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Five years of thermal intra-urban monitoring in Florence (Italy) and application of climatological indices

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Abstract This paper presents 5 years of detailed intra-urban thermal measurements carried out in Florence (Italy) by a network of 25 air temperature stations. Daily, hourly, and degree-day indices were applied to hourly data to evaluate the difference within the complex urban environment of Florence. Stations were grouped in four clusters with similar thermal regimes in each season. Our results evidence a mean difference of almost 2°C between the hottest and the coolest cluster in all seasons. Furthermore, the coolest cluster had on average more than ten frost days in winter and the hottest cluster more than 12 summer days in summer. The intra-urban difference of tropical nights was even more evident, with values of 42 versus 10 days between the hottest and the coolest cluster during the summer period. The results of this study contribute to quantify the thermal intra-urban differences in the city of Florence, suggesting important applications in plant phenology, aerobiology, human health, urban planning, and biometeorology.

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1 Introduction

Air temperature in urban areas and the Urban Heat Islands (UHI) can be influenced by several factors, such as latitude, land use, and urban features (Oke 1976; Bottyan et al. 2005; Svensson and Eliasson 2002). The placement of a building on the landscape gives rise to radiative, thermal, moisture, and aerodynamic modification of the surrounding environment (Oke 1987); the effects of a large number of buildings in close proximity, as in a city, are greater than the sum of the effects of the individual buildings due to the complex interactions between them (Erell and Williamson 2007). The large number of parameters capable of affecting the air temperature distribution within an urban area makes it difficult to identify a clear relationship with urbanization features, and therefore, it is necessary to enhance our knowledge of local climate and, more specifically, urban climate.

Structures and features of the UHI of some cities in temperate climatic zones are well documented (Landsberg 1981; Kuttler et al. 1996; Unger 2004; Bottyan et al. 2005; Yan et al. 2009). However, whereas over recent years several papers have been published regarding the Italian regional climate (Brunetti et al. 2006; Bartolini et al. 2008), there is still a shortage of information about the climate in Italian cities and UHI (Kumar et al. 2005; Zauli Sajani et al. 2008; Petralli et al. 2006a). Furthermore, the meteorological and climatological description of a city is often based on a single meteorological station, frequently located in the city center or at the airport, and therefore not representative of the entire city. The methods frequently used to identify the nature of the urban climate, and in particular, the phenomenon of the UHI, usually analyze data from fixed weather stations or mobile transects or visible and thermal bands of satellite imagery. Each measurement technique has advantages and

disadvantages, and the choice of methods usually depends on the purpose of the study. The advantage of fixed sites, assuming that they can be deemed representative of certain land cover types in the urban canyon layer of the city, is that they normally allow for diurnal/seasonal and long-term temporal trend analyses (Oke 1987; Hedquist and Brazel 2006). For this purpose, our paper presents an analysis of data collected by an intra-urban network of fixed air temperature sensors located in Florence. Moreover, in order to analyze climatically intra-urban differences, analyses of statistical differences among the stations seasonally clustered according to a hierarchical method were carried out on some widely used climatological indices.

2 Materials and methods

2.1 Study area and meteorological data

A network of air temperature and relative humidity sensors (HOBO® PRO series Temp/RH Data Logger, Onset Computer Corporation, Pocassette, MA, USA; operating range T, −30°C to 50°C; RH, 0–100%; resolution, 0.2°C between 0°C and 40°C) with naturally ventilated solar radiation shields (RS1-HOBO® PRO accessories) was set up in the city of Florence (Italy; latitude, 43.77; longitude, 11.26; elevation, 50 m a.s.l.). The city lies in a plain to the southwest of the Apennine mountains in the central part of Italy and is characterized by a sub-Mediterranean climate with a hot, dry summer, a mild and quite wet winter, and a wet autumn and spring. The network consisted of 35 loggers randomly located in the urban area of Florence since 2004. They were positioned in two different kinds of soil: paved surfaces and green areas, at a height of approximately 2 m in order to analyze the thermal conditions at pedestrian level, and spaced more than 2 m away from buildings in order to obtain representative measurements in built-up areas (Oke 2004).

Data were collected every 15 min from each station, and hourly average values were calculated. Data series completeness was checked, and stations with a high missing data rate per year were excluded from the analysis. A total number of 25 stations with a negligible percentage of data gaps were selected. Gaps were filled by applying a linear interpolation method of reconstruction using the most correlated station according to the Pearson product moment correlation. All the analyses were made by season according to the WMO standard (winter=DJF, spring=MAM, summer=JJA, and autumn=SON) for the period December 2005 to November 2008.

2.2 Indices of climate extremes

Daily temperature indices (°C), daily extreme indices (number of days), hourly extreme indices (number of hours), and degree-day indices (°C) were calculated for characterizing meteorological variability among the weather stations in each season. Daily extreme indices were calculated on a pre-defined arbitrary threshold according to the European Climate Assessment (ECA) indices definition (Peterson et al. 2001). Temperature thresholds of 0°C, 20°C, and 25°C were used to calculate frost days (FD), tropical nights (TR), and summer days (SU), respectively, according to the ECA indices definition. A temperature threshold of 30°C was also chosen to calculate summer days (SU30) since this is the approximate average summer maximum temperature in Florence (Kumar et al. 2005). We also calculated hourly extremes applying the definition of daily indices on an hourly basis.

(a) Daily temperature indices

   1. TG: mean of average daily temperature (°C)
   2. TN: mean of minimum daily temperature (°C)
   3. TX: mean of maximum daily temperature (°C)

(b) Daily extreme indices

   1. FD: frost days (TN<0°C; days)
   2. SU: summer days (TX>25°C; days)
   3. SU30: summer days (TX>30°C; days)
   4. TR: tropical nights (TN>20°C; days)

(c) Hourly extreme indices

   1. FH: frost hours (T<0°C; hours)
   2. SUH: summer hours (T>25°C; hours)
   3. SUH30: summer hours (T>30°C; hours)
   4. TRH: number of tropical hours during the night (T>20°C; hours; night=from 10 p.m. to 5 a.m.)

(d) Degree-day indices: Two more daily indices commonly used to estimate energy consumption for indoor heating and cooling were also calculated. These indices are based on degree-day estimation. In this study, the method of adding hourly temperature differences and dividing by 24 was applied since this is the most exact method (and most mathematically precise) of calculating degree-days, as suggested by the CIBSE technical report (Day 2006).

   1. $HDD=\sum(\Delta T_i)/24$ for $i=1$–24 where $\Delta T_i=T_{bHDD}-T_{hi}$ if $T_{bHHD}-T_{hi}>0$; otherwise, $\Delta T_i=0$ (HDD= heating degree-days in degree centigrade: average positive difference ΔT_i between base temperature T_{bHDD} and hourly temperature recorded T_{hi})
   2. $CDD=\sum(\Delta T_i)/24$ for $i=1$–24 where $\Delta T_i=T_{hi}-T_{bCDD}$ if $T_{hi}-T_{bCDD}>0$; otherwise, $\Delta T_i=0$ (CDD= cooling degree-days in degree centigrade: average positive difference ΔT_i between hourly temperature recorded T_{hi} and the base temperature T_{bCDD})

Different values of base temperature (T_b) were proposed for both HDD and CDD (Jiang et al. 2009; Dombaycı 2009)

since the optimal value for estimating energy consumption depends greatly on climatic and environmental factors.

In this study, a 17°C base temperature was chosen for calculating HDD according to the ECA indices definition. As no definition of CDD was included in the ECA document; CDD was calculated using a base temperature of 22°C which is the value used by the UK's National Weather Service (Met Office) (http://www.metoffice.gov.uk).

2.3 Statistical analysis

Cluster analysis, in particular hierarchical clustering (Ward's method), was used to identify homogeneous groups of stations (Ward 1963) with similar thermal regimes in each season. This method was applied to all the stations to tabulate average seasonal minimum, average, and maximum air temperature data. An important decision in clustering analysis is the number of clusters to maintain. Visual analysis of the dendrogram was adopted to determine the optimal number and composition of clusters. The dendrogram is a graphical representation of the cluster analysis results, showing at what level of similarity or distance any two clusters are joined. Through the visual analysis, it is possible to identify clusters according to a predefined level of similarity.

A descriptive analysis of all the daily and hourly indices was performed for each cluster, and statistical differences were tested by applying the Bonferroni test to the analysis of variance (one-way analysis of variance).

All the statistical analyses were performed by using SPSS for Windows version 17.

3 Results

The hierarchical clustering technique identified four categories with similar temperature regimes in each season. Clusters were numbered according to increasing maximum temperature regimes (TX), from cluster 1 (including stations with the lowest mean temperature values) to cluster 4 (including stations with the highest temperature values). The composition of the clusters changed slightly with the season, but generally, a single station always belonged to the same cluster. According to this classification, 18 out of 25 stations always belonged to the same clusters in all the seasons as shown in Fig. 1. Stations located in green areas in the outskirts of the city were grouped in cluster number 1, stations located in the main gardens of the city were grouped in cluster number 2, stations located in densely populated areas near the historic center of Florence were grouped in cluster number 3, and stations located in densely populated urban areas of the suburbs surrounding the city were grouped in cluster number 4. The historic center of

Florence is characterized by a densely populated built-up area, with buildings mostly three storeys high, while the suburbs surrounding the city are characterized by the same density but with taller buildings (more than four storeys) than in the historic center.

In DJF, MAM, and JJA, the statistical differences between the clusters were the same for all the daily temperature indices (Table 1): TX in cluster number 4 was significantly higher (almost 2°C) than in all the other clusters, and no statistical difference was observed for this index between the other clusters. TG and TN had the same significant differences: cluster number 1 was cooler than all the other clusters, while cluster numbers 3 and 4 were warmer than cluster numbers 1 and 2. In autumn, cluster number 4 was confirmed as significantly warmer than cluster numbers 1 and 2 in all cases (TX, TG, and TN). TX and TN had the same significance as the other seasons. In TG, there were only two groups: clusters 1 and 2 were significantly cooler than clusters 3 and 4.

As regards daily and hourly indices, FD, FH, SU, SUH, SU30, SUH30, TR, and TRH, statistical differences between clusters were found in all seasons (Table 2). In winter, cluster 1 had the highest number of FDs (20 days) and FHs (143 h), and cluster 3 the lowest, with a mean difference of 12 days and 104 h in the whole season (Fig. 2). FD and FH were also recorded in spring and autumn: in cluster 1, the number of FDs was on average more than 2, while in the other clusters, it was lower than 1 per season, and the same trend was observed for FH, with an average of 9 h in both seasons in cluster 1.

No SU and SUH were recorded in winter (Table 2); in summer, the main difference between the cluster with the highest number of SU and SUH (cluster 4) and the other clusters was 5 days (85 vs. 80 days) and 236 h, which corresponds to an average of 2 h per day for the whole season. The highest difference between the clusters was recorded in spring and autumn (Fig. 2): cluster number 4 was on average 11 days (SU) and 90 h (SUH) higher than the other clusters (SU, 29 vs. 18–20 in spring and 33 vs. 20–23 in autumn; SUH, 189 vs. 99–101 in spring and 240 vs. 132–147 in autumn). The same statistical differences were found for SU30 and SUH30, with cluster 4 always higher than the other clusters, with a main difference of 3 days (SU30) and 11 h (SUH30) in spring, 11 days (SU30) and 130 h (SUH30) in summer, and 5 days (SU30) and 34 h (SUH30) in autumn.

The highest number of tropical nights was found in summer in cluster numbers 3 and 4 (42 and 37 days, respectively) and was statistically higher than cluster 2 (22 days) and cluster 1 (10 days), with a difference of almost 20 or 30 nights, respectively, per season (Fig. 2). In spring, less than one tropical night per season was found in clusters 3 and 4, while in autumn, the number of tropical
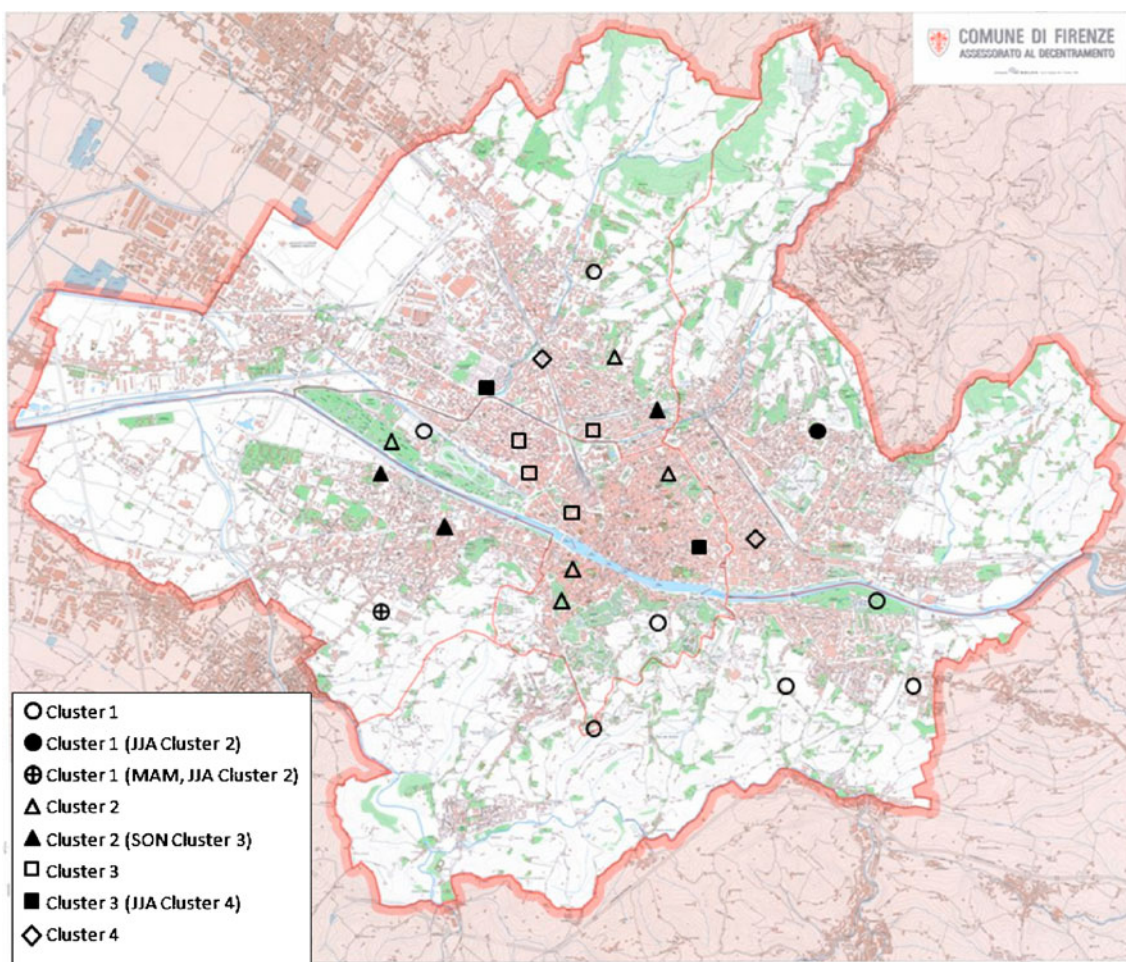
Fig. 1 Florence municipality map and cluster classification of the 25 air temperature sensors. *Empty circle*=stations classified in cluster 1 in all seasons; *filled circle*=stations classified in cluster 1 in all seasons except in JJA which are classified in cluster number 2; *crossed circle*= *filled circle*=stations classified in cluster 1 in all seasons except in JJA and MAM which are classified in cluster number 2; *empty triangle*= stations classified in cluster 2 in all seasons; *filled triangle*=stations classified in cluster 2 in all seasons except in SON which are classified in cluster number 3; *empty box*=stations classified in cluster 3 in all seasons; *filled box*=stations classified in cluster 3 in all seasons except in JJA which are classified in cluster number 4; *empty diamond*= stations classified in cluster 4 in all seasons. JJA=summer; MAM= spring; SON=autumn). Topographical base from SELCA, Florence (authorized)

nights was slightly higher: on average, three nights per season in clusters 3 and 4, and two nights per season in clusters 1 and 2 (Table 2).

Some important intra-urban differences were also found for degree-day indices (Table 3). In winter, the maximum HDD difference between the clusters reached 90°C but was not statistically significant. In spring and autumn, cluster 1 always had the highest number of HDDs and was statistically different from the others, while clusters 3 and 4 showed no difference and had the lowest values.

Finally, as regards the CDD index, clusters 1 and 2 always had lower values than clusters 3 and 4. During summer, when the cooling demand is higher, only two different groups were identified: clusters 1 and 2 were grouped together with a lower demand for cooling (276–291°C), while clusters 3 and 4 showed the highest demand for cooling (339–375°C), with a main difference of almost 70°C (Table 3).

The annual difference in HDD between clusters was 300°C (1,606°C in cluster 1 vs. 1,306°C in cluster 4). Taking into account all the degree-days, both HDD and CDD, the annual difference between the clusters undergoes very little reduction until reaching almost 200°C (1,956°C vs. 1,761°C), high-lighting an important intra-urban differentiation.

4 Discussion and conclusions

Cluster classification suggests that the environment imme-diately surrounding the stations has important consequences on thermal data, confirming previous studies on the relation-ship between urban geometry and air temperatures in complex environments (Oke 1981; Bärring et al. 1985; Eliasson 1996). One important result of this study is the changing in cluster composition: this demonstrates that the thermal

Table 1 Florence seasonal cluster subdivision

	Cluster	No.	TX±σ (°C)		TG±σ (°C)		TN±σ (°C)	
DJF	1	9	11.3±0.26	a	6.9±0.36	a	3.3±0.37	a
	2	8	11.2±0.41	a	7.4±0.23	b	4.2±0.25	b
	3	6	11.3±0.31	a	8.1±0.15	c	5.3±0.2	c
	4	2	12.8±0.17	b	8.3±0.25	c	5±0.34	c
MAM	1	8	19.9±0.45	a	14.1±0.34	a	8.7±0.35	a
	2	9	19.9±0.36	a	14.7±0.28	b	9.7±0.33	b
	3	6	20.3±0.47	a	15.5±0.15	c	11.0±0.09	c
	4	2	21.7±0.09	b	15.8±0.16	c	10.6±0.33	c
JJA	1	7	30.2±0.5	a	23.3±0.33	a	16.6±0.3	a
	2	10	30.1±0.69	a	23.9±0.37	b	18.0±0.46	b
	3	4	30.3±0.72	a	24.8±0.34	c	19.5±0.05	c
	4	4	31.8±0.36	b	25.2±0.06	c	19.1±0.34	c
SON	1	9	20.8±0.31	b	15.1±0.33	a	10.4±0.36	a
	2	5	20.2±0.27	a	15.5±0.19	a	11.4±0.25	b
	3	9	20.9±0.55	b	16.4±0.28	b	12.3±0.52	c
	4	2	22.8±0.32	c	17.0±0.37	b	12.4±0.52	c

Different letters indicate significant differences for $p<0.05$ evaluated by the Bonferroni test

DJF=winter; MAM=spring; JJA=summer; SON=autumn cluster=cluster number; No.=number of stations per cluster; σ=standard deviation; TX=mean of maximum daily temperature; TG=mean of average daily temperature; TN=mean of minimum daily temperature

regimes of some areas of the city may vary with the season. The cluster variations in seven stations were caused more by different exposure to the sun than by environmental characteristics: the two stations that pass over from cluster 1 (stations located in green areas in the outskirts of the city) were located in green areas with a lower percentage of arboreal plants, and the same was observed in the case of the three stations from cluster 2 that were grouped in cluster 3 in autumn. The two stations with variations between cluster 3 (DJF, MAM, and SON) and cluster 4 (JJA) were positioned in areas with greater sun exposure during the daytime. Indeed, the passage of these two stations during the summer from cluster 3 to cluster 4 is mainly due to the values of maximum temperatures that were closer to those of cluster 4

Table 2 Daily and hourly indices for Florence clusters expressed as mean seasonal number of days±standard deviation (σ)

	Cluster	No.	FD±σ (days)		FH±σ (h)		SU±σ (days)		SUH±σ (h)		SU30±σ (days)		SUH30±σ (h)		TR±σ (days)		TRH±σ (h)	
DJF	1	9	20±2.7	a	143±33	a	–		–		–		–		–		–	
	2	8	14.1±1.1	b	93±19	b	–		–		–		–		–		–	
	3	6	7.7±1.4	c	39±7	c	–		–		–		–		–		–	
	4	2	10.2±0.7	bc	61±9	bc	–		–		–		–		–		–	
MAM	1	8	2.3±0.3	a	9±2	a	18.3±3.7	a	99±21	a	2.8±0.8	a	14±4	a	0±0	a	14±3	a
	2	9	0.8±0.5	b	3±2	b	17.7±2.6	a	101±15	a	2.4±0.8	a	12±4	a	0±0	a	24±5	b
	3	6	0.1±0.1	c	0±0	b	20.3±3.6	a	131±26	b	3.1±0.9	a	18±5	a	0.6±0.2	b	46±4	c
	4	2	0.3±0	c	1±0	b	29±0.9	b	189±0	c	5.2±0.7	b	29±4	b	0.5±0.2	b	40±8	c
JJA	1	7	–		–		80.5±1.5	a	820±50	a	51.1±3.2	a	333±38	a	9.6±2.2	a	324±39	a
	2	10	–		–		80.1±1.6	a	878±50	a	49.8±4.9	a	331±46	a	22.5±5.8	b	443±39	b
	3	4	–		–		81.2±1.8	a	1025±51	b	50.1±5.7	a	376±57	ab	41.8±0.4	c	549±6	c
	4	4	–		–		85.8±0.8	b	1056±5	b	61.9±2.8	b	464±22	b	36.8±3.4	c	525±16	c
SON	1	9	2.4±0.9	a	9±5	a	22.8±1.4	a	147±13	a	5.8±0.7	a	26±3	ab	1.5±0.7	a	46±9	a
	2	5	0.3±0.3	b	0±1	b	19.5±1.9	a	132±11	a	4.3±0.5	a	19±3	a	2.2±0.2	a	66±10	b
	3	9	0.1±0.2	b	0±0	b	23.1±3.8	a	172±22	b	5.7±1.6	a	29±8	b	3.5±0.8	b	94±14	c
	4	2	0±0	b	0±0	b	33.7±2.8	b	240±8	c	11.5±0.2	b	53±2	c	3±0.5	b	97±9	c

Different letters indicate significant differences for $p<0.05$ evaluated by the Bonferroni test

DJF=winter; MAM=spring; JJA=summer; SON=autumn; cluster=cluster number; No.=number of stations per cluster; FD=frost days; FH= hours with mean temperature lower than 0°C; SU=summer days; SUH=hours with mean temperature higher than 25°C; SU30=number of days with maximum air temperature higher than 30°C; SUH30=hours with mean temperature higher than 30°C; TR=tropical nights; TRH=night hours with mean temperature higher than 20°C
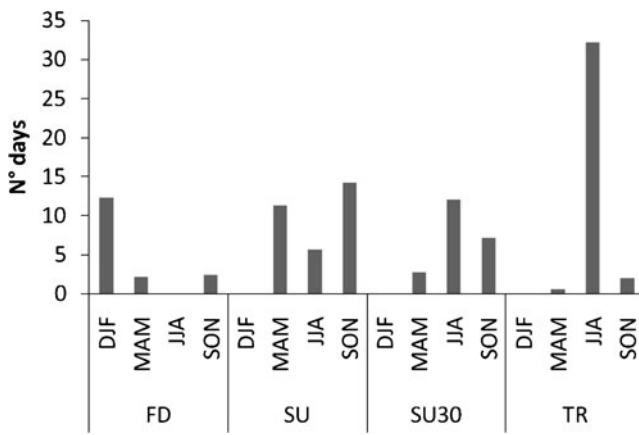
Fig. 2 Maximum differences in the number of days among the clusters for the daily indices in all seasons (FD=frost days; SU= summer days; SU30=number of days with maximum air temperature higher than 30°C; TR=tropical nights; DJF=winter; MAM=spring; JJA=summer; SON=autumn)

(Fig. 3). The differences among the clusters occurred especially during the JJA and SON, signifying a higher influence of solar radiation exposure on air temperature values of the area surrounding the stations, as in a previous study on urban albedo which reported that the use of high albedo materials reduces the amount of solar radiation absorbed through building envelopes and urban structures and keeps their surfaces cooler (Taha 1997). At times, it
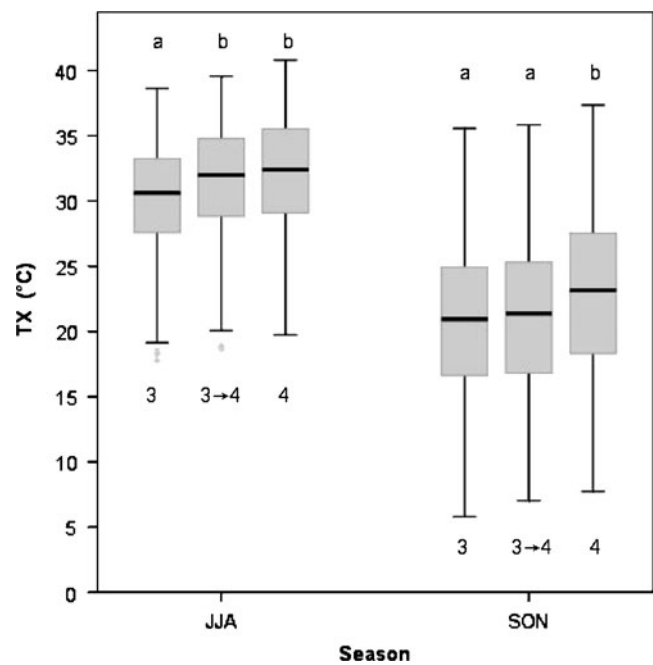
Table 3 Degree-day indices for Florence clusters expressed as mean seasonal degree-days (°C)±standard deviation (σ)

	Cluster	No.	HDD±σ (°C)		CDD±σ (°C)	
DJF	1	9	876±91	a	–	
	2	8	847±52	a	–	
	3	6	793±19	a	–	
	4	2	784±22	a	–	
MAM	1	8	384±21	c	30±5	a
	2	9	326±35	b	31±4	a
	3	6	285±4	a	40±6	b
	4	2	288±13	ab	56±0	c
JJA	1	7	24±3	c	276±22	a
	2	10	13±3	b	291±24	a
	3	4	6±0	a	339±27	b
	4	4	7±1	a	375±7	b
SON	1	9	322±20	c	44±4	a
	2	5	288±12	b	39±3	a
	3	9	245±17	a	53±7	b
	4	2	227±24	a	76±2	c

Different letters indicate significant differences for $p<0.05$ evaluated by the Bonferroni test

DJF=winter; MAM=spring; JJA=summer; SON=autumn; cluster= cluster number; No.=number of stations per cluster; HDD=heating degree-days; CDD=cooling degree-days

Fig. 3 *Box plot* of summer and autumn maximum air temperature (TX) values of stations belonged to cluster 3, to cluster 4, and of the stations that cross over from cluster 3 to cluster 4. *Different letters on the top of the box plot* indicate significant differences for $p<0.05$ evaluated by the Bonferroni test (JJA=summer; SON=autumn; 3= stations of cluster 3; 3→4=stations that cross over from cluster 3 to cluster 4; 4=stations of cluster 4)

might be difficult to change the albedo of the surfaces, but a similar effect could easily be achieved by using trees to provide shade, as for instance in Los Angeles where it was demonstrated that large-scale urban forestation can be as effective in reducing air temperature as the use of high albedo materials (Taha 1997). Furthermore, studies carried out in the Mediterranean city of Tel Aviv have shown that the cooling effect of the trees in summer can reduce temperatures by 3–4°C and that this effect depends mostly on the canopy coverage level and planting density (Shashua-Bar et al. 2010).

The differences found in FD and FH between clusters could be particularly important, especially for early and late frosts in spring and autumn. The difference in the number of frost days and hours estimated in the urban area may give some indications as to the type of crops or trees (Nkemdirim and Venkatesan 1985) that could be preferred (less or more susceptible to frost damage) depending on the location in the city.

As regards indices of summer days, summer hours, and tropical nights, our results also demonstrate important consequences on tree phenology and human health. Several studies attribute advanced flowering in urban environments to the Heat Island Effect (Neil and Wu 2006). A study conducted in Phoenix (USA) on the differences between urban and non-urban areas on the flowering responses showed that 24% species had a significant advanced response, suggesting that

urbanization may have a significant effect on a small but substantial proportion of plants, which is likely to affect native biological diversity due to potential changes in population and community dynamics (Neil et al. 2009). The results of our study highlight that even inside the city, a species may have a different phenological response. For example, flowering may start earlier in hotter areas than in other areas and, as a result, extend the flowering period. Timing of phenological phases may also have an impact on human health, for example, pollinosis that can be induced by large amounts of airborne allergenic pollen. A longer period during which it is possible to find allergenic pollen in the urban atmosphere results in longer exposure of people with allergies. In this case, the choice of plants with lower allergenic pollen may be a solution for reducing the presence of this contaminant in the urban atmosphere.

Alternatively, phenological monitoring associated with biometeorological forecasting may represent an important information service for physicians. These studies were used in Florence (Italy) to create a useful model for predicting the starting and ending date of the dispersal period of Cupressaceae in order to be fruitfully exploited by the allergic population that could benefit from the possibility of starting anti-allergic therapy several days earlier than the onset of symptoms and ending it when the pollen concentration in the air is low (Torrigiani Malaspina et al. 2007). Our study suggests that such a model could be implemented with phenological and thermal observations in different locations in the city.

The urban–rural air temperature difference (UHI effect) is particularly evident during the late afternoon (Landsberg 1981; Oke 1981), determining a number of tropical nights which is higher in urban than in rural areas. Our results highlight a huge difference in TR between the clusters, particularly during the summer period.

It is common knowledge that an increase in extreme temperature events during the summer period can have many adverse impacts on human health, thus causing deaths or injuries (Morabito et al. 2005). The relationship between nighttime conditions and human health during the summer period seems to be very significant. Some studies on heat-related illnesses stressed how oppressive nighttime conditions after a very hot day might be more stressful than the maximum temperature itself (Kalkstein and Davis 1989; Petralli et al. 2006b). The results of this study show how very different nighttime conditions may exist in the city, possibly with a different impact on human health. As a result, people living in different areas of the city may have higher or lower risks of heat-related illnesses during heat waves. Further investigation on heat-related illnesses and intra-urban meteorological differences needs to be performed.

An analysis of degree-day indices provides interesting suggestions about energy demand during all seasons in different parts of the city. The significant difference in spring and autumn HDD among clusters determines a differentiation in the demand for heating and cooling depending on the area of the city in these seasons. In Florence, the intra-urban seasonal difference in cooling and heating degree-days can easily reach 90–100°C, determining important differences in energy demand and consumption. The annual intra-urban difference in heating demand was 19%. Similar results have been reported by several European authors (Unger and Makra 2007; Santamouris et al. 2001) on analyzing the differences in HDD between rural and urban areas, where they estimated an urban–rural difference in heating demand of 12% in Athens and 19% in Szeged, showing that the intra-urban variation is comparable with the urban–rural variation.

All these results should be taken into consideration by urban planners. As reported by Svensson and Eliasson (2002), even though several publications on climatic design and on urban climatology have been available since the 1960s (Morgan 1960; Aronin 1953; Givoni 1969) and some data is still to be published, several authors have shown that climatic aspects have a low impact on the urban planning process, which focuses more on energy consumption reduction rather than on the heating effect of buildings and the consequences on local climate (Oke 1984). Indeed, the heating effect of buildings produces a variation in HDD and CDD, as demonstrated by the results of this study on the high diversification of these indices in the city, and this variation should not be overlooked by urban planners.

The results of this study help quantify the intra-urban thermal differences in the city of Florence (Fig. 2), revealing important applications in phenology, aerobiology, urban planning, and biometeorology.

Further studies will be carried out to analyze the relationship between the built-up environment and the air temperature distribution in Florence in various meteorological conditions, taking into account the characteristics of the area in which the meteorological instruments are located, such as instrument exposure, number and height of buildings, and the presence of green areas and trees surrounding the station.

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