hourly average values $(\bar{t}_{o,h})$ of the 1983÷2002 period, the heating (October to April) and cooling (June to September) degree-days (HDD and CDD, respectively) were calculated (base temperatures 10÷20°C and 20÷28°C, respectively) for both cities.

The total number of heating degree-days for a month was calculated as:

$$HDD(t_{bal}) = \frac{1}{24}\sum_{i=1}^{HR}(t_{bal} - \bar{t}_{o,h})^{+} \tag{1}$$

where HR is the number of hours of the month and t_{bal} the base temperature. The "+" sign indicates that only positive values are summed.

Respectively the total number of cooling degree-days for a month was calculated as:

$$CDD(t_{bal}) = \frac{1}{24}\sum_{i=1}^{HR}(\bar{t}_{o,h} - t_{bal})^{+} \tag{2}$$

The yearly HDD and CDD were calculated by summing the monthly values.

Indicatively, and for base temperatures 15°C for heating and 24°C for cooling (the usual balance temperatures of buildings with average internal and solar thermal gains, insulated according to Greek Regulation for Building Insulation), the results are plotted in Figures 2 (for Athens) and 3 (for Thessaloniki).

As it can be clearly seen in Figures 2 & 3, there is a marked reduction trend of HDD and increase trend of CDD, especially after the year 1996. From 1996 onwards, the annual HDD systematically result lower and the CDD higher than the respective 20-year average.

In Tables 2 and 3 the monthly HDD for Athens and Thessaloniki respectively are given, while Tables 4 and 5 show the monthly CDD for the two cities.
Each Table contains data of the two decades, namely 1983-2002 and 1993-2002, and of the twenty year period 1983-2002 as well. It is clearly seen that the monthly as well as the yearly values of HDD were reduced in the second decade, while the monthly and yearly values of CDD were increased. The reduction in the yearly values of HDD was in the range of 9.5 to 22% in Athens, and in the range of 5 to 9% in Thessaloniki, depending on the base temperature, with the highest changes observed at the lowest base temperatures. The increase of the yearly values of CDD was in the range of 25 to 53% in Athens, and in the range of 10 to 16% in Thessaloniki, depending on the base temperature, with the highest changes observed at the highest base temperatures. The above results confirm the aforementioned indication of climate change towards milder winters and hotter summers, in line with the general reduction of HDD and increase of CDD reported by the Norwegian Meteorological Institute for Europe, based on data of 63 measuring locations [14]. As in the case of average temperatures, it is recommended to use the average HDD and CDD values of the twenty-year period 1983-2002, for energy studies in the two cities.

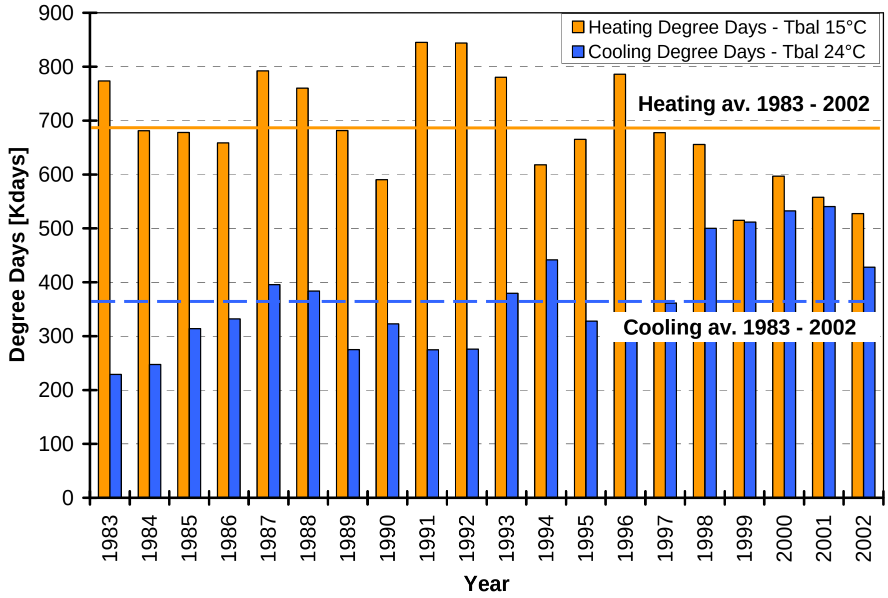

Figure 2. Heating and cooling degree days during 1983-2002 for Athens

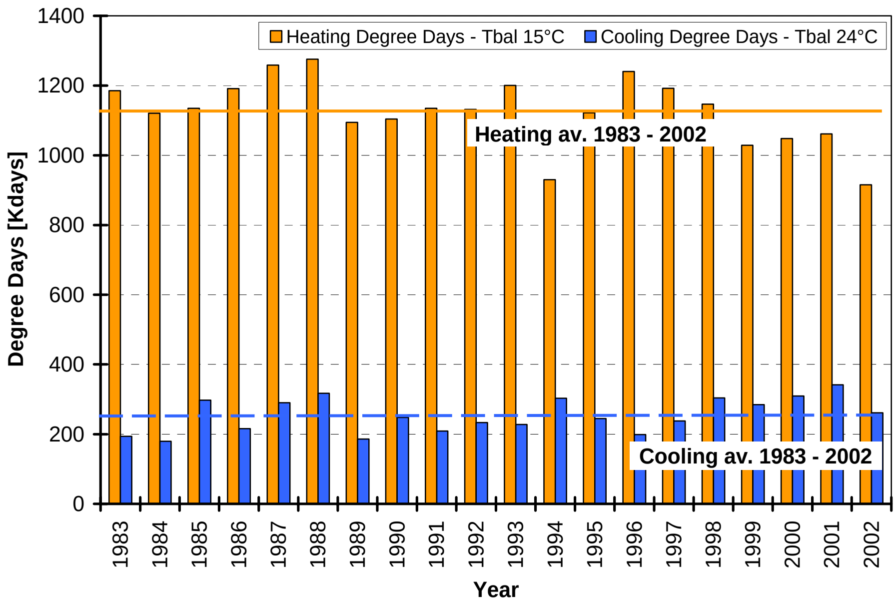

Figure 3. Heating and cooling degree days during 1983-2002 for Thessaloniki

Table 2. Monthly heating degree days to various temperature bases – Athens, Greece.

Month	Base Temperature	Period		
		1983 – 1992	1993 – 2002	1983 – 2002
Oct.	18	47	31	39
	16	22	14	18
	14	9	5	7
	12	2	1	2
	10	0	0	0
Nov.	18	131	114	122
	16	84	70	77
	14	46	38	42
	12	21	18	20
	10	7	7	7
Dec.	18	244	212	228
	16	184	153	168
	14	128	100	114
	12	80	59	70
	10	44	31	37
Jan.	18	266	257	261
	16	204	195	200
	14	146	138	142
	12	95	87	91
	10	54	48	51
Feb.	18	243	213	229
	16	189	159	175
	14	137	110	124
	12	92	67	80
	10	56	36	46
Mar.	18	206	193	199
	16	150	139	145
	14	100	92	96
	12	60	54	57
	10	32	28	30
Apr.	18	90	91	90
	16	50	52	51
	14	23	25	24
	12	8	10	9
	10	2	3	3
Total	18	1227	1111	1168
	16	883	782	834
	14	589	508	549
	12	358	296	329
	10	195	153	174

These changes in degree-days obviously affect directly the energy consumption of the buildings by increasing the cooling and decreasing the heating energy demands calculated, changes already reported in the relevant literature [15-28]. Other critical parameters influenced by the above mentioned climate change are the temperature design conditions, the design loads and obviously the size and capacity of the HVAC equipment [29, 30].

Table 3. Monthly heating degree days to various temperature bases - Thessaloniki Greece.

Month	Base Temperature	Period		
		1983 – 1992	1993 – 2002	1983 – 2002
Oct.	18	90	74	82
	16	53	42	48
	14	28	22	25
	12	12	10	11
	10	4	4	4
Nov.	18	215	196	206
	16	159	143	151
	14	108	96	102
	12	67	59	63
	10	37	33	35
Dec.	18	354	327	340
	16	292	266	279
	14	231	207	219
	12	171	151	161
	10	117	102	109
Jan.	18	368	362	365
	16	306	300	303
	14	245	239	242
	12	186	180	183
	10	130	125	128
Feb.	18	312	287	301
	16	257	232	246
	14	203	179	192
	12	152	130	142
	10	106	86	97
Mar.	18	256	249	252
	16	198	191	194
	14	143	138	141
	12	95	91	93
	10	57	55	56
Apr.	18	118	130	124
	16	74	85	79
	14	39	49	44
	12	16	24	20
	10	5	10	7
Total	18	1713	1625	1670
	16	1339	1259	1300
	14	997	930	965
	12	699	645	673
	10	456	415	436

In the framework of this study, the dry-bulb temperature design conditions for the cold and warm season were calculated in the two cities, using the same period of recordings, namely the years from 1983 to 2002. The annual dry-bulb design conditions are listed in Table 6. These are [2]:

- The dry-bulb temperature corresponding to 99.6 and 99.0% annual cumulative frequency of occurrence (cold conditions), ºC.
- The dry-bulb temperature corresponding to 0.4, 1.0 and 2.0% annual cumulative frequency of occurrence (warm conditions), ºC.
- The daily temperature range for hottest month, ºC (defined as mean of the difference between daily maximum and daily minimum dry-bulb temperatures for hottest month).

Table 4. Monthly cooling degree days to various temperature bases - Athens Greece

Month	Base Temperature	Period		
		1983 – 1992	1993 – 2002	1983 – 2002
Jun.	20	139	192	165
	22	91	138	114
	24	55	92	73
	26	29	56	43
Jul.	20	222	272	247
	22	162	211	187
	24	110	153	132
	26	69	103	86
Aug.	20	210	257	234
	22	151	196	174
	24	100	139	119
	26	61	91	76
Sep.	20	113	131	122
	22	71	83	77
	24	41	48	44
	26	21	25	23
Total	20	684	852	768
	22	475	628	552
	24	306	432	368
	26	180	275	228

Table 5. Monthly cooling degree days to various temperature bases - Thessaloniki Greece

Month	Base Temperature	Period		
		1983 – 1992	1993 – 2002	1983 – 2002
Jun.	20	114	137	125
	22	74	92	83
	24	43	56	50
	26	23	30	26
Jul.	20	186	205	196
	22	132	149	140
	24	87	100	94
	26	53	62	58
Aug.	20	174	193	184
	22	121	136	129
	24	79	90	84
	26	47	54	50
Sep.	20	84	79	82
	22	51	48	49
	24	28	25	27
	26	13	12	12
Total	20	558	614	587
	22	378	425	401
	24	237	271	255
	26	136	158	146

Values of ambient dry-bulb temperature corresponding to the various annual percentiles, represent the value that is exceeded on average by the indicated percentage of the total number of hours in a year (8760). The 0.4, 1.0, and 2.0% values are exceeded on average 35, 88, and 175 h per year, respectively, for the period of record. The design values occur more frequently than the corresponding nominal percentile in some years and less frequently in others. The 99.0 and 99.6% (cold season) values are similarly defined but they are usually viewed as the values for which the corresponding temperature is lower than the design condition for 88 and 35 h, respectively. Simple design conditions were obtained by binning hourly data into frequency vectors, then deriving from the binned data the design condition having the probability of being exceeded a certain period of time. Coincident temperature ranges were also obtained by double binning daily temperature ranges (daily maximum minus daily minimum) versus maximum daily temperature.

It is worth to be mentioned that these design data from the meteorological stations of NOA and AUTh are not included neither in the climate data of ASHRAE [2] nor of the Hellenic Regulation on Energy Efficiency of Buildings (KENAK) [31].

Table 6. Annual dry-bulb design conditions for Athens (NOA) and Thessaloniki (AUTh)

City	Latitude	Longitude	Elevation [m]	Heating DB [ºC]		Cooling DB [ºC]			Daily range[ºC]
				99.6%	99%	0.4%	1%	2%	
Athens	37º58’	22º57’	107	1.5	3.1	36.2	34.6	33.3	9.5
Thessaloniki	40º37’	23º43’	31	-2.5	-1.0	34.3	32.9	31.7	10.4

2.3 Temperature bins

The cumulative results for the frequency of occurrence (in h) of 2.8 K (5°F)-wide temperature bins per period (summer, winter and intermediate) are shown in Figures 4-6 for Athens and 7-9 for Thessaloniki for the two decades.

The winter period, during which the buildings need heating, includes the months November to April. Similarly, the summer period, during which cooling is required, consists of the months June to September, the remaining months (May and October) forming the intermediate period, during which neither heating nor cooling is needed. It can be clearly seen that, for both cities and for all periods, a reduction of the low and an increase of the high temperature bins is observed between the 1983-1992 and 1993-2002 decades.

Based on the data presented in Figures 4-9, considering the median temperature as representative of the bin temperature range and by neglecting bin values lower than 100 h, the percentage change of the frequency of occurrence of each temperature range between the two decades for both cities and for the energy consuming periods is calculated. The results are shown in Figure 10.

It can be clearly seen that there is a fairly good linear correlation of occurrence frequency change with temperature. All four regression lines have positive slopes, meaning that the increase of occurrence frequency in the 1993-2002 decade, compared to that of 1983-1992, increases with the temperature level. For the same period (winter or summer), the slopes for Athens are steeper than those for Thessaloniki, an observation confirming this conclusion, since Athens is located southern and evidently the temperatures observed are higher.

This conclusion is further confirmed by the comparison of winter and summer slopes of the same city, the latter, which obviously corresponds to significantly higher temperatures, being notably steeper.

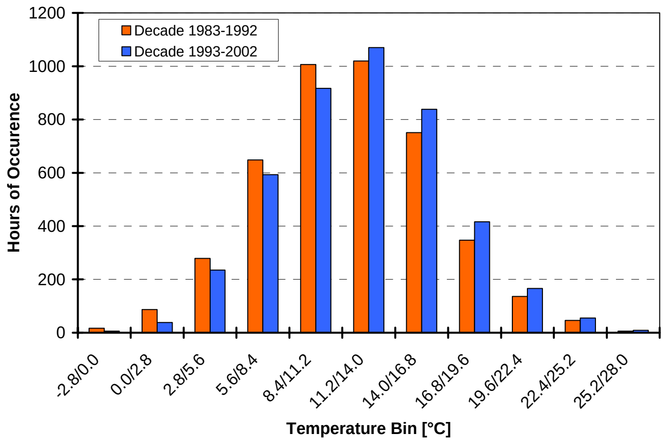

Figure 4. Temperature bins hours of occurrence. Decades 1983-1992 and 1993-2002. Athens – Heating period (November to April)

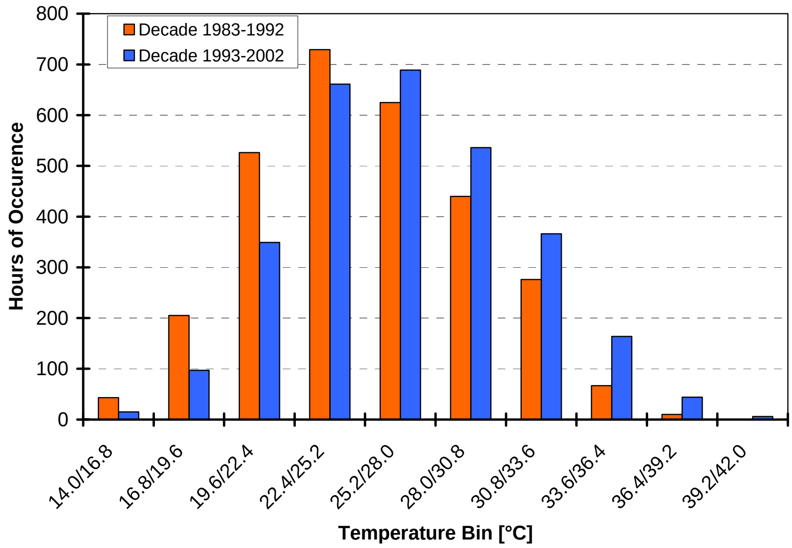

Figure 5. Temperature bins hours of occurrence. Decades 1983-1992 and 1993-2002. Athens – Cooling period (June to September)

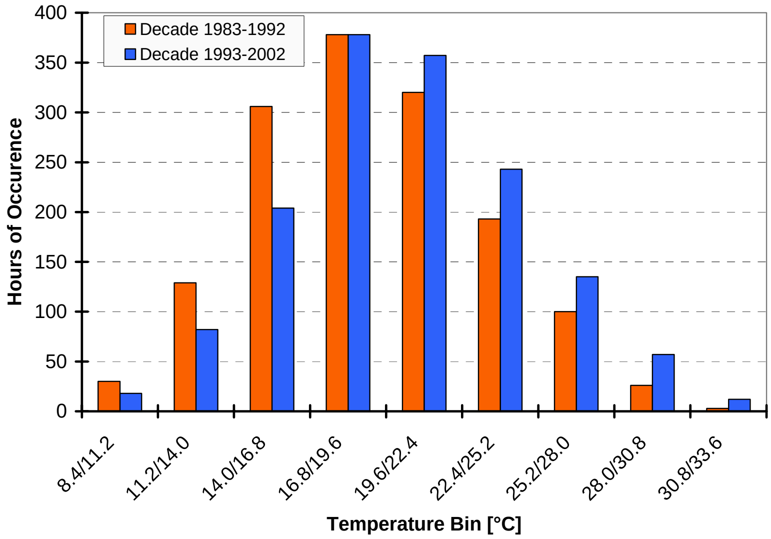

Figure 6. Temperature bins hours of occurrence. Decades 1983-1992 and 1993-2002. Athens – Intermediate period (May and October)

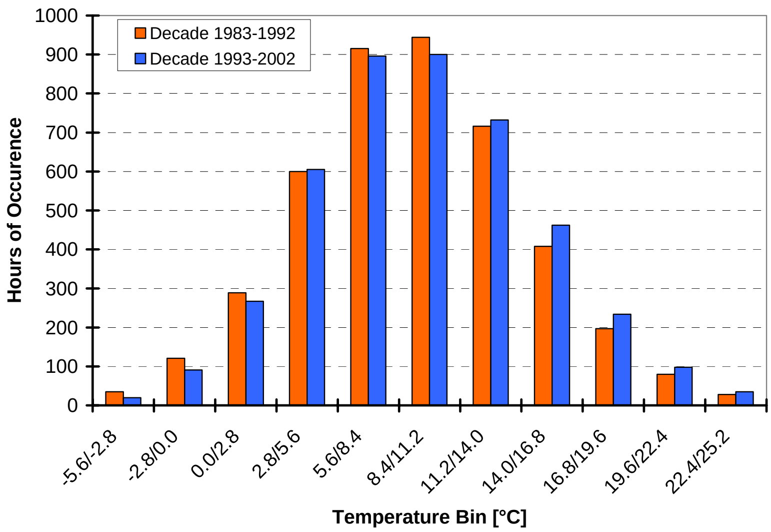

Figure 7. Temperature bins hours of occurrence. Decades 1983-1992 and 1993-2002. Thessaloniki – Heating period (November to April)

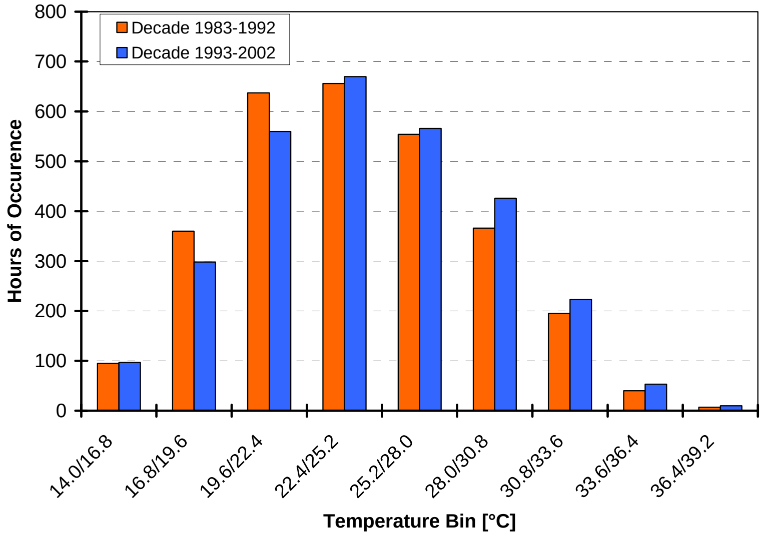

Figure 8. Temperature bins hours of occurrence. Decades 1983-1992 and 1993-2002. Thessaloniki – Cooling period (June to September)

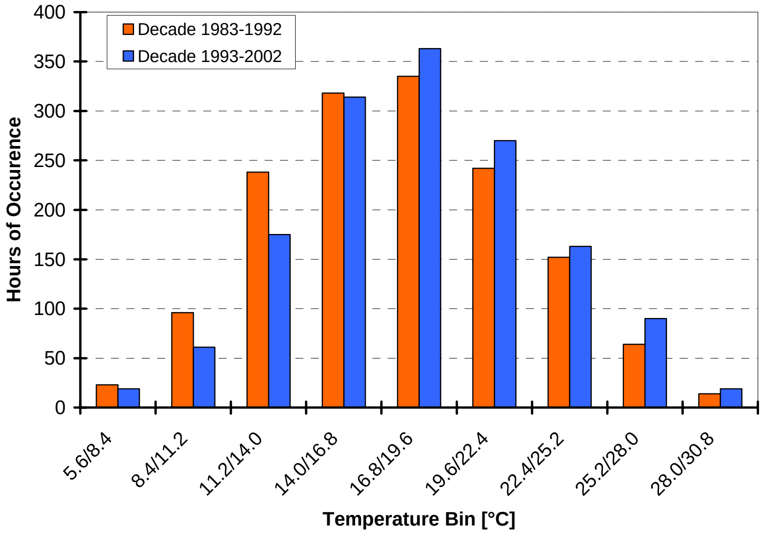

Figure 9. Temperature bins hours of occurrence. Decades 1983-1992 and 1993-2002. Thessaloniki – Intermediate period (May and October)

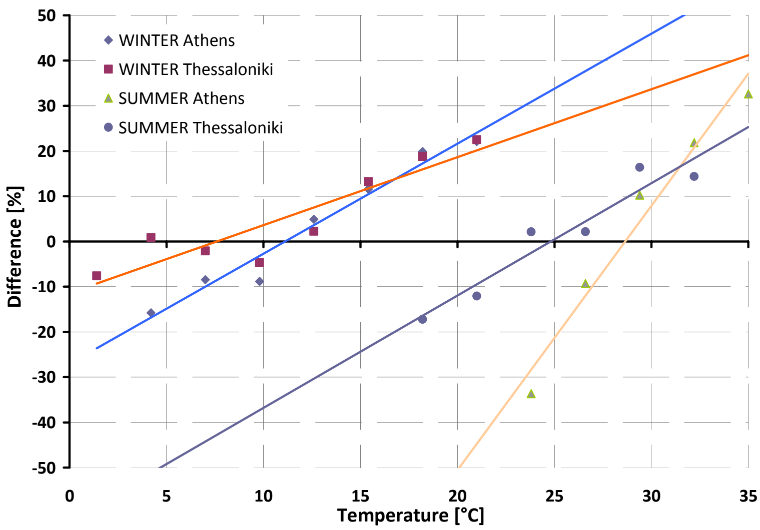

Figure 10. Percentage differences between the 1983-1992 and the 1993-2002 decades of the temperature occurrence frequency in both cities. Energy consuming periods

3. Impact of degree-day data change on the energy consumption for heating and cooling and on CO_2 emissions

In order to reach conclusions regarding the effect of temperature data changes on the energy consumption of buildings, the energy demands of a typical residential building-model were estimated for heating and cooling. The method used was that of variable base degree-days [2, 3, 5, 6].

The building is a two–story apartment building, with a flat roof, pilotis and two 88 m^2 apartments per floor. The height of every story is 3 m. The openings are distributed on the northern and southern sides of the building and represent 13% and 33% of the exterior surface respectively. The building sides facing east and west were considered in touch with open air but without any openings, in the case that adjacent buildings will be built in the future.

The building insulation is of typical insulating materials available to the Greek market, and the heat transfer coefficients of the building elements are as close to the Greek Insulation Code as possible.

The interior temperature of the building θ_{int} was set constant during all day and equal to 20ºC for the winter period and 26ºC for the summer period. The rate of the ventilation was assumed equal to 0.5 ach except for the WC-bathrooms, where it was considered equal to 1.5 ach. The overall heat transfer coefficient of the building H, as the sum of the transmission heat loss coefficient H_T and the ventilation heat loss coefficient H_V, according to EN 12831 [32], was calculated equal to 730 W/K.

The overall efficiency of the heating system assuming an oil-fired boiler was considered equal to 0.85 and the performance factor of the cooling system (A/C units) equal to 2.8. The heat gains from people, lights and appliances as well as the solar heat gains were calculated according to the Greek regulations [33, 34].

The energy calculations were performed for all the winter and summer months for the two cities, and the energy requirements of the building were calculated for heating and cooling with temperature data of the decade 1983-1992 as well as of the 1993-2002 decade. The total results for the two cities are presented in Tables 7 and 8. The thermal energy for heating Q_{ht} was estimated based on the winter energy requirements and the overall efficiency of the heating system. Respectively, the electric energy estimation for cooling Q_{ce} was based on the summer energy demand and on the performance factor of the cooling system. The primary energy for heating Q_{hp} and cooling Q_{cp} were determined from the thermal Q_{ht} and the electric Q_{ce} energy, using the conversion factors of 1.1 and 2.9 respectively, according to [31]. Obviously, the total primary energy Q_{tot} is the sum of Q_{hp} and Q_{cp}.

From the results presented in Tables 7 and 8, it is concluded that for the 1993-2002 decade heating period, a decrease of the energy requirements of the building is observed in both cities as compared to the 1983-1992 decade. The percent reduction of energy requirements for heating is 11.3% for Athens and 6.1% for Thessaloniki. On the contrary, for the cooling period of the 1993-2002 decade, an increase of the energy demands of the building for both cities is observed compared to the 1983-1992 decade. For Athens the increase in cooling demands is 28.5% and for Thessaloniki 13.2%. Obviously, directly proportional to the energy demand for heating and cooling is the fuel (diesel oil) and electricity consumption and hence the CO_2 emissions, presented in Tables 9 and 10, for Athens and Thessaloniki respectively. As it can be seen, the total CO_2 emissions were increased (1.8%) in Athens, while in Thessaloniki were decreased by 2.1%.

Table 7. Energy requirements (kWh) of the model residential building for Athens, calculated with degree-day data of the 1983-1992 and 1993-2002 decades

Period	Thermal energy, Q_{ht}	Electric energy, Q_{ce}	Primary energy for heating, Q_{hp}	Primary energy for cooling, Q_{cp}	Total primary energy, Q_{tot}
	[kWh_{therm}]	[kWh_{el}]	[kWh]	[kWh]	[kWh]
1983-1992	18239	2407	20063	6981	27044
1993-2002	16176	3093	17794	8970	26764

Table 8. Energy requirements (kWh) of the model residential building for Thessaloniki, calculated with degree-day data of the 1983-1992 and 1993-2002 decades

Period	Thermal energy, Q_{ht}	Electric energy, Q_{ce}	Primary energy for heating, Q_{hp}	Primary energy for cooling, Q_{cp}	Total primary energy, Q_{tot}
	[kWh_{therm}]	[kWh_{el}]	[kWh]	[kWh]	[kWh]
1983-1992	27651	1894	30416	5492	35908
1993-2002	25961	2144	28557	6218	34775

Table 9. CO_2 emissions (kg) of the model residential building for Athens, by the use of diesel oil for heating and electricity for cooling demands

Period	Oil	Electricity	Total (Oil+Electricity)
	[$kgCO_2$]	[$kgCO_2$]	[$kgCO_2$]
1983 – 1992	4815	2380	7195
1993 – 2002	4270	3059	7329

Table 10. CO_2 emissions (kg) of the model residential building for Thessaloniki, by the use of diesel oil for heating and electricity for cooling demands

Period	Oil	Electricity	Total (Oil+Electricity)
	[kgCO2]	[kgCO2]	[kgCO2]
1983 – 1992	7300	1873	9173
1993 – 2002	6855	2120	8975

4. Conclusion

The 1983-1992 and 1993-2002 decades temperature data comparison of Athens and Thessaloniki reveals an increasing trend of the monthly average values, resulting in reduction of the average heating and in increase of the average cooling degree-days, in reduction of the lower and in increase of higher temperature bins, all suggesting a climate change towards milder winters and hotter summers. The increase of the higher temperature bins results to be directly related to the temperature level.

The consequence of the reported trend towards milder winters and hotter summers is the reduction of energy consumption for heating and the increase of energy consumption for cooling. Analog results are observed for the CO_2 emissions by the use of diesel oil and electricity for heating and cooling. The total CO_2 emissions were slightly increased (1.8%) in Athens, during the 1993-2002 decade, as compared to the 1983-1992 period, while in Thessaloniki were decreased by 2.1%.

These trends however should be treated with caution and need further investigation, since the decade time horizon is relative short for drawing solid conclusions regarding the climate and consequently the estimation of energy demands and CO_2 emissions.

In the case the above mentioned trends are confirmed, the climate input data used in energy behavior calculations and for designing the HVAC systems of buildings, either for winter or for summer conditions, must be periodically re-examined and reviewed.

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