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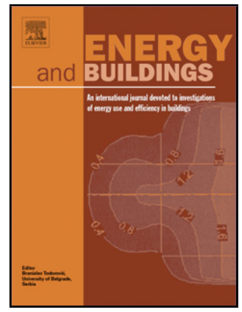

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On the assessment of urban heat island phenomenon and its effects on building energy performance: A case study of Rome (Italy)

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HIGHLIGHTS

- Assessment of the climatic conditions in Rome and its surroundings;
- Evaluation of the occurrence of the Urban Heat Island during the whole year;
- Test of the weather data differences by means of a well-known dynamic software;
- Impacts of UHI on cooling and heating energy demands.

Abstract – A wide variety of weather-data are readily available for simulating buildings energy performance by using dynamic software. However, climate change and its effects on buildings energy performance represent a critical issue, also considering the implications of climate change on human comfort. Starting from this, the present study aims at analyzing the climatic conditions in Rome and its surroundings, evaluating the occurrence of the Urban Heat Island (UHI) phenomenon. Therefore, meteorological data derived from two airports near the city and climatic data registered for two years in a central, densely-built zone of Rome were analyzed and compared. Furthermore, the differences among weather data were tested by means of a well-known and widely used dynamic software in order to evaluate the effects of different climatic boundary conditions on building energy performance, in terms of heating and cooling energy demands. The results highlight significant differences with regard to temperature, wind velocity and relative humidity, as a result of a prevailing UHI phenomenon in central Rome throughout the year. The simulations show an average increase of cooling energy demand of about 30% and an average reduction of heating energy demand of about 11%. Such differences give the rise for the investigation of the reliability of weather-data files commonly used in building simulations, in order to properly estimate the buildings energy demand under a sustainable city perspective.

Keywords: *urban heat island; weather data; dynamic simulation; summer cooling; winter heating; air temperature; relative humidity; wind velocity.*

1. Introduction

During the last years, the scientific community has been attracted by issues related to building energy performance and energy savings [1–7]. The importance of buildings energy savings comes from the need to reduce fossil fuels consumption and mitigate pollutant emissions, according to International Protocols and EU Directives [8,9]. Urban growth has impacted the energy performance of buildings and human comfort, among others, by changing the landscape, as buildings and other infrastructures substitute open land and vegetation. This growth leads to the development of the so-called Urban Heat Island (UHI) phenomenon, characterized by higher temperatures in the densely built areas than the ones of the rural surroundings. These temperature differences can range between 1°C to 3°C in cities with one million or more inhabitants [10]. The UHI phenomenon is expected to increase in intensity as a consequence of the global warming and the growth of urban population [11]. In order to preserve human health and improve the livability in the cities, the UHI has to be controlled by different mitigation strategies applied by urban and buildings designers [12].

The overheating of the city is caused by many different interacting factors such as land cover, absence of vegetation, occurrence of impervious surfaces, presence of water, population density and combustion effects in the urban environment [13]. An important aspect concerns the presence of green or cool surfaces and vegetation because these can reduce the latent heat that also weakens the effects of the UHI. In urban areas, there are also significant effects resulting from tall buildings that hinder the heat dispersion through thermal radiation. This phenomenon is particularly strong during the night and it reduces the buildings night cooling potential [14]. Moreover, the heat dissipated from buildings to the external environment by the use of air-conditioning systems, increases the UHI phenomenon [15]. Human activities therefore contribute to this urban overheating phenomenon both in a direct way, through the industrial and transport activities, and in an indirect way, altering the radiative properties of the atmosphere caused by air pollution.

During the summer, UHI phenomena can be stronger when the sky is clear and there is no wind. On the other hand, high wind velocities increase the atmospheric shuffling, lowering the temperature difference between urban and rural zones [16].

The effects of the UHI on the energy consumption of buildings have been widely investigated, documenting a significant increase of the cooling loads and electricity consumption in the building sector [17,18]. On the other hand, warmer external temperatures may reduce the energy consumption for heating in colder regions. The peak cooling load is estimated to increase in a range of 0.5% and 8.5% for every centigrade increment of the external temperature in different countries around the world [19]. In Beijing [20], it has been reported that the UHI has increased the cooling energy demand by 11% (+7% considering the peak cooling load) and has reduced the heating energy demand by 16% (-9% if the peak heating load is considered). In the South America Pacific coast the UHI causes a rise in the cooling energy demand ranging from 15% to 200% [21], while in Barcelona the increase of the cooling demand has been estimated to range from 18% to 28% [22].

The previous studies demonstrate that the effect of the UHI on building energy consumption is not negligible and in many cases it is not considered in dynamic calculation software, which assess the building-plants' performance considering the building envelope performance and the evolution of the physical phenomena over time [23]. For this reason, a methodology that includes the UHI effect in the dynamic simulation software, employed for the building energy consumption calculation, is strongly recommended.

Building simulation codes can consider inertial effects and climatic variations by using Typical Meteorological Years (TMY), representing conditions considered to be typical for a given location, produced from measured data over a long time-period (e.g. 10-, 20- or 30-years) [24]. Many commercial software support simulations employing TMY files, such as TRNSYS [25] and EnergyPlus [26]. Regardless of the simulation tool, climate changes and their effects on buildings energy performance, human comfort and air quality represent a critical issue and may explain the variations observed in building thermal simulations and thermal comfort conditions [27,28]. Climatic files can also be derived by means of database of meteorological information [29] and calculation procedures, with statistical data for every location in the world, which can be useful for the design of solar systems.

In many cases weather data are obtained from airports, but these stations are usually far away from the densely-built part of a city. As a result, these measured data cannot account for the UHI effects and realistically account for the prevailing conditions in urban environments [22]. Typical meteorological years are useful for the design and the energy performance assessment of new buildings [30]. Meteorological data obtained outside the urban texture are not affected by the UHI phenomenon and they can be considered reliable for new buildings typically realized in new neighborhoods characterized by a low urban density, far away from the city center and built paying attention to sustainability aspects. New buildings are designed taking into account technical solutions able to counteract the UHI phenomenon through cool roofs, cool pavements, green zones and so on.

On the contrary, the same considerations do not prevail for existing buildings in urban environments (e.g. in ancient cities' densely-built areas) for which countermeasures are difficult to realize Building retrofits are based on calibrated energy models but it is well-known that, in order to obtain comparable results, the calibration parameters need to be related to the period of time in which the model is defined.

The novelty of this work is the assessment of the climatic conditions in Rome, the most populated Italian city, characterized by a high built density, employing meteorological data registered from three different locations for two years, and assessing the occurrence of the UHI phenomenon and its impact on building heating and cooling energy

demand. The present work uses data from long term field monitoring, since the UHI effects should be considered for long periods and the adopted countermeasures need to be effective over time.
The structure of the paper is as follows. Section 2 presents the aim and scope of the research. In Section 3, the materials and methods are defined. Section 4 elaborates the results and highlights the significant effects of the different weather data on the simulation of building energy demands. Section 5 summarizes the main conclusions.

2. Aim and scope

As highlighted in the previous section, climate change and its effects on buildings energy performance and human comfort constitutes a significant issue. The aim of this research is to first analyze the climatic conditions in Rome and its outlying areas, by highlighting the differences between weather data from the two airports near the city (Fiumicino and Ciampino) and from a meteorological station located in a densely-built zone of Rome (Fig. 1), using a two-year monitoring data that is available for the period of October 2014 to 2016. The airport of Fiumicino is 24 km away from the center of Rome (in an area not densely built, rich in vegetation and close to the sea), while the airport of Ciampino is located 13 km away from the city center, in the inner part of Lazio region (also this area is not densely built).
The second aim of the work is to evaluate the UHI phenomenon in Rome using the measured meteorological parameters: dry bulb temperature, wind speed, wind direction and relative humidity. Dry bulb temperatures allow the evaluation of the occurrence of UHI phenomenon, by calculating the temperature differences between urban and rural areas. The increase in temperatures can be also related to wind velocities because in summer urban heat islands are most intense when the winds are calm. Several studies have confirmed that the evapotranspiration phenomenon increases relative humidity and indirectly contributes to the reduction of the temperature in the city. Due to this, an evaluation of the UHI phenomenon was carried out considering the meteorological differences between Rome and its surrounding areas.
The two-years set of measured data were also used to generate a sample year which was then compared with meteorological data listed in the Italian Standard UNI 10349 [31]. The 2016 review of the UNI 10349 updated the climatic data for the calculation of the annual heating and cooling energy demand, and provides for 101 Italian cities the average daily direct and diffuse solar radiation values on the horizontal plane, the monthly average and annual wind speed and direction values. This comparison was carried out to highlight the reliability of updated climatic conditions reported in the UNI Standard compared to in-situ measurements;
Finally, weather data differences were evaluated by using them as input to a well-known dynamic software in order to assess the influence of different climatic boundary conditions on the building energy performance in terms of the estimated heating and cooling energy demand.
In the last years, energy efficiency in buildings has played a key role aiming to support the design of (nearly) zero energy solutions. The ever-increasing employment of building-integrated systems based on renewable energies has motivated a comprehensive analysis of microclimate conditions, in order to maximize the annual energy production and, consequently, to understand the investment’s affordability. In particular, in cases that heritage buildings need significant retrofit interventions, the accuracy of the simulation results is a fundamental issue in order to achieve the best results under a sustainable city perspective.
In this context, the main objectives of this work are to:

- Investigate the differences between weather conditions in a densely-built zone of Rome and its outlying areas;
- Evaluate the UHI phenomenon in a densely-built Mediterranean city like Rome;
- Generate a sample year to be compared with meteorological data listed in the Italian Standard UNI 10349 [31];
- Analyze the influence of different climatic boundary conditions on the building energy performance in terms of the estimated heating and cooling energy demand.

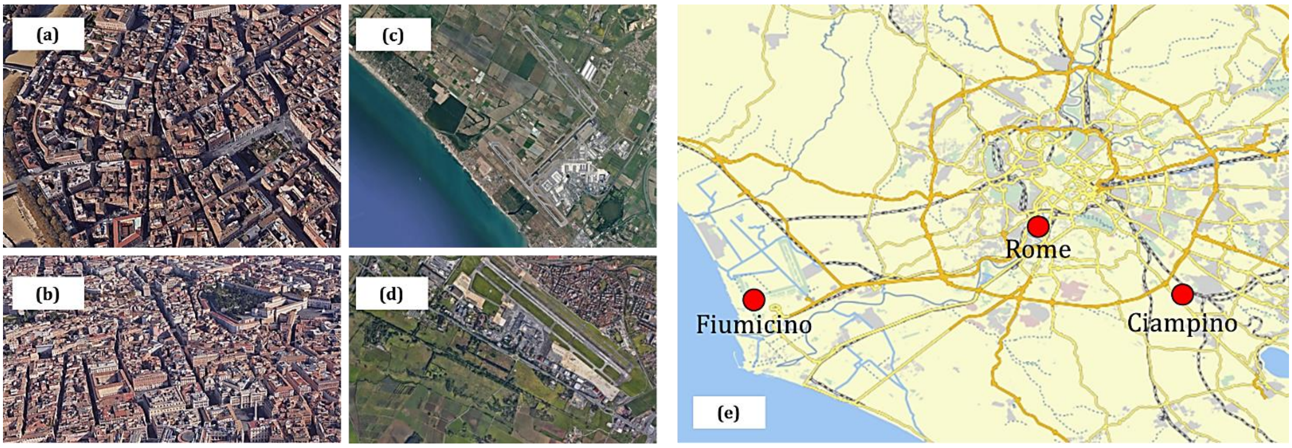

Fig. 1. (a), (b) Densely-built urban areas of Rome; **(c)** Fiumicino airport area; **(d)** Ciampino airport area; **(e)** locations of the weather stations.

3. Materials and methods

3.1 Relevant characteristics of Rome

Rome (approximately 41°54′N 12°29′E and ranging from 13 to 120 meters above sea level) is one of the most densely-built Italian cities, and the most populated, with more than 4.3 million of inhabitants [32]. The city rises on the banks of the Tiber river, about 24 km from the Latium coast. According to the classification of the Köppen climates (the most widely used among climatic classifications for geographic purposes), Rome belongs to the "*Csa band*", that is the temperate climate of the median latitudes, characterized by hot summers. With a maximum average temperature higher than 30°C, the summer in Rome is very hot. Over the last decades, due to climate change, Rome registered an increase in the intensity of heat waves with uncomfortable temperatures and adverse conditions, during the day and night. In the summer, the mitigating influence of the Tyrrhenian Sea is more perceptible on the western side of the city. The climatic conditions are significantly different in the city center, since it is only partially reached by winds because of the strong urbanization. Even warmer are the eastern districts, since they are almost completely deprived from the benefits of any significant wind effects.
From an architectural point of view, Rome is the result of a continuous urban overlap and expansion over the various centuries. The urban blocks size differs within the city, according to different historical periods. The central zones are characterized by large homogeneous blocks linking a complex street network (Figs. 1a and 1b) while green open areas are mainly present in the outskirts of the city.

3.2 Methodology

Meteorological data acquired from the two airport stations were processed in order to make them comparable with the urban data. Taking into account the two-year monitoring, monthly average air temperatures of Fiumicino, Rome and Ciampino were compared, covering the same period of October 2014 to October 2016. Data related to monthly average maximum and minimum temperatures were also processed and employed to quantify the UHI phenomenon in Rome. The characteristics of the meteorological station in Rome are listed in Table 1. The weather station is located in an old neighborhood of the city, surrounded by tall buildings and urban parking lots that are covered by asphalt, with an albedo coefficient of about 0.12. Surrounding green areas are negligible and the Tiber river flows at a distance of about 1 km from the measurements location. Both the Fiumicino and Ciampino airport stations are reference meteorological stations for the Meteorological Service of the Military Air Force [33] and for the World Meteorological Organization (WMO) [34]. Table 2 lists some information about the two weather stations, including their height above sea level (a.s.l.), the WMO code of each station and their coordinates.

Table 1. Technical specifications of the meteorological station located in Rome.

Meteorological station model	Davis Vantage Vue		
Type of installation/Coordinates	Urban / 41°51'16.2" N 12°28'12.0" E		
Sensor height	35 m above sea level		
Meteorological parameter	**Resolution**	**Range**	**Accuracy**

Wind speed	1 km/h	From 0 to 241 km/h	3 km/h or 5%
Wind direction	1°	From 0° to 359°	3°
External temperature	0.1°C	From -40 to 65°C	0.5°C
Relative humidity	1%	From 0 to 100%	3%

Table 2. Characteristics of the airport meteorological stations.

Airport	**Height a.s.l.**	**WMO code**	**Coordinates**
Fiumicino	3 m	16242	41°47'53.66" N 12°14'22.36" E
Ciampino	129 m	16239	41°48'29.49" N 12°35'05.82" E

Moreover, wind speed and relative humidity values were used to provide a comparison among the different geographical locations. Measured data were also employed to develop a sample year in order to make a comparison with the UNI 10349 updated values. Finally, the influence of different weather-data was tested by means of the dynamic simulation software TRNSYS [25], reproducing hourly meteorological data by employing the Type 54-Weather generator. The Type 54 is the most common method to generate typical climatic data where observed meteorological data is not available and has been used for several purposes [35,36]. The input parameters include the monthly average wind speed, monthly average dry-bulb temperature and solar radiation on horizontal surface. However, as shown in Table 1, the meteorological station does not monitor solar radiation. For this reason, the necessary solar radiation data were obtained by the default weather-data file generated by TRNSYS. Rome, Fiumicino and Ciampino meteorological data in 2015, the sample year weather data and UNI 10349 climatic data were used and compared as different input data for the simulations in order to highlight differences and similarities. The simulations are performed for a simple detached building (Fig. 2). Each wall has a surface area of 36 m^2. Three different wall configurations were considered in the simulations. These stratigraphies are based on the TABULA residential building typologies [37] that include a breakdown of Italian buildings since 1900 according to the typical construction techniques of different periods. The simulated walls refer to three different construction periods and they are characterized by different materials, as shown in Table 3. In particular, Building Envelope (BE) 1 is a typical construction from 1900 to 1950, characterized by a thick main layer made of solid bricks, still widespread in Italy. BE 2 is a thinner stratigraphy, composed by a central layer made of concrete, typical from 1955 to 1975 and characterized by particularly high thermal transmittance value (*U-value*). Finally, BE 3 represents the construction technique that is typical of the most recent buildings, with the addition of a thermal insulation layer.

Table 3. Typical Italian building envelope (BE) stratigraphies employed in the simulations.

	Material layer	**Thickness [m]**	**Thermal conductivity [W/mK]**	**Specific heat capacity [J/kgK]**	**Mass density [kg/m³]**	**U-value [W/m²K]**
BE 1 (1900-1950)	Plaster	0.02	0.700	1000	1400	1.020
	Solid bricks	0.58	0.770	840	1600	
	Plaster	0.02	0.700	1000	1400	
BE 2 (1955-1975)	Plaster	0.02	0.700	1000	1400	2.800
	Concrete	0.26	2.000	1000	2400	
	Plaster	0.02	0.700	1000	1400	
BE 3 (1991-2005)	Plaster	0.02	0.700	1000	1400	0.600
	Thermal insulation	0.04	0.034	1450	50	
	Concrete	0.22	0.730	1000	1600	
	Plaster	0.02	0.700	1000	1400	

All the building envelopes are characterized by a solar absorptance coefficient equal to 0.6. The single pane windows have a total area of 18 m^2 and a thermal transmittance of 5.61 W/m^2K. The infiltration rate is set at 0.5 1/h. Internal heat gains account for occupancy (sensible heat of 65 W and latent heat of 55 W) and appliances (thermal power equal to 140 W). The indoor set-point temperature is 26°C for cooling and 20°C for heating, while the desirable relative humidity is set at 50% for both winter and summer. This is a simplified assumption since the commonly used local air conditioning units cannot control humidity independently of the temperature.

The sample building model (setup as a free standing building) was thermally stressed by imposing different climatic conditions: the acquired climatic data at urban and peripheral sites were then employed as input for a set of energy simulations using TRNSYS. The overall procedure is illustrated by a flow-chart in Fig. 3.

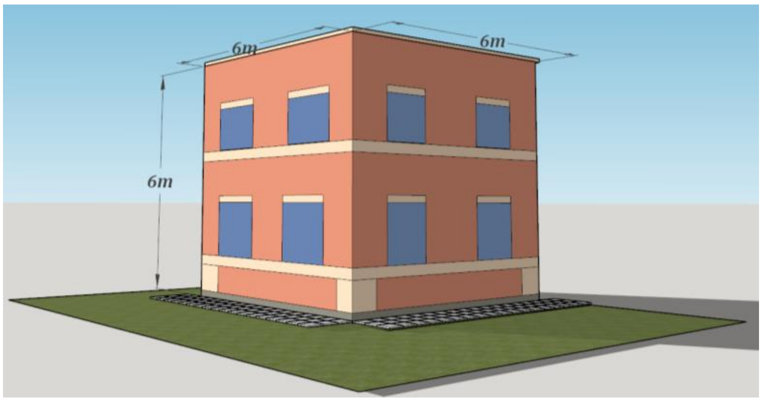

Fig. 2. Sample building 3D view.

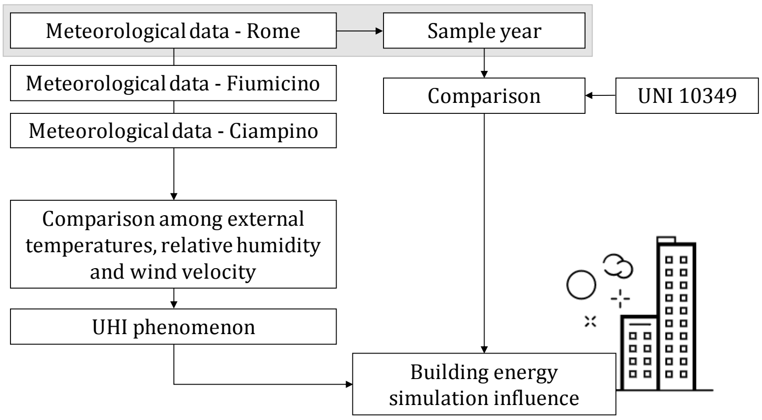

Fig. 3. Flow-chart of the procedure employed to compare meteorological data.

4. Results and discussion

4.1 UHI in Rome: meteorological data comparison

In order to provide a global view of the climatic conditions of Rome and its surrounding areas, the first step was to compare the monthly average air temperatures of Fiumicino, Rome and Ciampino (Fig. 4a). The figure also shows the maximum temperatures to identify the highest discrepancies in temperature variations. One can observe that Rome and Ciampino are characterized by similar average values during the hottest months (from June to September), both in 2015 and 2016. During winter, Ciampino has lower temperatures than Rome, with a temperature difference between Fiumicino and Ciampino of -1.2°C in January 2015 and -2.3°C in October 2016. On the other hand, Fiumicino is characterized by the opposite trend: during winter, the temperature values are similar with those measured in Rome and the highest differences are observed during summer. Analyzing the maximum temperatures in summer, the differences between Rome and Fiumicino reached 2°C (July and August 2015).
The observed trends confirm the presence of the UHI phenomenon, which is also supported by the analysis of the wind speeds (Fig. 4b). There are high differences among the locations. During the two-year monitoring, the average wind speed in Fiumicino (measured at 10 m height) ranged between 7.4 km/h and 16.9 km/h, while in Rome the values ranged between 0.9 km/h and 5.9 km/h. As shown in Fig. 4b, the wind speeds in Ciampino (measured at 10 m height) are higher than the ones in Rome (the lowest wind speed is equal to 6.8 km/h), but lower than those of Fiumicino (the highest wind speed is equal to 14.8 km/h). As shown, the winds in Rome are characterized by the lowest values and this is due to its complex urban terrain that influences the wind flows. From an aerodynamic point of view, cities are characterized by significantly different air circulation compared to rural areas and tall buildings hinder and reduce wind speeds. It is important to observe that even if Fiumicino is not actually a “rural area”, the Fiumicino airport area is characterized by small and low-height buildings, with a low building density. The airport area extends for about 350,000 m^2, characterized by a central zone with passenger main terminal with airplane gates access, airplane runways and aircraft hangars are all around; the meteorological station is installed far away from this central zone.
Fig. 4c shows the comparison in terms of Relative Humidity (RH). Also in this case, Rome is characterized by lower values than Fiumicino, except for some months, during winter. Relative humidity indirectly contributes to the reduction

of the urban temperatures because it reduces the evapotranspiration effect. It is well-known that green areas can significantly contribute to environmental cooling through the evapotranspiration effects, derived from vegetation, urban agriculture and water bodies [38]. Fiumicino is located on the Latium coastline, close to the sea, and as a result it has relatively higher humidity levels during summer. Moreover, the Dew Point (DP) temperatures shown in Fig. 4d can be used to analyze the impacts of local sources of water vapor, providing additional information about the absolute water content of the air at the corresponding air temperature.

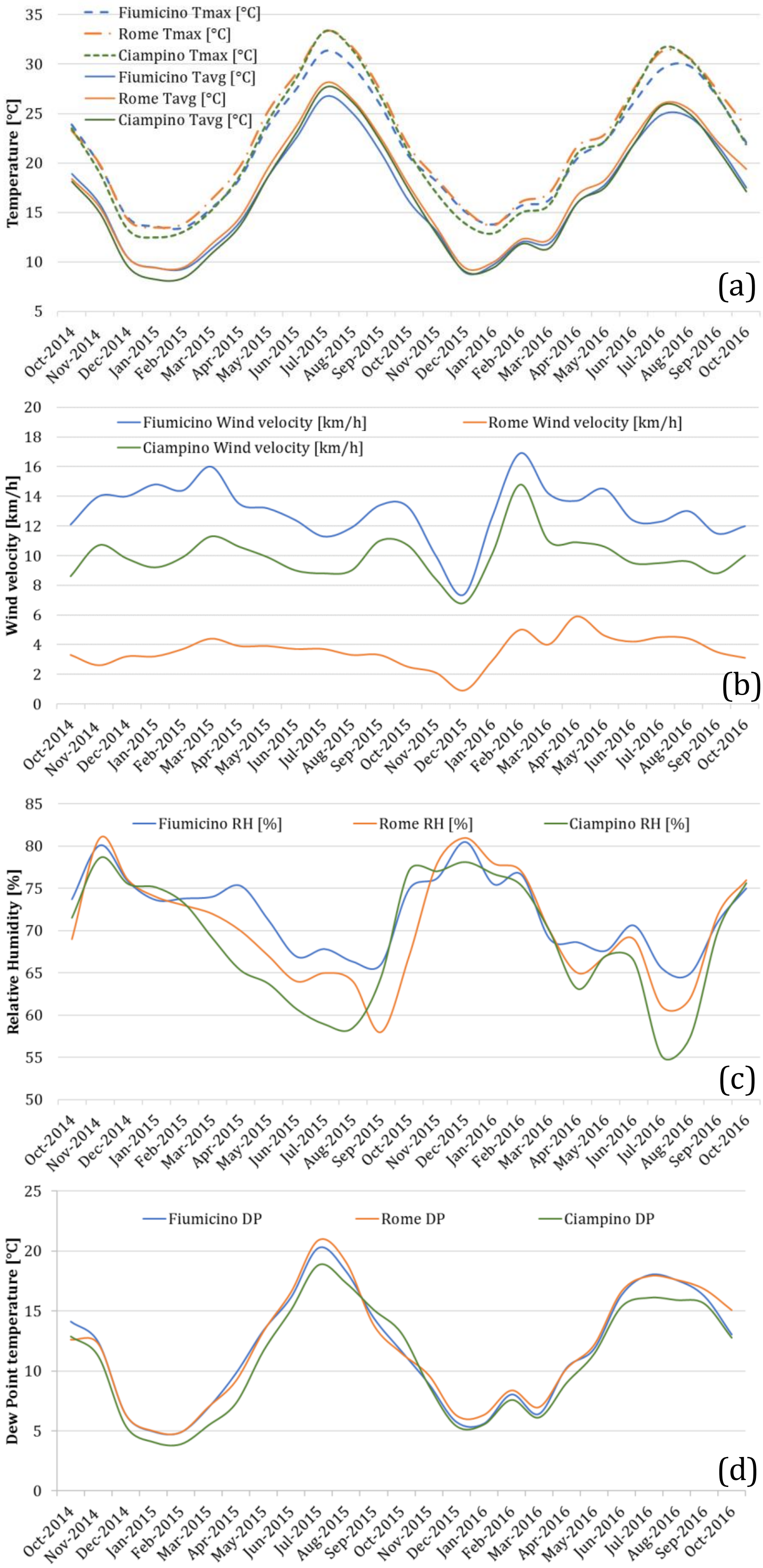

Fig. 4. Variations of air temperature **(a)**, wind speed **(b),** relative humidity **(c)** and dew point temperature **(d),** recorded in Fiumicino, Rome and Ciampino (Tavg = average temperature; RH = relative humidity; DP = dew point).

Analyzing and processing the temperature differences between Rome and Fiumicino, Fig. 5a shows the monthly UHI intensity during the day and night. In addition, Fig. 5b shows the same information taking into account the comparison between Rome and Ciampino.
Fig. 5a highlights that the highest differences can be reached during the night (2.9°C). UHI phenomenon is not related only to the summer season but it can be observed during the whole year, becoming more evident between May and September. Considering the two-year monitoring data, the urban-rural temperature difference average values are 0.84°C during the daytime and 1.40°C during the night.
On the other hand, Fig. 5b highlights the differences between Rome and Ciampino. Again, the highest values are reached during the night (3°C). In this case, the temperature difference average values are 0.74°C during the daytime and 1.30°C during the night. These values are slightly lower than the previous ones and this can be traced back to the geographical position of Ciampino, which is closer to Rome and far away from the sea.

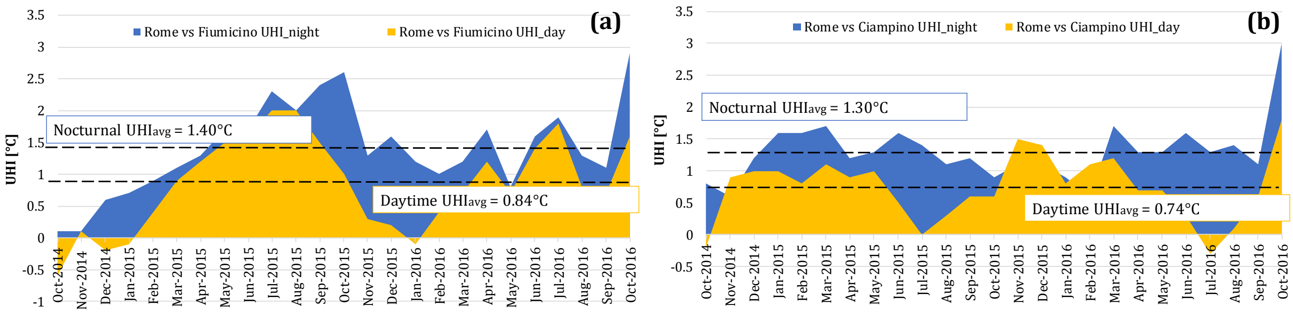

Fig. 5. UHI along the two-year monitoring, comparing Rome and Fiumicino stations **(a)** and Rome and Ciampino stations **(b)** during the day and night.

Many neighborhoods in Rome are characterized by tall buildings and high urban density, creating tall canyons that trap radiant heat in their walls. Furthermore, Rome is a city where pollution levels are quite high and the haze of air pollution acts as an infrared absorbing layer [39], preventing the outgoing thermal radiation to escape from the city. In addition, the heat exhausted from air-conditioned buildings in summer can further increase urban temperatures [40].
Starting from the results shown in Fig. 5, a more detailed comparison was performed considering three summer months (June, July and August) in 2015. Fig. 6a shows only the comparison between Fiumicino and Rome in terms of daily average air temperatures and maximum air temperatures, also considering the monthly average values suggested by the Standard UNI 10349. Analyzing Fig. 6a, it is possible to observe that the UNI Standard air temperature values are very close to the average temperatures related to Fiumicino, during June and July. These similarities are less evident in August, when the actual average temperatures are lower, with differences reaching +2.4°C during the day and -4.6°C during the night. The comparison of the values from the UNI Standard and the daily average temperatures related to Rome, reveals more pronounced differences. In June, July and the first ten days of August, daily average temperatures were higher than those suggested by the UNI Standard, with differences that reached +4.1°C during the day and -5.3°C during the night.

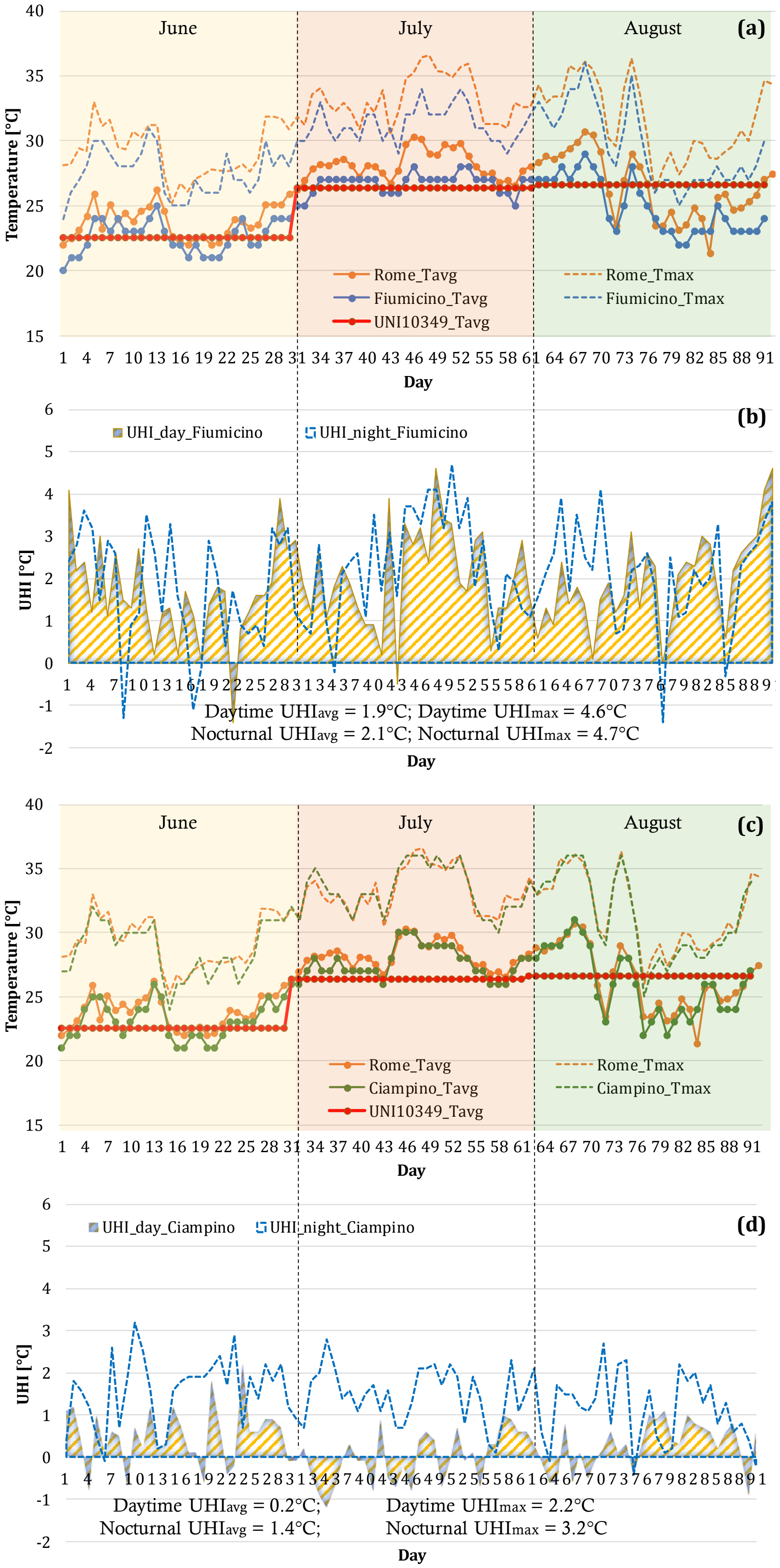

Fig. 6. Comparison between Rome and Fiumicino stations during June, July and August **(a)** and UHI variations over time, with average and maximum values **(b)**. Comparison between Rome and Ciampino stations during June, July and August **(c)** and UHI variations over time, with average and maximum values **(d)**.

In addition, Fig. 6b shows the urban-rural temperature differences during the summer, in order to provide a better description of the UHI phenomenon during the three analyzed months. In particular, daytime and night temperature differences were calculated, providing the average and maximum values shown in Fig. 6b.
The same comparison was achieved analyzing the climatic conditions in Rome and Ciampino (Fig. 6c). Observing the average daily temperatures and the maximum ones, it is possible to observe closer values compared to the previous analysis regarding Fiumicino and Rome. In this case, the temperature differences are less evident and consequently the UHI intensity (Fig. 6d) seems to be less evident. However, while the UHI intensity reaches 2.2°C during the day, the phenomenon increases during the night, reaching 3.2°C. Considering the entire period of the three summer months, the analysis reveals that the average value of the UHI intensity during the day is equal to 0.2°C, reaching 1.4°C during the night.

4.2 Sample year and Standard comparison

Starting from the two-year monitoring, a sample year was created by averaging the acquired meteorological data in Rome. The obtained climatological year was then compared with the updated data reported in the Standard UNI 10349. In 2016, this Standard was revised with the updated monthly average values related to air temperature, relative humidity, solar radiation and wind speed. In the previous edition of the UNI Standard (1994), climatic data were obtained from airport weather stations. In the 2016 version of the Standard, new monthly average temperatures were provided by the regional environmental protection agencies [41], only considering the meteorological data related to recent years (Fig. 7). From a statistical elaboration of these data, the new edition of the UNI Standard (2016) provides a typical year, which is composed by the set of actual data for months that best represent the average climate of a specific location.

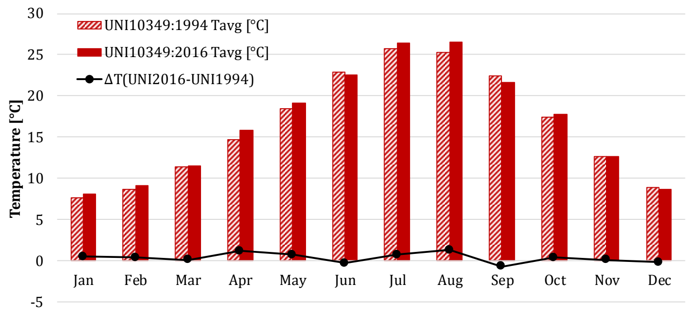

Fig. 7. Comparison between UNI 10349:1994 and UNI 10349:2016 temperature data.

Fig. 7 illustrates that the updated edition of the UNI Standard shows an increase of average temperatures for almost all months, except for June, September and December. During the summer, these differences are more significant, reaching values of about 1.5°C.
Fig. 8a shows the comparison among the monthly average temperatures obtained by the sample year and the Standard. UNI 10349 and the sample year are characterized by very similar values (i.e. temperature differences are less than 1°C), especially from March to October. During winter, especially in January and February, air temperatures provided by the UNI Standard are lower than the ones in the sample year, with temperature differences reaching 1.6°C and 1.8°C, respectively (illustrated with the grey bars referred to the right axis in Fig. 8a). Other differences can be observed during the summer, in particular in July and August (0.7°C in both cases), and during the winter, in November and December (1.8°C and 1.2°C, respectively).
Fig. 8b shows a comparison between wind speed and relative humidity. Wind speed values in UNI 10349 refer to definition of "wind zone", considering a subdivision of the Italian peninsula in different zones, characterized by different wind speeds. Rome belongs to the "Area C" with an average wind speed of 6.1 km/h and a prevailing wind direction South-West (SW). As illustrated in Fig. 8b this value is higher than those obtained by the sample year, which range between 2 km/h and 4.9 km/h.
Furthermore, Fig. 8b shows a comparison between relative humidity values from the UNI Standard and the sample year. UNI 10349 reports lower values (from -1.5% up to -15%) than the sample year, except for January (+12%), March (+3%) and December (+5%).

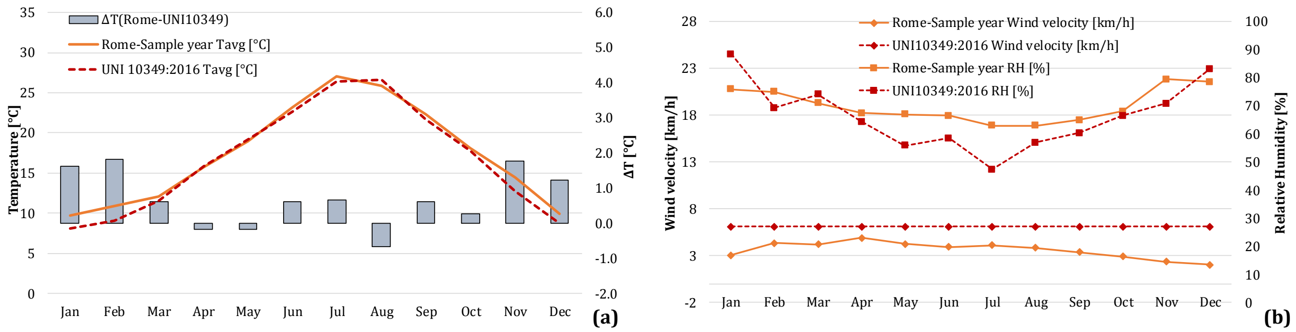

Fig. 8. Comparison between the sample year and UNI 10349 temperature data **(a)**; Wind speed and relative humidity **(b)**.

4.3 Weather data influence on building energy performance

As mentioned in the methodology Section, TRNSYS was used to simulate the energy performance of the sample building in order to quantify the influence of different climatic conditions on the results. Given that the meteorological station located in Rome does not report solar radiation data, the corresponding values were obtained by the default weather-data file provided by the weather generating component within TRNSYS (Type 54). Each time, the corresponding wind speed values from each data set were used to calculate the convective heat transfer coefficients, by using specific correlations [42,43] for estimating the coefficients calculated by TRNSYS. Fig. 9 shows a comparison among the convective heat transfer coefficients (h_c) obtained by employing the different wind speed data (v_{wind}) from the five data sets, using the well-known formula $h_c=4+4v_{wind}$ [44], where the wind speed is expressed in m/s. Fig. 9 illustrates the different h_c values and corresponding data through their quartiles, highlighting significant differences. Using the wind speeds measured in Rome during 2015 provide a convective heat transfer coefficient ranging from 4.15 W/m^{2}K to 14.62 W/m^{2}K, while the h_c obtained by employing the UNI 10349 lead to higher values. As shown by the box-plot, the values achieved by using wind speeds in Fiumicino (light blue) are very high compared to the other values and they cannot be considered representative of the actual heat transfer conditions. This assessment allows a better understanding of the differences when h_c coefficients are calculated inside the dynamic code, employing the different wind speeds.

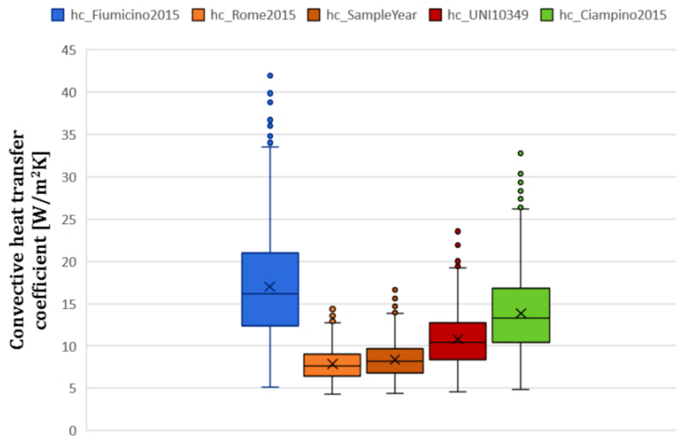

Fig. 9. Convective heat transfer coefficient box-plot considering different wind speed data.

Table 4 summarizes the simulation results for the normalized total (sensible and latent) heating and cooling energy demand using the five different climatic datasets. The three different building envelope (BE) constructions for the sample building are defined in Table 3. Significant discrepancies are noticeable both during winter and summer. The lowest values in terms of heating energy demand were obtained for each of the three investigated typical constructions, using the actual climatic conditions in 2015 and the sample year, because of a higher overheating of the urban areas compared to the peripheral ones. On the other hand, the UHI phenomenon in Rome plays a crucial role in calculating the building cooling energy demand. Although the UHI will have a positive effect during winter, an inappropriate climatic data may not realistically capture the effects on building energy performance throughout the year and that would result to unrealistic results.

Table 4. Energy demand of the sample building under different climatic conditions.

Climatic data	BE 1		BE 2		BE 3	
	Heating [kWh/m^2]	Cooling [kWh/m^2]	Heating [kWh/m^2]	Cooling [kWh/m^2]	Heating [kWh/m^2]	Cooling [kWh/m^2]
Rome 2015	86.7	34.8	186.2	24.2	55.9	43.1
Fiumicino 2015	93.6	24.6	202.6	14.5	61.3	32.6
Ciampino 2015	99.4	30.9	210.4	20.8	66.4	38.9
UNI 10349	93.3	28.1	197.7	17.7	62.9	36.4
Sample year	76.7	29.5	171.5	18.4	49.7	38.1

Table 5 highlights the percentage differences of heating and cooling energy demand, using the different climatic conditions in the simulations, compared to the reference conditions of Rome 2015 and the sample year generated by averaging the meteorological data along the two-year monitoring. The three different building envelope (BE) constructions are defined in Table 3.

Using the Fiumicino 2015 climatic data (with all three typical constructions), leads to the highest percentage differences for the calculated cooling energy demand (+41.5%, +66.8% and +32.2% for the three wall constructions, respectively). The heating energy demand has a homogeneous percentage difference, averaging 8%.

Similar trends can be observed by comparing Rome 2015 and UNI 10349 climatic data. In this case, the highest and the lowest percentage differences result from the simulations using the BE 2 simulations (+36.7% and -5.8%). Using the meteorological dataset of Ciampino 2015, comparable percentage differences between heating and cooling energy demands are obtained for the three typical wall constructions. A thermally insulated wall construction (BE 3) results to a lower percentage difference during the summer (+10.8%) and a higher difference during the winter (-15.8%) compared to the typical constructions characterized by higher U-values.

On the other hand, a different trend is shown when the Sample year and the UNI standard are compared. In this case, the highest percentage differences are observed during the winter and this is related to the temperature discrepancies during the winter months of January, February, November and December (Fig. 8a).

The resulting deviations are related to the air temperature differences among the various locations, characterized by different urban texture and buildings geometrical characteristics, which are responsible for a significant UHI phenomenon in Rome throughout the year.

Table 5. Percentage differences for energy demand using different climatic data.

Climatic data	Percentage difference [%]					
	BE 1		BE 2		BE 3	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
Rome 2015 vs Fiumicino 2015	-7.4	+41.5	-8.0	+66.8	-8.8	+32.2
Rome 2015 vs Ciampino 2015	-12.8	+12.6	-11.5	+16.3	-15.8	+10.8
Rome 2015 vs UNI 10349	-7.1	+23.8	-5.8	+36.7	-11.1	+18.4
Sample year vs UNI 10349	-17.8	+5.0	-13.2	+5.6	-21.0	+4.7

5. Conclusions

This work analyzed the climatic conditions in the city of Rome and its surrounding areas, in order to assess the possible UHI phenomenon and its impact on the energy performance of buildings over the long run. The findings of this study reveal non-negligible differences among the different climatic parameters in the three locations. Comparing Rome and Fiumicino, it was highlighted that there is an average temperature gap of about 0.84°C during the day and 1.40°C during the night, which become 4.60°C and 4.70°C when considering only the summer months. Moreover, differences are also observed for the wind speed and relative humidity values. Accordingly, the wind speeds in Rome, which is a representative Mediterranean metropolitan city, are the lowest because of the complex urban geometry that influences the wind flows. Significant differences for the relative humidity were pinpointed, especially during the summer. On the other hand, comparing Rome and Ciampino, the temperature differences are lower and consequently the UHI phenomenon seems to be less significant. Nevertheless, it cannot be considered negligible, reaching values up to 2.2°C during the day and 3.2°C during the night. On principle, one may consider sustainable cooling strategies in the city in order to mitigate the phenomenon. For example, more green areas could positively influence the prevailing conditions in the urban neighborhoods as a result of evaporative cooling. However, in densely populated ancient cities, such as Rome, there are limited opportunities for significant changes due to the urban texture characteristics.

By comparing the meteorological conditions of urban and peripheral areas, the occurrence of the UHI phenomenon clearly affects the energy performance of buildings. Based on the simulations performed in this work for three Italian residential building typologies, the cooling energy demand can increase by more than 65%, when the climatic conditions of Fiumicino and Rome are compared. Even though Ciampino is closer to Rome than Fiumicino, using climatic data from the airport of Ciampino does not properly take into account the UHI effects that will impact the building's performance in Rome, resulting to differences in cooling energy demand which can increase by more than +16%. However, there is a positive UHI effects during winter, reducing the heating energy demand ranging from -15.8% to -7.4%. Considering the anisotropy of urban geometries and the variability of the wind vectors in different urban environments, the obtained results are strictly related to the area where the measurements were conducted. However, it is not advisable to use measured weather data from airports or outlying areas (outside the urban texture) since this can lead to inaccurate estimates of building energy demand, especially when considering buildings in densely-built zones.

Overall, the availability of more localized meteorological data inside big cities (that are affected by the UHI phenomenon) is desirable. Such data can be used to facilitate the generation of consistent and more realistic climatic data for improving the predictive accuracy of building simulation models, to improve the estimation of operational energy costs, indoor environmental conditions and make more rational assessments of energy conservation measures in existing buildings. On the basis of the results from this work, climatic data acquired from airports should not be used (if possible) to simulate energy performance of buildings located in central areas of cities. In addition, more frequent updates of standard weather files are necessary, in order to avoid oversizing air conditioning systems in winter and the undersizing during summer.

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