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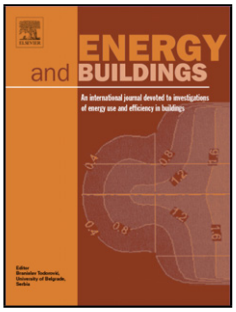

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Assessing the urban heat island and its energy impact on residential buildings in Mediterranean climate: Barcelona case study

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Highlights

- The maximum urban heat island intensity(UHI) reaches 4.3°C during summer
- During daytime, air temperatures at the street level are higher than the roof level
- The sea breeze has a positive effect on the roof level temperatures during summer
- The UHI determines an average increase of the cooling load between 18% and 28%
- The energy impact of the UHI is more relevant for higher solar gains

Abstract: The Urban Heat Island (UHI) effect is particularly concerning in Mediterranean zone, as climate change and UHI scenarios foresee a fast growth of energy consumption for next years, due to the widespread of air conditioning systems and the increase of cooling demand. The UHI intensity is thus a key variable for the prediction of energy needs in urban areas.

This study investigates the intensity of UHI in Barcelona (Spain), the densest Mediterranean coastal city, and its impact on cooling demand of residential buildings.

The experimental analysis is based on temperature data from rural and urban Weather Stations and field measurements at street level. The maximum average UHI intensity is found to be 2.8 °C in winter and 1.7°C in summer, reaching 4.3°C at street level. Simulations performed with EnergyPlus indicate that the UHI intensity increases the sensible cooling load of residential buildings by around 18% to 28%, depending on UHI intensity, amount of solar gains and cooling set point.

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In the light of the results, the UHI intensity in Mediterranean context should be properly considered in performing energy evaluations for urban contexts, since standard meteorological data from airport weather stations are not found to be accurate enough.

Keywords: Urban heat Island; cooling demand; Mediterranean climate; energy modelling; urban climate; energy consumption; EnergyPlus; climate data; weather file

1. Introduction

One of major concerns of our days is to reduce energy consumption and environmental footprint of cities and buildings. In Mediterranean climate, this issue is more and more associated with the summer season. The widespread use of air conditioning in residential buildings has led to a fast increase of electricity consumption over the last few decades [1]. This trend is particularly alarming, because electricity consumption is growing much faster than Gross Domestic Product (GDP), primary energy consumption and population growth [2]. Furthermore, climate change and urban warming contribute to raise the cooling energy consumption even more in this context. In effect, the predicted climate scenarios for the next 100 years [3] foresee an increase of tropical nights (>20°C) and hot days (>35°C) for the Mediterranean basin. So, the combination of global warming with the so-called "urban heat island" (UHI) effect makes the energy issue particularly concerning in Mediterranean basin.

Higher temperatures cause a significant increase of the buildings' energy consumption, since they affect the already onerous cooling demand [4–10]. It is indeed estimated that temperate and mid-latitude climates will experience the largest increase in annual energy consumption due to climate change and UHI scenarios, because cooling will be needed also in autumn and spring periods [11,12]. The UHI intensity is therefore a crucial variable for the estimation of buildings energy performance in Mediterranean climate. Nonetheless, it is still rather overlooked in the practice of energy assessment.

The aim of this paper is to quantify the average UHI intensity in a dense urban area facing the Mediterranean Sea and its impact on cooling energy demand for residential buildings. To this purpose, the city of Barcelona, Spain, has been selected as case study.

1.1 Background

Urban climate and UHI have been widely investigated in the last decades [13,14] and several studies have been conducted in the Mediterranean zone. According to the review by Santamouris [15], the UHI intensity varies between 2°C and 10°C in this context.

The UHI intensity was firstly investigated in Greece, in the area of Great Athens, by considering air temperature

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data collected from a network of urban and sub-urban weather stations between 1996 and 1998 [16–18]. A strong UHI intensity was recorded in summer during the daytime, when the temperature difference between suburban weather stations and urban stations reached up to 15 °C in locations far away from surrounding buildings. During the night time, the temperature difference was smaller ranging between 2°C and 5°C. More recently, Giannopoulou et al. [19] reported a variation of the UHI intensity in Athens between 3.0 °C and 5.3 °C during the day time and between 1.3 °C and 2.3 °C during the night time. Kolokotsa et al. [20] studied the UHI in the Hania, Greece, finding a maximum daily UHI intensity of 8°C and an average urban-rural temperature difference of almost 2.6°C. A further study was conducted by Giannaros and Melas in the coastal city of Thessaloniki [21], who identified a maximum UHI intensity between 2 °C and 4 °C. An average maximum UHI intensity of 2°C was found also in Volos, a medium-sized coastal city in central Greece [22].

In Spain, an early study on the UHI intensity in Barcelona was carried out by Moreno-Garcia in the 90s [23], based on air temperature data (daily maximum and minimum) recorded by two fixed meteorological stations during the period 1970-1984. The average difference between urban and rural temperature was found to be +1.4ºC (+2.9º C referring to the average daily minimum), while the maximum UHI intensity exceeded 8°C. According to the study, the average UHI intensity was slightly greater during winter months.

In Italy, the UHI intensity was firstly investigated in Rome by Colacino and Lavagnini [24], using daily minimum temperature data measured from a network of urban and rural weather stations over the period 1964–1975; the UHI intensity was found to be approximately 2.5°C during winter and 4.3°C during summer. More recently, Bonacquisti et al. [25] reported an urban-rural temperature difference of around 3°C, with a maximum of 5°C in summer, during night-time. These results were confirmed by additional studies carried out in Rome [26–28], which detected an average UHI intensity between 3°C and 4 °C, with a peak intensity of 4.5° C in summer. Besides experimental studies, some numerical analysis on the UHI over the metropolitan region of Rome and the influence of the sea breeze on the urban boundary layer have been recently presented [29,30].

For what concern the Mediterranean area, it has to be mentioned also the work carried out in Tel Aviv, Israel, by Saaroni et al. [31]; the authors found that the UHI intensity in the coastal city varies between 5°C at street level and only 2.5 °C at roof level, thanks to the mitigating effect of the Sea breeze.

Several studies on the UHI also detected a spatial variability of urban temperatures, mainly due to building density, presence of parks, water bodies or orographic characteristics of the different areas within the city [32–34]. Many relationships between the UHI intensity and the canyon geometry have also been identified [35–40]. However, results on this topic are still contradictory, being strictly dependent on the reference climate and the methodologies adopted in the studies.

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Differently, many studies agree on the negative impact of the UHI on the building energy performance. According to the studies scrutinized by Santamouris in a recent review [41], the UHI determines an average increase of 11% of the annual energy demand (23% for the cooling load). The same author used hourly data of air temperature recorded in the city of Athens to calculate the energy loads for an office building with TRNSYS model [17]; the results showed an increase of about 120% of the monthly cooling load for the building in the city centre with respect to the suburban location and a decrease of the heating load by 38%. Another study by Hassid et al. [8] estimated the impact of the UHI on residential cooling loads in Athens, using the energy model DOE2.1E. and climate data from four urban stations and two rural stations; an increase of the sensible cooling loads of about 15–50% was found with urban temperatures instead of rural temperatures.

Akbari et al. [42] investigated the energy-saving potential of different heat island reduction strategies, for about 240 locations in the US.A.. According to calculations with DOE-2.IE model, the potential energy saving was about 12- 25% for residential buildings, 5-18% for office buildings and 7-17% for retail stores. Bueno et al. [43], instead, presented a new "urban canopy and building energy model" to evaluate the change of energy demand of residential buildings under different UHI scenarios; results showed a 5% increase of cooling demand per 1 K increase in the maximum UHI effect at night.

The impact of the UHI on buildings energy performance has been widely investigated also in tropical climates. Ignatius et al. [38] estimated the UHI intensity in the city of Singapore with the "STEVE" tool and calculated its impact on buildings energy performance with the "Integrated Environmental Solutions" (IES) software; the analysis showed that the cooling load for an office building increased by 8% under an average UHI intensity of about 1-2°C, and up to 3.5 °C with regard to the maximum temperatures. Chan [44] studied the impact of the UHI on the cooling load calculation for an office building and a typical residential building in Hong Kong; the study was carried out with EnergyPlus model (using a modified input weather file to take into account the UHI effect) and showed an average 10% increase in air-conditioning demand in both cases.

In Mediterranean climate, the impact of UHI on buildings energy performance was studied by Fanchiotti et al. [27] for residential buildings in Rome, using temperature measurements over the period July-September 2011 as input for simulations with TRNSYS model; results showed an increase of the cooling loads up to the 57% for a maximum UHI intensity of about 4.5 °C. With the same methodology, Magli et al. [45] estimated the impact of the UHI on the cooling loads of a university building in Modena (Northern Italy), finding an increase of about 10% for the urban situation compared to the suburban one.

The UHI effect determines an increase of overall energy demand of building stock even in colder climates. Many studies highlighted the negative impact of UHI on cooling loads and risk of overheating for buildings in

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London [46–49]. Kolokotroni et al. [50] used measurements of air temperature to run simulations for an office building with the energy model TAS; the results showed that in London area the cooling load is 25% higher than the rural load, while the heating load is reduced only by 22%. Dorer and Allegrini [51] analysed the cooling and heating demand for office and residential buildings in Basel, Swiss, using TRNSYS model and urban and rural air temperatures; the results showed an increase of the cooling demand in the urban environment up to 10 times as much as the rural one, while the reduction of the heating demand was much less significant.

In the light of these findings, standard meteorological data seem to be rather inaccurate to run energy simulations of buildings in urban areas, since they refer to out-of-town weather stations- normally airports- that cannot detect the UHI effect [38,44,47,52].

2. Methodology and case studies

This study investigates the UHI intensity at the local scale and the microscale [53] in Barcelona city and the relating impact on energy performance of buildings during summer time.

The assessment of the UHI intensity at local scale is based on the comparison of air temperature measurements from urban and rural fixed weather stations. The variability of the UHI intensity at microscale has been instead investigated through field measurements in different urban canyons.The temperature data at urban and rural sites have been then used as input for a set of energy simulations with EnergyPlus [54,55], by means of the Design Builder interface, to estimate the impact of the UHI on the sensible cooling load of a residential building, considering different cooling set points and different solar gains.

2.1 Barcelona relevant features

Barcelona (latitude 41° 23' 24.7'' N, longitude 2° 9' 14.4'' E) is the densest Mediterranean coastal city, with about 1.6 million inhabitants in the central area and almost 5 million in the metropolitan area. According to the Köppen-Geiger climate classification, the city belongs to the ‘’Csa’ region (dry Summer Mediterranean climate). The Mediterranean Sea in the southeast border and the mountain chain of “Serra de Collserola" (whose peak is 512m high) in the north-west side characterize the topography of the city. To the southwest and to the north-east the metropolitan area is bounded by the valleys of the rivers Llobregat and Besós (figure 2).

Urban temperature and ventilation are influenced by the proximity to the sea and the mountain chain. The diurnal temperature range is quite narrow during the whole year (table 1); prevailing wind directions are North and North-west in Winter and West, South-West in Summer. The urban texture is continuous, dense and compact; the average height of buildings ranges between 15 and 30 m. The urban blocks size varies within the city, according to different age of planning. The central district ‘Eixample’ is composed of large homogeneous blocks interlocking an orthogonal street network (Plan Cerdá); the ancient core has kept the

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Medieval urban structure while the district of Gracia, north of downtown, is characterized by smaller urban blocks on a finer street network. The land occupation is very high across the city, while vegetation and parks scarce in the centre.

2.2 Evaluation of the UHI intensity at local scale

The quantification of the UHI intensity in Barcelona is based on hourly air temperature data recorded by two fixed urban weather stations and one rural station. The reference rural station is located at approximately 13 Km distance from the city centre in south-west direction, at El Prat Airport (WMO Station Number: 08181). The temperature sensor is located near the landing strip, at 6 m height above sea level (a.s.l.) and approximately 1 Km distance from the coastline. In fact, this site does not conform entirely to Oke's definition of rural site, given the presence of the sea and some surrounding neighborhoods. However, the climate data used for building energy simulations normally refer to the weather stations of the airport. [56]; so, assuming the airport as the reference rural site, it is possible to assess how much urban temperatures differ from the data normally used for building thermal modelling.

The reference urban weather stations are located in two dense neighbourhoods of the city centre: Gracia and Raval. The weather station in Raval is owned by the meteorological service of Catalunya, METEOCAT, and it is located on the roof of a University building. The weather station in Gracia is a private weather station of the "Meteoclimatic" network, located on the roof of a four-storey residential building. Detailed characteristics of the sensors accuracy and position are given in table 2.

Raval is located in the district of Ciutat Vella, the ancient core of the city very close to the sea. The district is characterised by an extremely dense and compact urban structure, composed of irregular blocks and narrow streets, mostly pedestrian. Considering the area in the weather station footprint [57], the average canyon aspect ratio is about 3.0, the building surface fraction is about 63% and the average buildings height is 17 m. The presence of trees in the roads is quite rare. The intended use is primarily residential, except for the northern area, where some university facilities and museums are located. The district is very close to the sea, just 1.3 km from the port; the distance from the rural station is about 11.5 km. Referring to the UCZ classification [58] the district matches the UCZ 2 ("Compact midrise").

Gracia is located just to the north of the city centre; is a dense neighbourhood composed of courtyard buildings organised on small urban blocks, clearly different from the predominant layout of the city set by Cerdà's urban plan. In the weather station footprint, the building surface fraction is about 55% and the buildings height ranges between 2 and 5 floors. The average canyon aspect ratio is quite high, about 2.5. Few vegetation is concentrated in the squares and main roads and accounts for 8% of the urban area. The intended use is mainly

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residential. The neighbourhood is located at approximately 4.2 km from the sea and 13.5 km from the airport. Referring to UCZ classification [58] the district matches the UCZ 2, as same as Raval.

The UHI intensity during the year 2014 has been evaluated using statistics of the hourly air temperature difference between the urban and the rural weather stations. The hourly temperature observations have been processed to analyse and compare the monthly average diurnal cycle of air temperature for each weather station.

The average UHI intensity is here defined as the monthly-averaged hourly difference between temperatures observed at the rural station and at the urban stations. The diurnal cycles of air temperature have been analysed for winter months and summer months, in order to highlight the variability of the UHI intensity during the year; the maximum UHI intensity observed at each site was also reported.

2.3 Evaluation of the UHI intensity at microscale

An air temperature measurement campaign has been carried out to evaluate the variability of the UHI intensity at the microscale. Air temperature measurements have been taken at street level in eight urban canyons located in Gracia and Raval and characterised by different aspect ratios (height/width) and orientations (NE-SW and NW-SE) (figure 7). The canyons presented similar characteristics for what concerns materials and claddings; the buildings were mainly masonry type, plastered and painted with light or halftone colours (albedo between 0.3 and 0.5) and the roads asphalted.

The measurements were taken on the 4th, 10th and 17th of July 2014, at two locations within each canyon and simultaneously in the two neighbourhoods, starting from 7:00 until 3:00 local standard time (LST). More information about the measurements and details of the equipment are given in table 3. The measurements at the street level have been compared to each other at first and also with the corresponding temperatures recorded at the roof level by the fixed meteorological stations. This allowed to identify the variability range of UHI intensity at the microscale, according to different aspect ratios of the urban canyons and the temperature difference between roof level and street level.

2.4 Evaluation of the UHI impact on the cooling demand

The last part of the study analyses the impact of the UHI intensity on the sensible cooling demand for residential buildings in Barcelona. A methodology already employed in several studies has been adopted [17,27,38,44,45,49,50]; this consists of using temperature data collected at urban and rural sites as input data for a set of energy simulations of a sample building. The difference between the results obtained with the two set of climate data is assumed to be due to the UHI effect.

The sensible cooling loads of a typical residential building have been calculated using two set of temperature

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data: 1) the air temperatures observed at the airport weather station and 2) the temperature measurements taken in the urban canyons; C. de Jesus (NE-SW orientation) in Gracia was chosen as reference for the trend of urban temperatures and the canyon morphology.

Calculations were carried out with respect to a 65 sq.m. sample apartment. The thermal properties of the building envelope (transmittance of external walls and glazing) refer to the typical masonry building type of Gracia. The main assumptions of the model as for the construction properties, occupancy schemes and environmental control refer to the technical code for Spanish construction [59] and are given in table 4.

Being the sensible cooling load highly affected by the amount of solar gains, calculations were performed for different heights and orientations of the sample apartment, in order to consider the variation of solar access within the canyon. Therefore, the entire morphological model of the urban canyon "C. de Jesus" has been modelled (figure 13) and the sensible energy balance for the sample apartment has been calculated for 4 positions within the canyon: at the first and last floor (4 m and 16 m high above the street level, respectively) and in two orientations (North-West and South-East).The apartments on the last floor have been modelled with an adiabatic surface on the top, in order to omit the heat transfer through the roof and to obtain comparable results with respect to the first floor. For each position, the sensible cooling load has been estimated also for different cooling set points, from 21°C to 27°C.

3.Results and discussion

The UHI analysis was carried out with regards to temperature data from 2014, which were slightly warmer than the average. Throughout most part of the year, both minimum and average monthly temperatures have been higher than historical data series recorded at El Prat Airport weather station over the period 1981-2010 (figure 8). Conversely, during summer period, the maximum temperatures have been lower than the average. No notable weather events were recorded.

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3.1 UHI intensity at local scale

Results for the UHI intensity during winter season and summer season are shown in figure 9. During winter time the UHI in Barcelona is evident, especially at night, with a similar trend in Gracia and Raval. The UHI intensity is variable during the day, stronger during the night and weaker or even absent from late morning until early afternoon. In the three winter months, the trend is very similar; the UHI is absent or at its lowest intensity between 13:00 and 17:00 LST, then it starts growing significantly from 19:00, reaching its average maximum intensity between 21:00 and 7:00 in the morning. From 8:00 it starts decreasing, until midday, when it reaches its minimum. The average maximum UHI intensity occurs in December and it is found to be 2.8 °C and 2.6 °C in Raval and Gracia respectively. In January, the average maximum UHI intensity is 2.2°C in Raval and 2.0°C in Gracia; in February, 2.4°C and 2.2°C in Raval and Gracia respectively. In all the cases, the UHI intensity is very low during daytime, ranging between 0 and 1°C. The maximum intensity during winter time is recorded on the 22nd and 25th of December, with an urban temperature increase up to 5.8°C at both stations, at 10:00 and 6:00 LST.

It is worth to highlight that day-time temperatures in Raval station are always higher compared to Gracia station, especially between 13:00 and 17:00 LST. This gap is probably due to the different position of the two sensors with respect to the roof; in Raval station the temperature sensor is located quite near the roof surface, at 1,5 m height, whereas in Gracia station it is located at 4,5 m height from roof level. The different distance of the sensors from the roof level may partially affect the temperature measurements, determining slightly higher temperatures in Raval above all during the hours of maximum solar radiation, when higher air temperature gradients occur and the radiative effect of the roof surface may be not negligible.

During summer time, the urban temperature trend is quite different. The UHI intensity at both urban stations is weaker than winter time. Furthermore, urban air temperature is higher than the rural one only during late night and early morning (from 1:00 to 8:00 LST). The monthly maximum UHI intensity is recorded in June, with an average value of 1.7°C and 1.3°C in Raval and Gracia respectively. In July and August, the UHI intensity is lower, with a monthly maximum value of 1.3°C and 0.8°C in July and 1.0°C and 0.5°C in August, in Raval and Gracia respectively. The maximum UHI intensity during summer is recorded on the 13th of June, with a temperature increase in Raval station up to 6.1°C

These results confirm the findings of Moreno-Garcia [23], who identified a stronger UHI intensity during winter time for Barcelona city. Such difference of UHI intensity in winter and summer time can be explained in light of some geographic characteristics of the city. The climate of Barcelona is affected by the thermoregulatory effect of the sea, which decreases the daily and annual temperature range (Tmax –Tmin), especially during

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summertime, when the effect of sea breeze is stronger. The breeze also mitigates temperatures in the layer of atmosphere above the roofs level during the hottest part of the day, preventing overheating of the surfaces and so contributing to reduce the UHI effect during night time. This work also confirms that maximum UHI intensity in Barcelona always occurs during night time. The average temperature difference between the airport and the city is instead slightly lower compared to the findings of Moreno-Garcia's work. However, the temperature data of that study refer to measurements at 1.5m from the ground level, while the data used in the present study refer to the roof-tops. The two kinds of measurements are substantially different, due to the different wind regime and radiative environment, so the results cannot be directly compared. This same holds true for the comparison with previous works on the UHI intensity in Rome and Athens, which were investigated using temperature measurements at about 2 m from ground level in the urban areas [17,25].

This study, instead, highlights some similarities between Barcelona and Tel Aviv about the urban temperature trend at roof level [31]; the maximum temperature difference between the stations is recorded during the second half of the night (00:00-08:00 LST) and the combined effect of the sea breeze during daytime and the UHI during night time determines a very small diurnal temperature range in the urban area. In effect, in August the temperatures in the Barcelona city centre are even lower than the airport during daytime and only slightly higher during night time. In Gracia, in particular, the temperature range varies from a minimum of 22.9 °C to a maximum of 25.6°C, while at the airport site the range is higher (from 22.3 to 26.7°C). These temperature differences may not be attributed only to the UHI effect, but also to the different height of measurement at the rural site, taken at 2m above the ground and not from roof-top level.

Finally, this study shows that the temperature in Raval is always higher than in Gracia. It is excluded that this difference is due to the different height of measurement with respect to the sea level, since the corresponding potential temperatures do not show relevant changes (the potential temperature has been calculated thanks to the availability of hourly data of temperature and pressure recorded at the two stations). So, the temperature difference is probably due to two factors: 1) the position of the sensors with respect to the roof level, as previously explained, 2) the characteristics of the two urban contexts. In effect, taking into account the prevailing wind direction from south-west, the footprint of Raval's station [57] is characterized by higher built surface fraction compared to that of Gracia (63% against 55%) and higher average height of the buildings (17m against 14 m). Since the different height of measurement with respect to the sea level is negligible, the temperature difference between Raval and Gracia is most probably related to the different building density of the two urban areas, just as observed in other researches [19,33].

It has to be highlighted that these results are limited to one year of observations in two specific urban sites. A

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wider data sample should be analysed in order to assess the spatial distribution of air temperature over the city. However, this is a useful preliminary assessment of the average UHI intensity in two central districts of the city, useful to understand the range of variability of the phenomenon in this context.

3.2 Summer UHI intensity at microscale

The hourly data of temperature, wind speed and direction during the days of measurement at street level are reported in figure 10, for the airport station and Raval and Gracia stations (roof-top observations). The decrease of wind speed in the city is clear when comparing urban data with the airport data, even though the measurements at the urban stations were taken at 10m above roof level. However, despite the attenuation of speed, the sea breeze produces a mitigation of the air temperature in the urban context during the hottest hours of the day, between 12:00 and 18:00 LST; in this time period, the air temperature remains almost constant at both the airport site and the urban sites. The wind direction observed in the urban area, instead, is very similar to that recorded at the airport site. The 17th of July was the hottest day among the three of measurements, with maximum temperatures of 28 °C at the airport, 28.9 °C in Gracia and 29.5 °C in Raval. The measurements were carried out under clear or slightly cloudy sky conditions. Due to a recorded downpour on the 4th of July at 7:00 LST, measurements started at 9:00 LST on that day, as opposed to the usual starting time 7:00 LST.

The air temperature trend in the eight urban canyons is reported in figure 11, in which the discontinuous temperature measurements, taken every two hours, have been interpolated for a better reading of the data.

In the graphs, the temperature observed at street level in each canyon is compared to that recorded at the airport and at the fixed weather station located at roof level in the same neighbourhood.

According to the measurements, the maximum UHI intensity at street level is found to be 4.3°C on the 17th of July at 7:00 LST, both in Raval (C. d'Elisabets) and Gracia (Gran de Gracia and C. de Jesus). The maximum temperature differences occur during daytime (between 13:00 and 15:00 LST), during night time at 3:00 and early in the morning at 7:00 LST.

During daytime, between 13:00 and15:00 LST, the UHI intensity ranges between 3°C and 4 °C, without significant variations between different canyon geometries and orientations. In this time period, two effects contribute to the increase of the air temperature at street level: 1) the maximum solar radiation and 2) the low wind speeds in the canyons with respect to the airport site.

In the same hours, in effect, the wind speed at the airport site is maximum; the activation of the sea breeze is indeed recognizable in figure 10, with the change of the wind direction, starting at about 12:00 LST, and the progressive increase of the speed, up to the maximum values reached between 15:00 and 16:00 LST.

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The breeze flow is quite decreased in the urban area at roof level, but it is definitely absent at street level, since the density of the buildings and the canyon geometry (H/W > 1) determines a skimming flow regime [36], characterized by stable circulatory vortices and very weak or absent interaction with the overlying atmosphere [60–62]. In effect, the temperature at street level reaches its maximum between 12:00 and 16:00 LST, while at roof level it remains roughly constant. This trend confirms the fact that the sea breeze cannot go through the canyons in the city centre and mitigate the temperature at street level, while it has a beneficial effect at roof level and at the airport site. Furthermore, in the same hours the solar radiation is at its maximum intensity and the solar elevation is between 65° and 70°; so, the sun rays can reach the road and the radiative trapping and the heat storage are increased in the canyon. The strong UHI intensity measured at street level during daytime is thus due to these two combined effects. A comprehensive discussion on this topic can be found in the work of Cantelli et al. [63].

During night time, at 3:00 LST, the UHI intensity reaches a second maximum in the deeper canyons, regardless of their orientation. In this case, being absent the solar radiation and low the wind speed, the UHI intensity is mainly related to the geometry of the urban canyon, which decreases the long wave radiative heat loss. In effect, in the canyons with high aspect ratio, the cooling rate slows down starting from 21:00 LST, causing high UHI intensities during the night, up to 4°C.

The measurements also highlight a substantial difference between the air temperature at street level and roof level, similarly to the case of Tel Aviv [31]. The temperatures at street level are always higher than those at roof level. The temperature gap is larger during daytime, when the sea breeze has a beneficial effect on the roof level temperatures, while it cannot have the same effect at street level because of the reduced wind speed in the urban canopy. As a result, the UHI intensity recorded at the fixed urban stations is negligible during daytime, while it is relevant at street level; the street-roof temperature difference between 13:00 and 15:00 LST reaches about 2 °C in most of the canyons.

The results on the UHI intensity at microscale in Barcelona agree with the findings of Moreno-Garcia's analysis and are comparable to the UHI intensities found in other cities using observations at street level, such as Rome [25–27], Athens [19], Tel Aviv [31] and other Greek coastal cities [21,22].

3.3 UHI intensity and canyon geometry

The comparison of the air temperature trend in the urban canyons with the highest difference of aspect ratio is reported in figure 12. In the same figure, it is also reported the direct solar radiation accumulated every two hours from the canyon's surfaces (road and walls), calculated with the software Heliodon2 [64] over simplified models of the urban canyons.

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In the upper part of the figure, the comparison between the air temperature trend in two urban canyons of Raval is reported: "C. d’Elisabets" and "Rambla del Raval", which have aspect ratios equal to 4.4 and 0.3, respectively. Due to the different geometric characteristics, "Rambla del Raval" receives much more direct solar radiation than "C. d'Elisabets" (figure 12, up-right); however, the different solar access does not entail a proportional trend of the air temperature in the two canyons. The air temperature in "Rambla del Raval" is higher than "C. d'Elisabets" between 7:00 and 15:00 LST. In this time lag, the air temperature raises rather quickly in the canyon with low aspect ratio (Rambla del Raval), in proportion to the increase of the incident solar radiation. However, the trend changes from 15:00 LST, when the temperature in "C. d'Elisabets" exceeds the one in "Rambla del Raval"; and remains higher until night. This happens because, even though "Rambla del Raval" receives much more solar radiation during the day with respect to "C. d'Elisabets", it is also able to cool down relatively quickly, thanks to the low value of the aspect ratio. Conversely, "C. d'Elisabets" is a very narrow canyon, so the long wave heat loss is reduced and trapped into the canyon during late afternoon and night, causing higher temperatures.

In figure 12, the comparison between the air temperature in two canyons of Gracia is also reported: "C.de Jesus" (H/W 4.6) and Tr. de Dalt (H/W 1.0). The two canyons have same orientation (NE-SW), but receive a very different amount of solar radiation due to the different geometry. As well as in Raval, the amount of solar radiation received by the canyons' surfaces is not proportional to the trend of the air temperature in them. However, the air trend in these two canyons of Gracia is different from the canyons just analysed for Raval.

In Gracia, early in the morning and until 15:00 LST, the temperature is higher in the canyon with high aspect ratio ("C. de Jesus"). In the afternoon and until 1:00 LST, instead, the temperature is higher in "Tr. de Dalt", the canyon with low aspect ratio. However, measurements show a reversal of trend during the night, since at 3:00 LST the temperature is, again, higher in the canyon with high aspect ratio. In effect, the cooling rate of "C. de Jesus" clearly decreases from 21:00 LST, while the rate of temperature decrease in "Tr. de Dalt" is quite constant. So, the different cooling rates, caused by different aspect ratios, lead to higher temperatures in the canyon with high aspect ratio during the night and the early hours of morning.

Therefore, the measurements at street level confirmed the relevance of the canyon geometry on the air temperature trend, especially at night [35,36]. During the night, the air temperature is higher in the canyons with higher aspect ratios, despite the lower solar access and independently from their orientation.

The maximum air temperature differences among urban canyons with different aspect ratios in the same neighbourhood reaches about 0.8-1.7 °C, depending on the day, and occurs at 3:00 and at 7:00 LST

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3.4 Impact of the UHI intensity on the sensible cooling load

The variation of the sensible cooling load according to urban and rural temperatures is presented and discussed for two days of calculation: the 10th and the 17th of July 2014. On the 10th of July 2014, temperature was slightly lower than the average; it ranged between 19°C and 26°C, while the average monthly values for Barcelona are 19.8°C-28°C. Conversely, warmer temperatures ranging from 22°C to 28°C were recorded on the 17th of July.

The analysis has been carried out on a sample apartment in four positions within the canyon; the amount of solar gains for each position is reported in figure 14. It is worth to analyse the difference in solar gains since it has a clear effect on the sensible cooling loads. The solar gains for the apartments located at the first floor are very low; the maximum values are 8,6 W/sq.m. at 14:00 for the SE orientation (P1) and 6,7 W/sq.m at 17:00 LST for the NW orientation (P2). In the last floor, instead, solar gains are much higher; the SE oriented apartment (P3) receives the larger amount of solar gains, with a maximum value of 47,5 W/ sq.m at 11:00, while in the NW orientation (P4) has the maximum solar gain at 18:00 LST, equal to 38,9 W/ sq.ms.

Figure 15 and 16 show the comparison between the sensible cooling load of the sample apartment calculated with urban temperatures and rural temperatures and for different cooling set points.

For the positions P1 and P2 (figure 15), which have low solar gains, the sensible cooling load required to achieve a comfort temperature of 27°C is negligible on both the 10th and the 17th of July, regardless of the UHI effect. The UHI effect provokes, instead, a relevant increase of the sensible cooling load for a cooling set point of 25°C on the 17th of July; the increase is not relevant on the 10th of July, since air temperatures were lower. The absolute increase on the 17th of July is equal to 56,8 Wh/sq.m for the SE orientation (P1) and 66,4 Wh/sq.m for the NW orientation (P2), which correspond to relative errors of 48% and 50% on the loads calculated with rural temperatures

However, for the apartments located at the first floor, the most relevant change in the sensible cooling load due to the UHI effect occurs for cooling set point equal to 23°C. In this case, on the 17th of July, the UHI effect determines an increase of the sensible cooling load up to 65,6 Wh/sq.m. for the SE orientation (P1) and 78,8 Wh/sq.m for the NW orientation (P2), which correspond to relative increases of 29% and 30%, respectively; significant change in the sensible cooling load is also estimated on the 10th of July, despite the lower outdoor temperatures. Conversely, for cooling set point equal to 21°C, the absolute and the relative increases of the sensible cooling load due to the UHI effect are less relevant. This happens because at the latitude of Barcelona, in summer, such a low indoor temperature is achievable only with mechanical cooling, also in positions protected from direct solar radiation. For the cooling set point equal to 21°C, the daily-average change in

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sensible energy demand due to the UHI effect for the positions at the first floor (P1 and P2) ranges between 14,1 Wh/sq.m. on the 10th of July and 45,6 Wh/sq.m. on the 17th of July; in terms of relative error, it corresponds to the 20% - 28% of the cooling load calculated using the airport temperatures.

Figure 16 shows the sensible cooling loads for the apartments located at the last floor (P3 and P4), which have much higher solar gains compared to the positions P1 and P2. The sensible cooling demand in these positions is much higher compared to the first floor; this holds true despite the heat transfer through the roof has been omitted in this analysis (see model assumption in section 2.4). In the SE-oriented apartment (P3), the most affected by the direct solar radiation, mechanical cooling is required even to keep the indoor temperature to 27 °C, especially in a hot day such as the 17th of July. In this case, the sensible cooling load calculated with the urban temperatures is 171,8 Wh/sq.m, which is 34% more than the estimation using the airport temperatures. The apartment in NW orientation (P4) on the same day and for the same cooling set point requires much less energy (57,3 Wh/sq.m with the urban temperatures), thanks to the lower amount of solar radiation reaching the façade compared to the SE orientation. On the 10th of July, instead, the cooling load for a cooling set point of 27°C is negligible for both orientations.

For cooling set point equal to 25 °C, the absolute change in sensible cooling demand due to the UHI effect is relevant for both orientations on the 17th of July; the increase of the sensible cooling load is equal to 65,18 Wh/sq.m. for SE orientation and 77,5 Wh/sq.m for the NW orientation, which are the 23% and the 39% of the loads calculated using the temperatures of the airport.

However, the maximum absolute increase of the sensible cooling load due to the UHI effect occurs for the cooling set point equal to 23°C. In this case, the apartment in SE orientation undergoes an increase up to 80,6 Wh/sq.m. on the 17th of July and 57,7 Wh/sq.m on the 10th of July, which represent a 20% and 28% relative increase of the load calculated using the temperatures of the airport; for the NW orientation, the increase of the cooling load is equal to 79,6 Wh/sq.m on the 17th of July and 38,9 Wh/sq.m on the 10th of July, meaning a relative error of 25% and 27% respectively. The relative increase of the cooling load is less relevant for cooling set point equal to 21°C, that entails high cooling loads even considering the rural temperatures. Nevertheless, a significant change occurs for the NW orientation, where the UHI effect determines an increase of the sensible cooling demand of 46,8 Wh/sq.m. (14% relative increase).

The daily-average change in sensible energy demand due to the UHI effect for the last floor positions is thus equal to 25,1 Wh/sq.m on the 10th of July and 59,8 Wh/sq.m on the 17th of July, which correspond to relative increases of 18% and 22% with respect to the cooling demand calculated using the temperatures of the airport. Considering all the case studies, the daily-average change in sensible energy demand due to the UHI effect

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varies between 19,3 Wh/sq. m and 52,3 Wh/sq. m on the 10th and the 17th of July, respectively, which correspond to relative increases between 19% and 24% of the loads calculated with the temperatures of the airport.

The impact of the UHI on the cooling load is more relevant for higher solar gains and for the range of cooling set points between 25°C and 23°C. The most relevant absolute error in the energy calculation performed with rural temperatures regards the SE oriented apartment on the last floor, for a set point of 23°C. This position is the most exposed to solar radiation and so the worst position with respect to sensible cooling demand. In this condition, the UHI effect determines a significant increase of the cooling load. However, the omission of the UHI effect entails relevant errors in the calculation of the cooling loads even for the apartments protected from the direct solar radiation (NW orientation or lower floor positions), especially in particularly hot days.

The results of the analysis are in line with previous works on the impact of the UHI on the energy demand of residential buildings. The results about the average daily energy demand change due to UHI intensity, as well as the ratio of the energy demand change, are very close to the findings of Bueno et al.[43]. The two studies agree that the absolute increase in sensible cooling demand due to the UHI is greater for higher solar gains, while the relative increase is smaller; this happens because when the solar gains are high, the overall energy demand is less related to the variation of the outdoor temperature. The results presented in this study are also comparable to the findings for Athens and different locations in the USA [8,42]. The analysis performed for Boston (MA) [65] showed, instead, a smaller impact of the UHI on the residential cooling demand; however, the climate of Boston is colder compared to Barcelona, so the cooling need is less relevant. Finally, the impact of the UHI intensity on the cooling needs is found to be greater on residential buildings compared to office buildings [38,44,45], whose energy needs are more related to the internal heat gains rather than outdoor temperature variation.

4.Limitation of the study and future works

The calculations of the sensible cooling loads were performed with regards to two days of July 2014, which recorded temperatures slightly over and below the historical trend of air temperatures for the month. A variability of the results shall be expected depending on different input weather conditions; however, the calculations over those two days were representative of the typical range of air temperature variability for the month.

The energy analysis is based on comparative calculations performed with EnergyPlus model, which has been extensively validated in the last years. However, a key limitation is the assumption that only the air temperature varies in the urban context compared to the rural environment. A change in humidity and wind velocity in the urban area is expected to produce a change in the natural ventilation rate, the convective heat transfers and the latent loads. The energy simulations also neglect the external longwave radiation exchange in the urban canyon, because EnergyPlus only considers the infrared exchange between the wall and the ground, the sky and the air. Thus, a more detailed energy simulation that considers the effect of multiple reflections and the long wave radiation fluxes in the canyon would improve the accuracy of the results. However, it has to be considered that the urban air temperature used in the calculation is actually the results of the overall urban energy fluxes, comprising anthropogenic heat sources, radiative heat transfers and wind movements. Since this work aims to show the impact of the urban air temperature increase on the cooling load calculation, these limitations are not particularly relevant for the purpose. Of course, they should be addressed in the future, to refine the accuracy of the energy performance predictions in the urban context.

A comprehensive interpretation of the results should also address the conformity of the building to the assumptions made as for the building construction, the systems characteristics and the occupancy schemes. In this study, the set of parameters used to perform the calculation was chosen to describe a typical residential building in the district of Gracia (Barcelona). A sensitivity analysis of the most influential parameters for the sensible cooling load at Barcelona's latitude was carried out taking into account the amount of solar gains, the variation of outdoor temperatures and different cooling set points. Further work on the influence of different building parameters (ventilation rate, glazing ratio, glazing and wall transmittance, occupancy density and occupancy schemes etc..) would determine a range of variation of the loads.

5.Conclusion

The UHI intensity and its impact on the sensible cooling loads of residential buildings have been analysed in the city of Barcelona. The UHI intensity at local scale and microscale has been analysed by means of air temperature measurements at roof and street levels in two central neighbourhoods of the city, with respect to the nearest airport site. A greater UHI intensity is recorded during wintertime than during summertime, as reported by roof level air temperature measurements for the reference year 2014. The maximum monthly average UHI intensity occurs in December, reaching 2.8 °C in Raval and 2.6°C in Gracia, during the night time (between 22:00 and 08:00 LST). In summer, the UHI intensity is weaker, reaching a maximum monthly intensity of 1.7 °C in June in Raval and 1.3°C in Gracia at 04:00 LST.

The mitigation of UHI intensity during summer season can be explained in the light of the effect of the sea breeze. In summer, especially during daytime, the sea breeze is strong and contributes to mitigate air temperatures at roof level during the hottest hours of the day.

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Nonetheless, during the same time, the UHI intensity recorded at street level is significant; the temperature difference between street level and roof level reaches up to 2°C during the hottest hours of the day (between 12:00 and 16:00 LST). The raise of the temperature at street level compared to roof level is due to the combined effects of radiative trapping and reduced wind speed in the canyon. So, depending on the aims of the analysis, attention shall be paid to the vertical distribution of air temperature in the canyon.

The measurements of air temperature at street level also show that canyons with greater aspect ratio have higher temperatures during night time and early morning; this happens because that kind of geometry enhances the radiative trapping during both day time, for the incoming solar radiation, and night time, for the longwave radiative heat loss. The maximum UHI intensity at street level is indeed recorded in the canyons with highest aspect ratio, at 07:00 LST, reaching 4.3°C both in Raval and Gracia. The temperature difference determined by the canyon aspect ratio ranges between 0.8°C and 1.7°C. Conversely, according to this analysis, the orientation of the canyon results quite irrelevant on the air temperature trend.

The urban air temperatures recorded at street level have been used to evaluate the impact of the UHI intensity on the sensible cooling demand of a sample apartment, considering different cooling set points and solar gains. The results confirm the detrimental effect of the UHI on the cooling loads in the Mediterranean climate, especially in particularly hot days. According to the case studies analysed, the UHI intensity determines an average relative increase of the sensible cooling load between 19% and the 24%, on the 10th and the 17th of July 2014, respectively.

The relative error in the estimation of the sensible cooling loads using airport temperatures instead of urban temperatures is greater for the apartments with low solar gains and cooling set points between 25°C and 27°C. However, the UHI determines the largest absolute increase of the cooling demand on the apartments with high solar gains. In those situations, calculations performed using the rural temperatures determine relative errors of the load estimation between 18% and 22%, which correspond to an absolute underestimation of 25,1 Wh/sq. m and 59 Wh/sq. m on the 10th and the 17th of July, respectively. The maximum absolute increase of the sensible cooling load due to the UHI effect occurs for the apartment with the highest amount of solar gains (top floor, South-East orientation) for a cooling set point of 23°C. In this case, the sensible cooling load calculated with the urban temperature is up to 80,6 Wh/sq.m higher than the one calculated with the rural temperature, which represents a relative increase of 20%.

Therefore, this analysis shows that meteorological data obtained from operational weather stations located outside the city, such as the airports, are very inaccurate to perform energy simulations of buildings in Mediterranean context, where the cooling demand is already onerous. Further analyses are necessary to assess the average annual energy impact of the urban heat island on residential and non-residential buildings in this region.

This preliminary work investigates the range of variability of UHI intensity in a relevant urban area of Mediterranean basin, such as Barcelona city, and the range of corresponding variation of the cooling loads for residential buildings in the urban context.

Results achieved so far intend also to stress the necessity of further investigations about the effects of urban warming on the energy performance of buildings; this field of investigation is indeed crucial to provide professionals and decision makers with suitable tools to face with awareness the issue of energy consumption of building stock in Mediterranean urban context.

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Figure 1: Research methodology flowchart (2- column fitting image)

Figure 2: Localisation of the weather stations and relevant topographic profiles of Barcelona elaborated with Google Earth (2- column fitting image)

Figure 3: Relative position of the three weather stations within Barcelona city (two- column fitting image)

Figure 4: Position of the urban Weather Stations in the districts of Gracia and Raval (two- column fitting image)

Figure 5: Raval fixed weather station (single column)

Figure 6: Gracia fixed weather station (single column)

Figure 7: Urban canyons analysed during the air temperature measurement campaign at street level (2- column fitting image)

Figure 8: Monthly daily mean, maximum and minimum air temperatures recorded at El Prat Airport weather station during the year 2014 and over the period 1981-2010 (single-column image)

Figure 9: Monthly average hourly temperatures observed in Raval, Gracia and El Prat in winter season and summer season. The Coordinated Universal time (UTC) is used in the graphs; the local standard time (LST) correspond to UTC+1 in winter and UTC+2 in summer. (2-column fitting image)

Figure 10: Air temperature, Wind speed and direction recorded at the airport weather station and at the two fixed urban stations during the days of the measurement campaign at street level. The Coordinated Universal time (UTC) is used in the graphs; the local standard time (LST) correspond to UTC+2 in summer. (2-column image)

Figure 11: Comparison between the air temperature trend in the canyons at street level, at the airport weather station and at the fixed weather station at roof level during the measurement campaign. The Coordinated Universal time (UTC) is used in the graphs (2-columns fitting image)

Figure 12: On the left: air temperature trend in canyons with different aspect ratio (4th and 10th of July). On the right: direct solar radiation reaching the canyon surfaces, according to the different aspect ratio and orientation. (2-columns fitting image)

Figure 13: a) Digital model of C. de Jesus in Design Builder, b) Layout of the reference apartment, c) studied positions of the apartment within the canyon (2-columns image)

Figure 14: Solar gains for the reference apartment in the four positions within the canyon (single column fitting table)

Figure 15: Daily sensible cooling demand variation for the lower floor positions (P1 and P2) according to different outdoor temperatures and cooling set points. The red line represents the sensible cooling loads calculated with the urban temperatures, the blue dotted line the ones calculated with the temperatures of the

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airport, the black dots the absolute difference between the two estimations and the grey bar the relative error of the estimation performed using the temperatures of the airport

Figure 16: Daily sensible cooling demand variation for the upper floor positions (P3 and P4) according to different outdoor temperatures and cooling set points. The red line represents the sensible cooling loads calculated with the urban temperatures, the blue dotted line the ones calculated with the temperatures of the airport, the black dots the absolute difference between the two estimations and the grey bar the relative error of the estimation performed using the temperatures of the airport

FIG1.TIFF

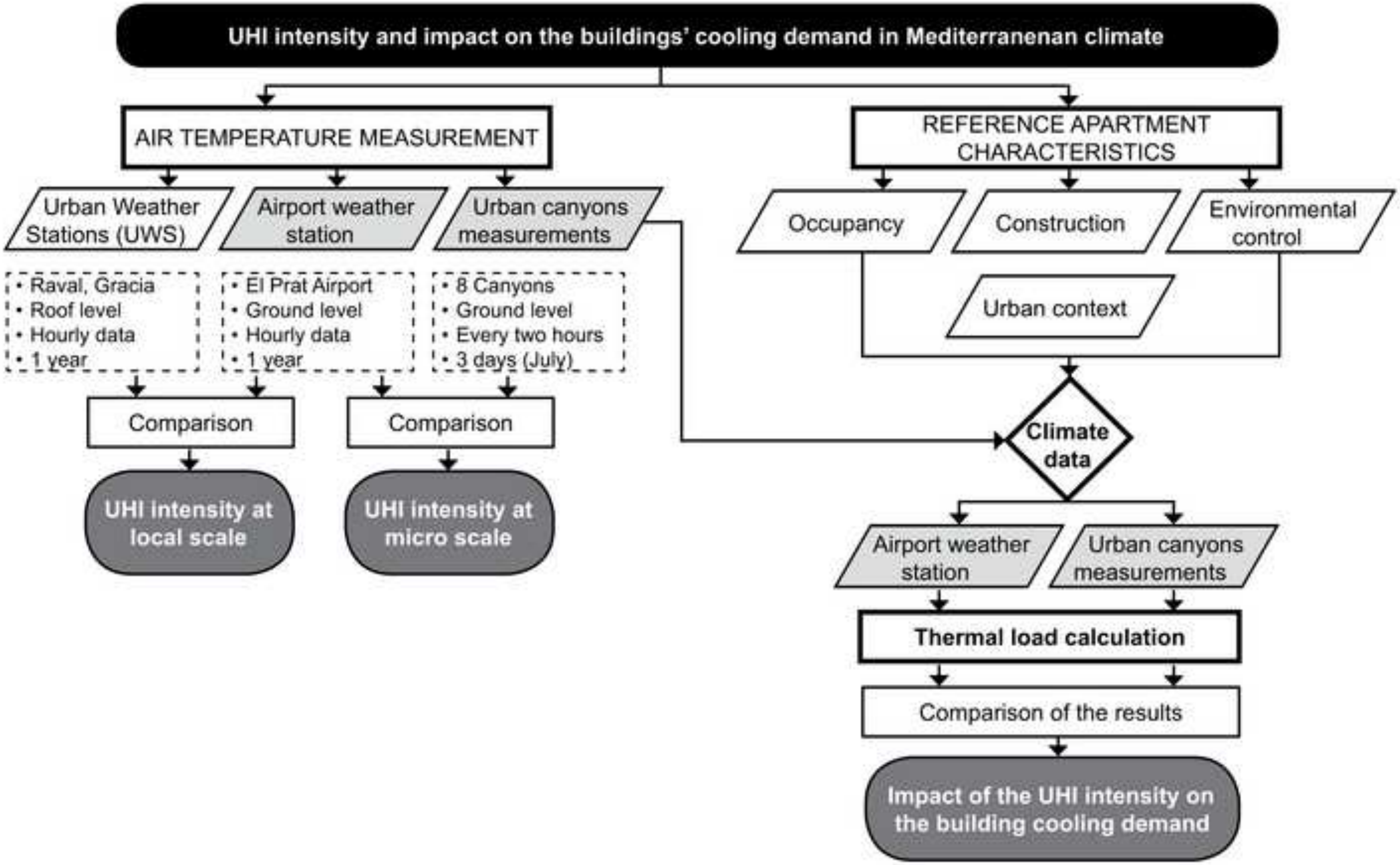
UHI intensity and impact on the buildings' cooling demand in Mediterranenan climate
AIR TEMPERATURE MEASUREMENT
Urban Weather Stations (UWS)
Airport weather station
Urban canyons measurements
• Raval, Gracia
• Roof level
• Hourly data
• 1 year
• El Prat Airport
• Ground level
• Hourly data
• 1 year
• 8 Canyons
• Ground level
• Every two hours
• 3 days (July)
Comparison
Comparison
UHI intensity at local scale
UHI intensity at micro scale
REFERENCE APARTMENT CHARACTERISTICS
Occupancy
Construction
Environmental control
Urban context
Climate data
Airport weather station
Urban canyons measurements
Thermal load calculation
Comparison of the results
Impact of the UHI intensity on the building cooling demand

FIG2

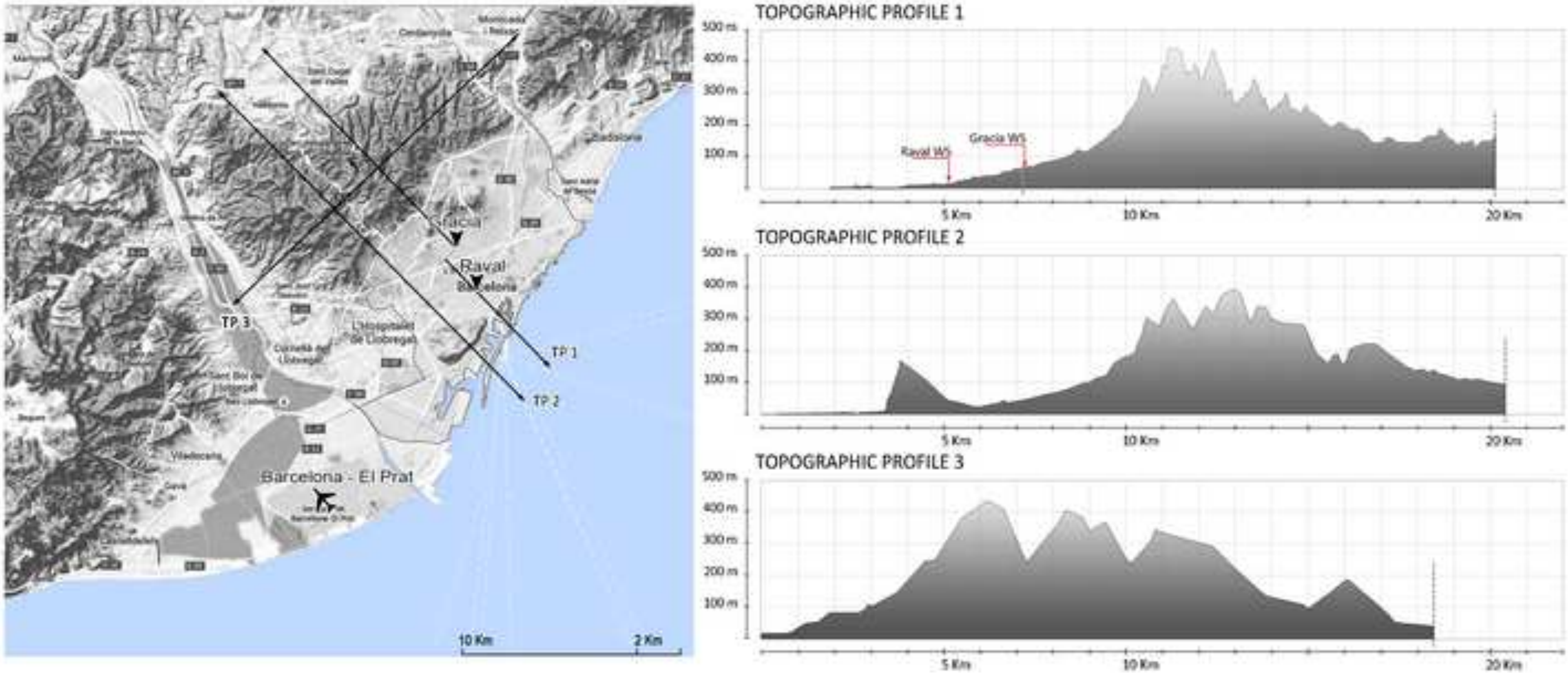
TP 1
TP 2
TP 3
Gracia
Raval
Barcelona
Badalona
L'Hospitalet de Llobregat
Cornellà de Llobregat
Sant Boi de Llobregat
Viladecans
Gavà
Barcelona - El Prat
10 Km
2 Km
TOPOGRAPHIC PROFILE 1
500 m
400 m
300 m
200 m
100 m
Raval WS
Gracia WS
5 Km
10 Km
20 Km
TOPOGRAPHIC PROFILE 2
500 m
400 m
300 m
200 m
100 m
5 Km
10 Km
20 Km
TOPOGRAPHIC PROFILE 3
500 m
400 m
300 m
200 m
100 m
5 Km
10 Km
20 Km

FIG3.TIFF

FIG4.TIFF

FIG5.TIFF

FIG6.TIFF

FIG7

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FIG8

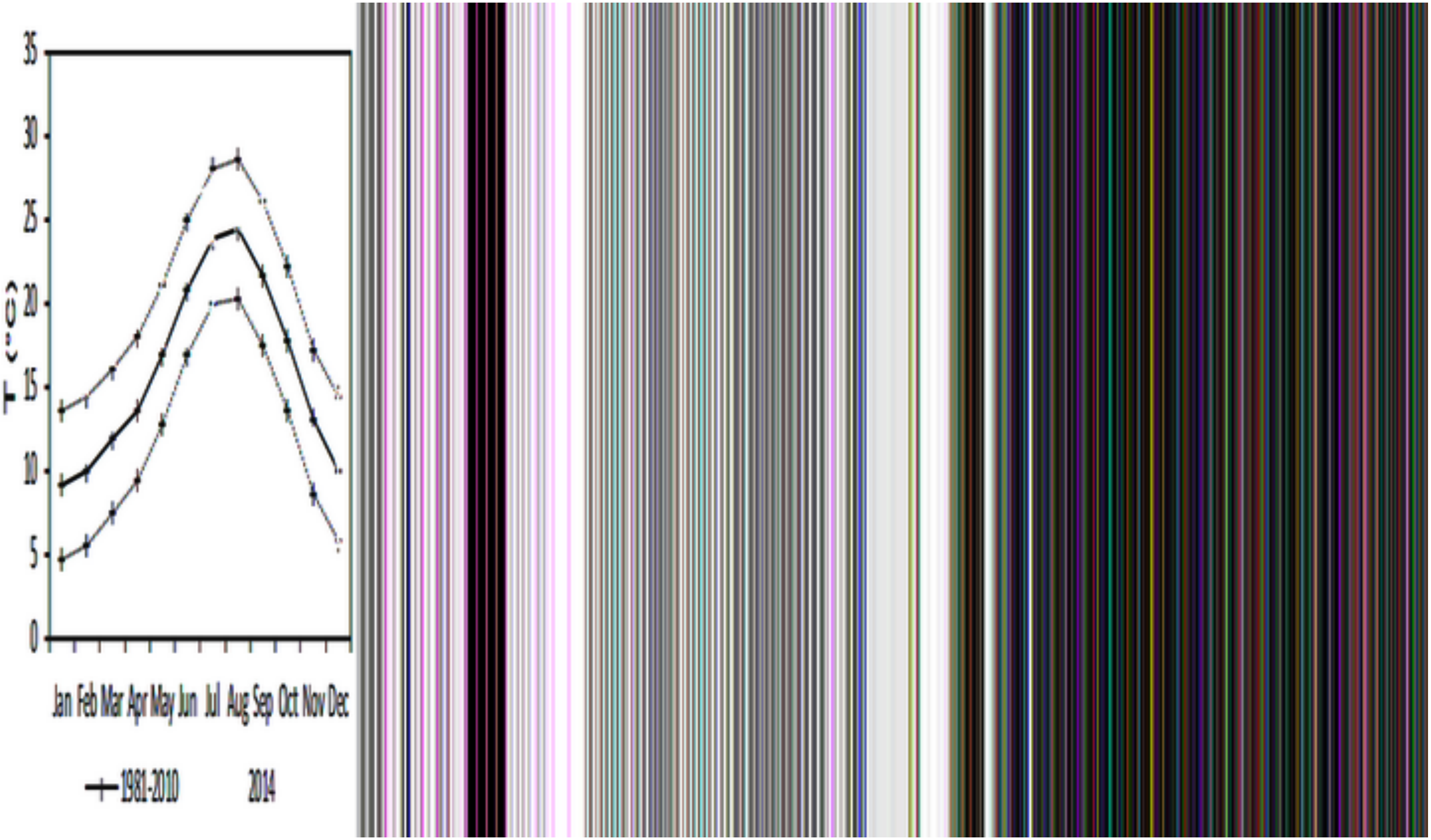

35
30
25
20
15
10
5
0
T (°C)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
1981-2010
2014

FIG9

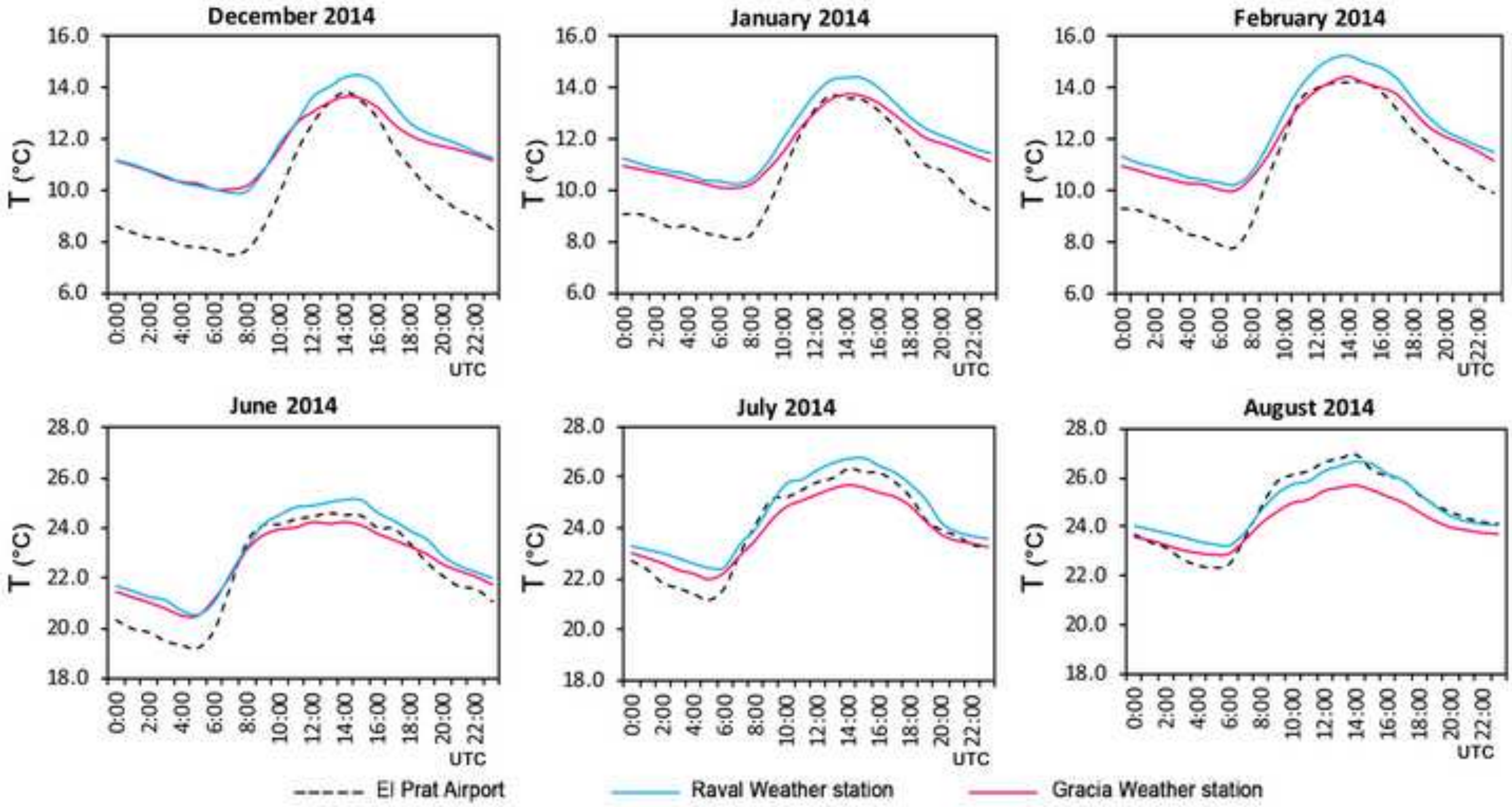

December 2014
January 2014
February 2014
June 2014
July 2014
August 2014
T (°C)
16.0
14.0
12.0
10.0
8.0
6.0
28.0
26.0
24.0
22.0
20.0
18.0
0:00
2:00
4:00
6:00
8:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
UTC
El Prat Airport
Raval Weather station
Gracia Weather station

FIG10

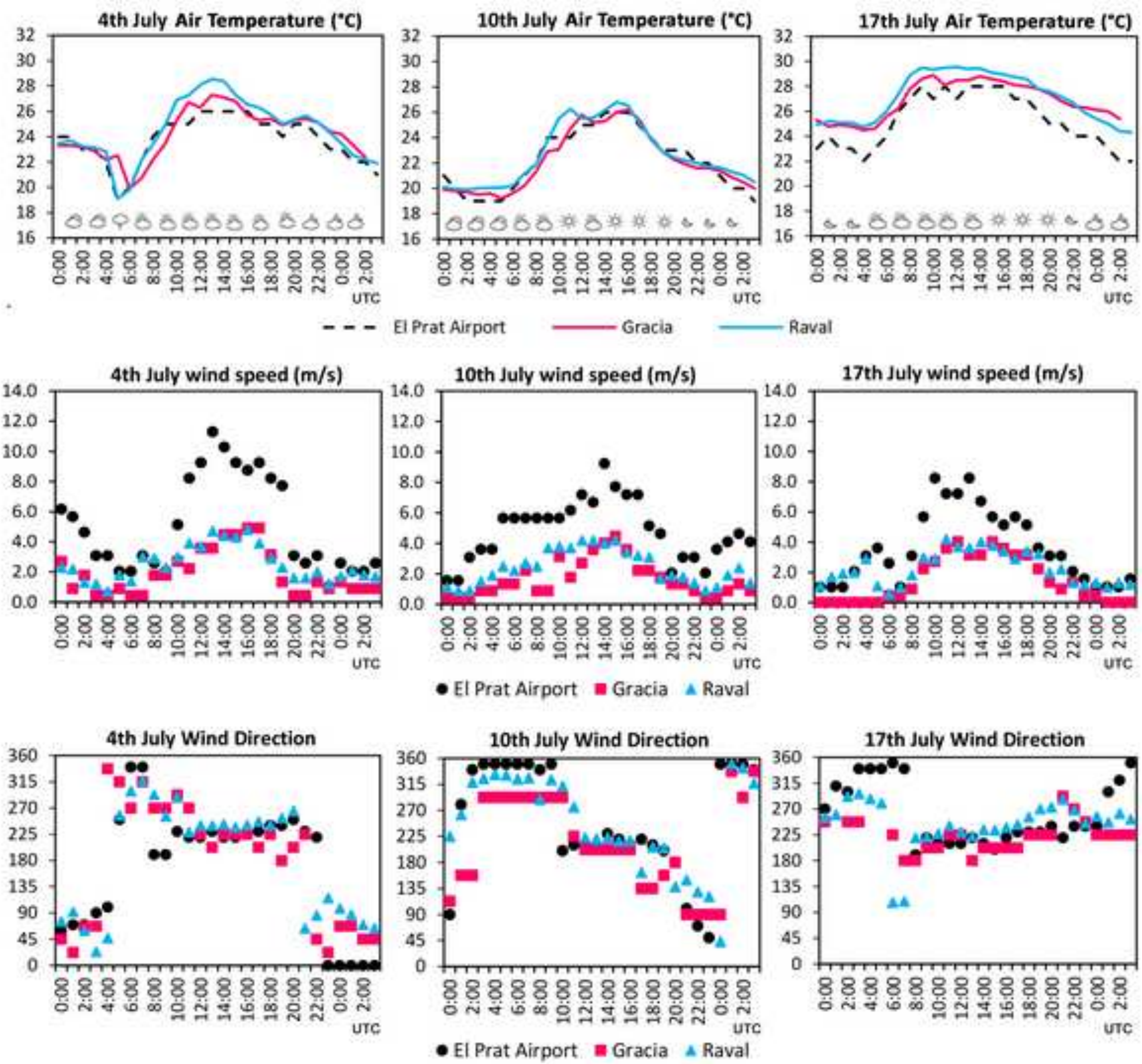

4th July Air Temperature (°C)
10th July Air Temperature (°C)
17th July Air Temperature (°C)
32
30
28
26
24
22
20
18
16
0:00
2:00
4:00
6:00
8:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
UTC
El Prat Airport
Gracia
Raval
4th July wind speed (m/s)
10th July wind speed (m/s)
17th July wind speed (m/s)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
● El Prat Airport ■ Gracia ▲ Raval
4th July Wind Direction
10th July Wind Direction
17th July Wind Direction
360
315
270
225
180
135
90
45
0

FIG11

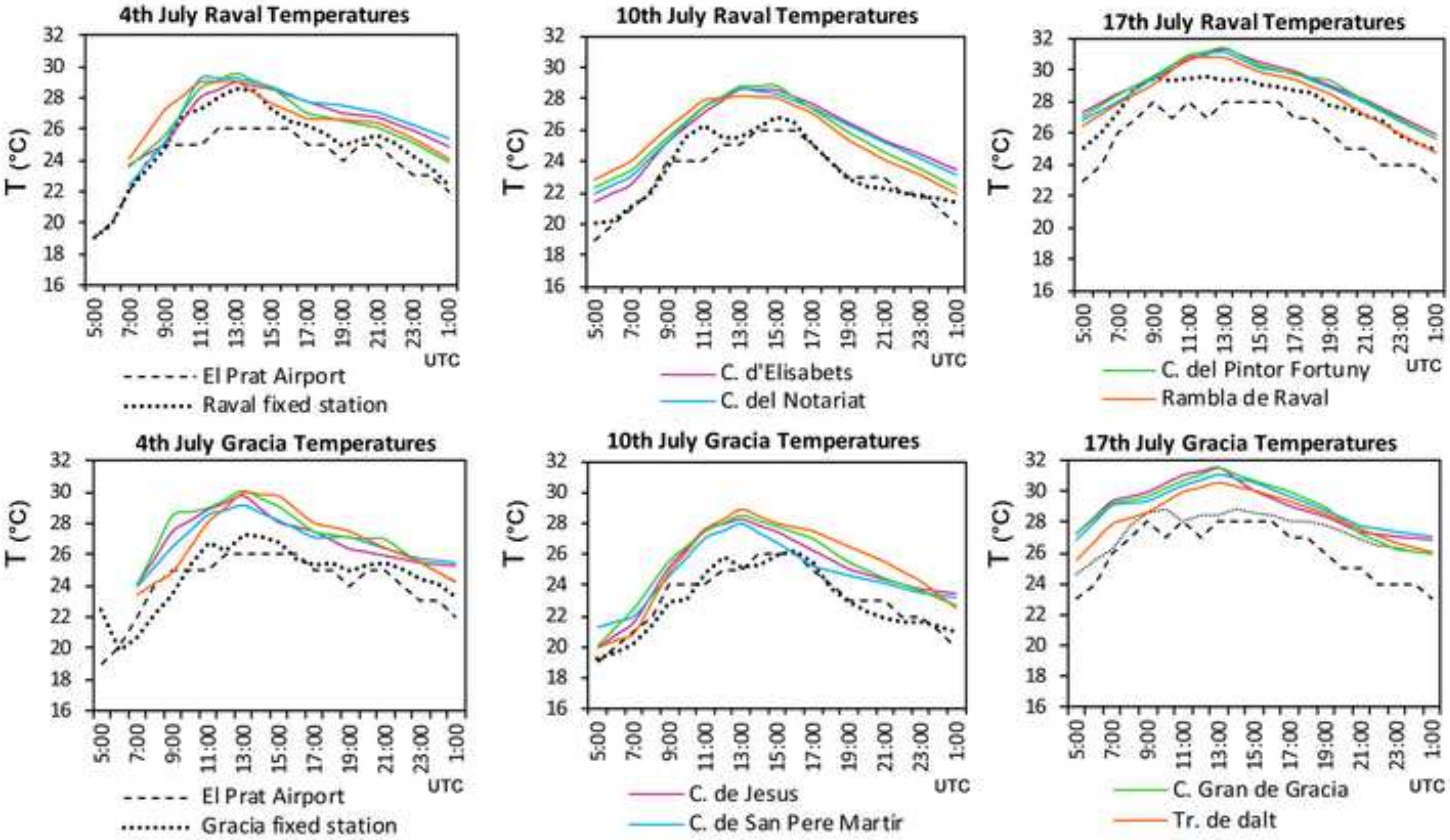

4th July Raval Temperatures
10th July Raval Temperatures
17th July Raval Temperatures
4th July Gracia Temperatures
10th July Gracia Temperatures
17th July Gracia Temperatures
T (°C)
32
30
28
26
24
22
20
18
16
5:00
7:00
9:00
11:00
13:00
15:00
17:00
19:00
21:00
23:00
1:00
UTC
El Prat Airport
Raval fixed station
C. d'Elisabets
C. del Notariat
C. del Pintor Fortuny
Rambla de Raval
El Prat Airport
Gracia fixed station
C. de Jesus
C. de San Pere Martir
C. Gran de Gracia
Tr. de dalt

FIG12

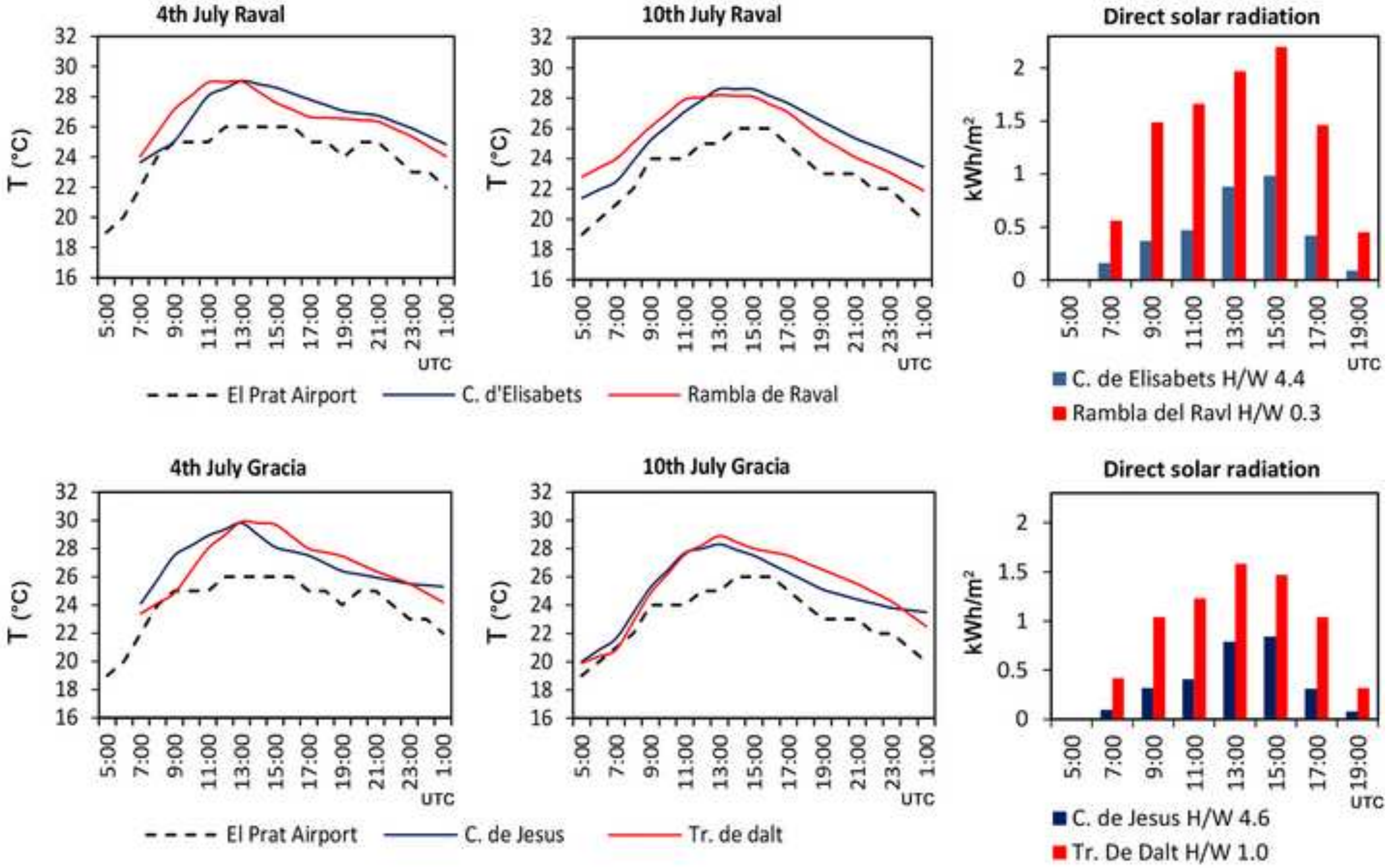
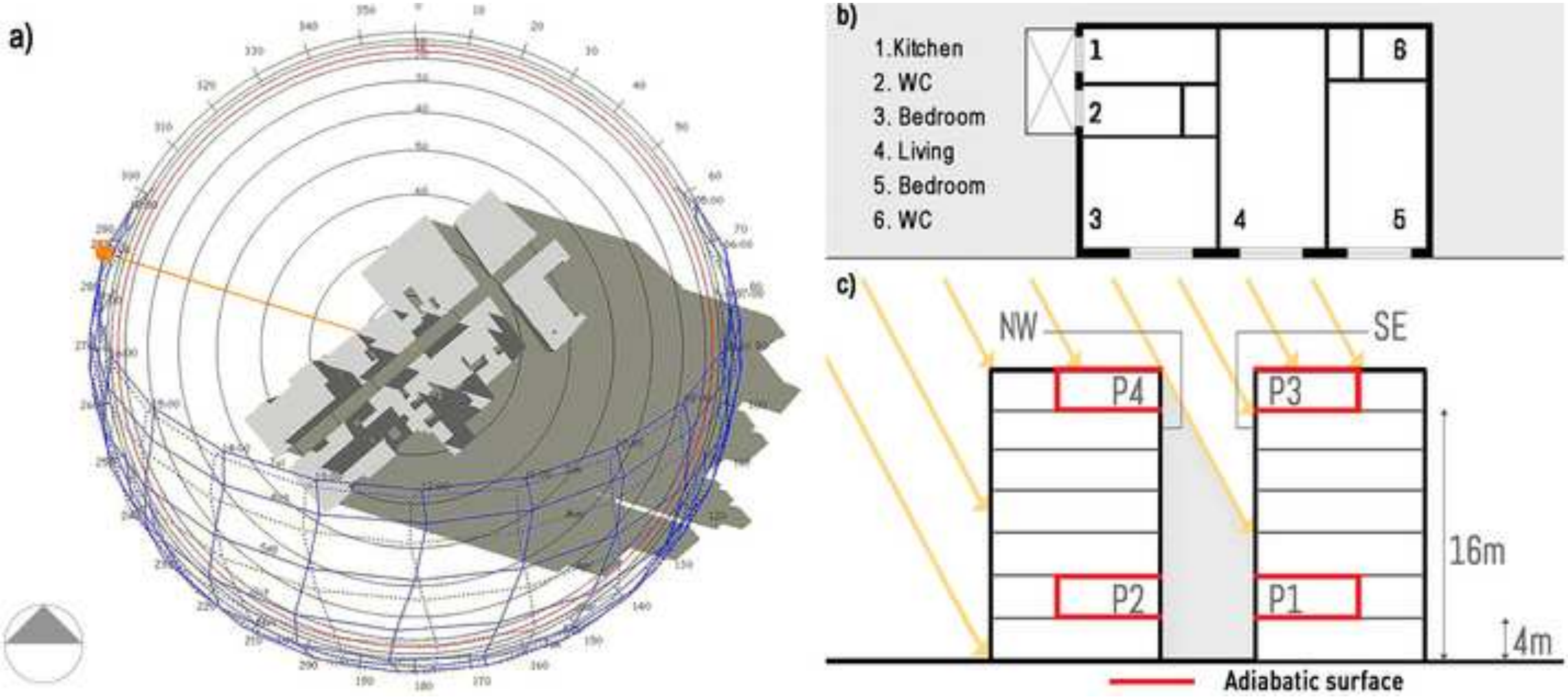

4th July Raval
10th July Raval
Direct solar radiation
T (°C)
kWh/m^2
32
30
28
26
24
22
20
18
16
2
1.5
1
0.5
0
5:00
7:00
9:00
11:00
13:00
15:00
17:00
19:00
21:00
23:00
1:00
UTC
El Prat Airport
C. d'Elisabets
Rambla de Raval
C. de Elisabets H/W 4.4
Rambla del Ravl H/W 0.3
4th July Gracia
10th July Gracia
Direct solar radiation
El Prat Airport
C. de Jesus
Tr. de dalt
C. de Jesus H/W 4.6
Tr. De Dalt H/W 1.0

FIG13.TIFF


a)
b)
1.Kitchen
2. WC
3. Bedroom
4. Living
5. Bedroom
6. WC
1
2
3
4
5
6
c)
NW
SE
P4
P3
P2
P1
16m
4m
Adiabatic surface

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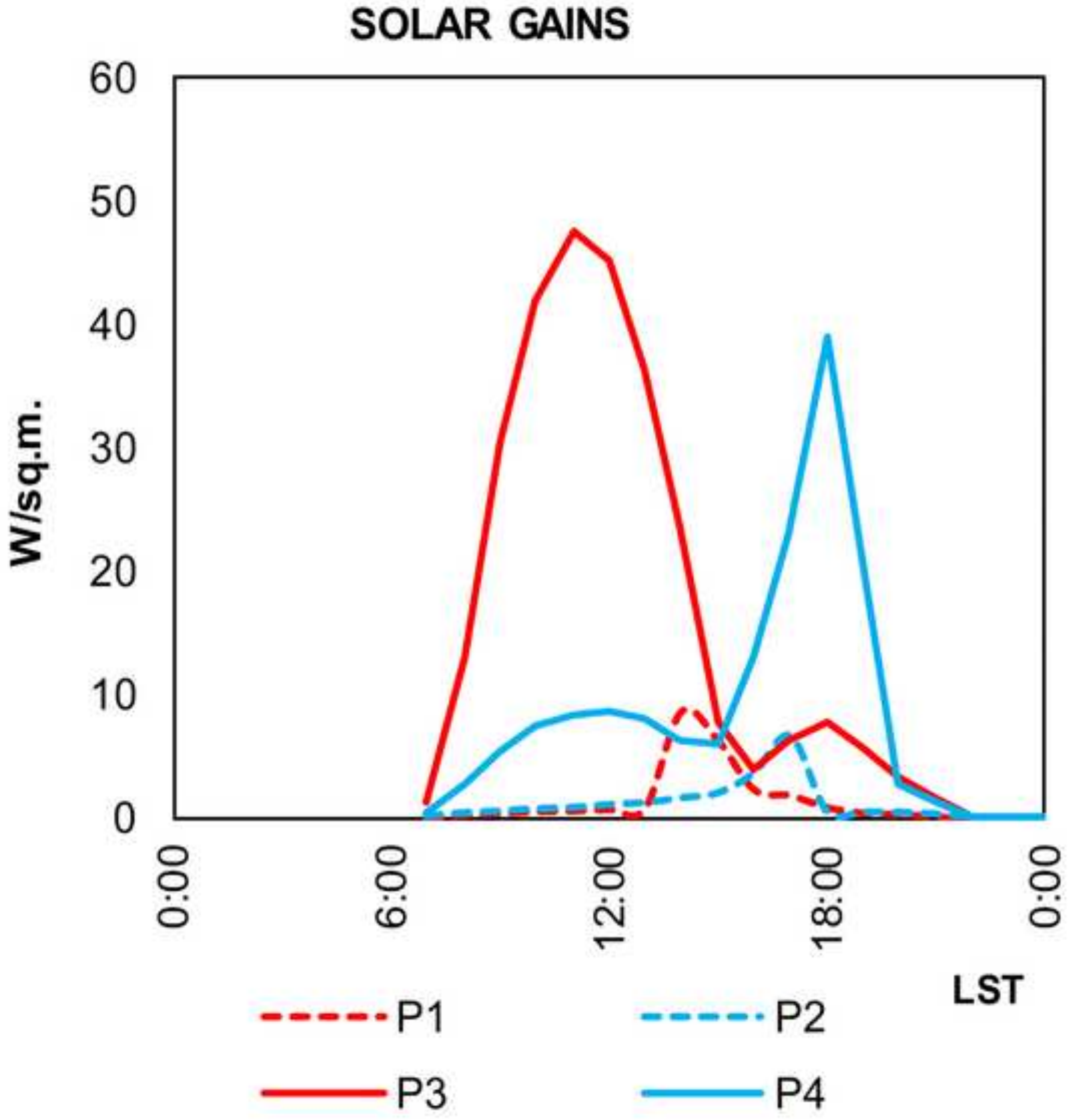


FIG15.TIFF

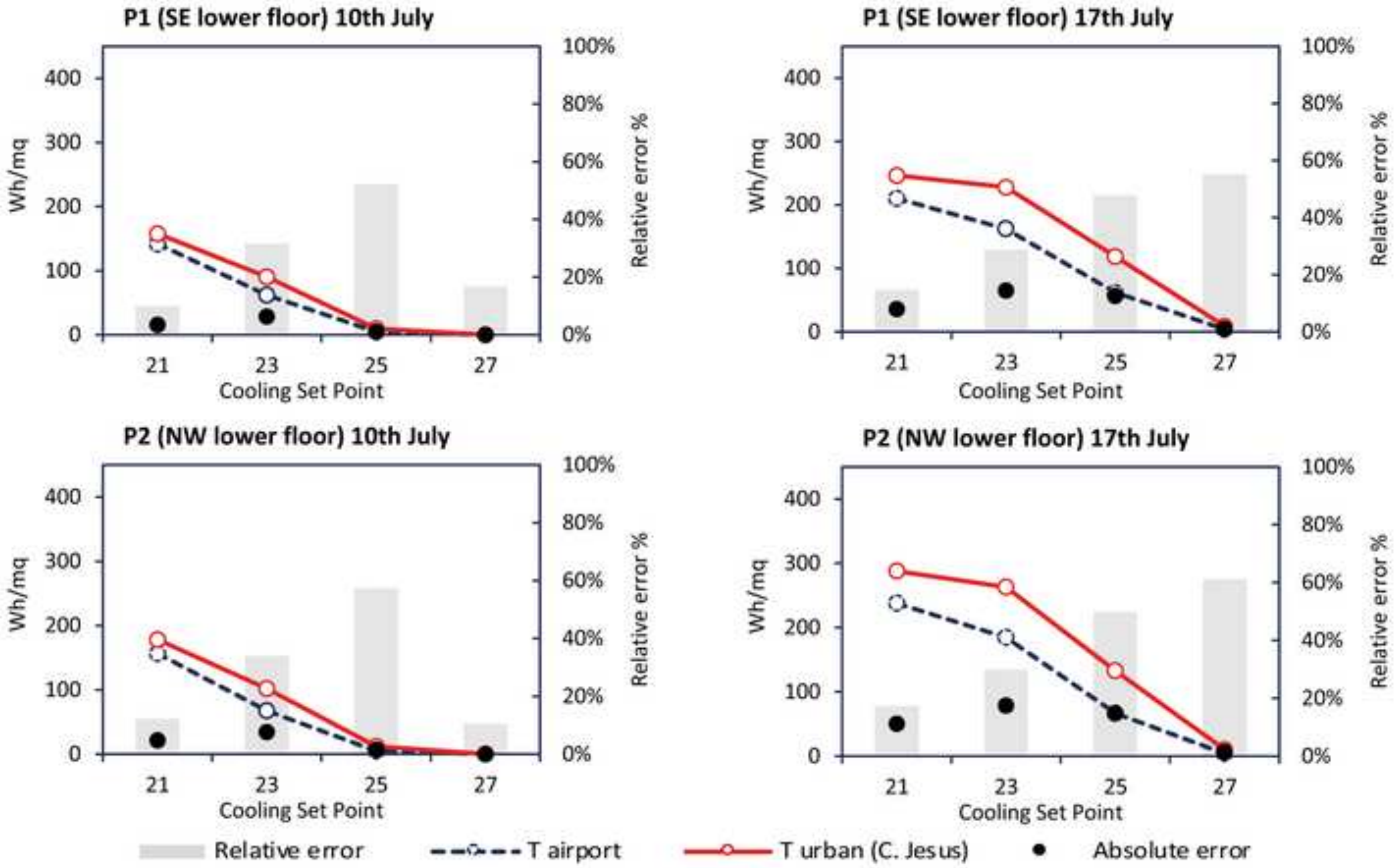
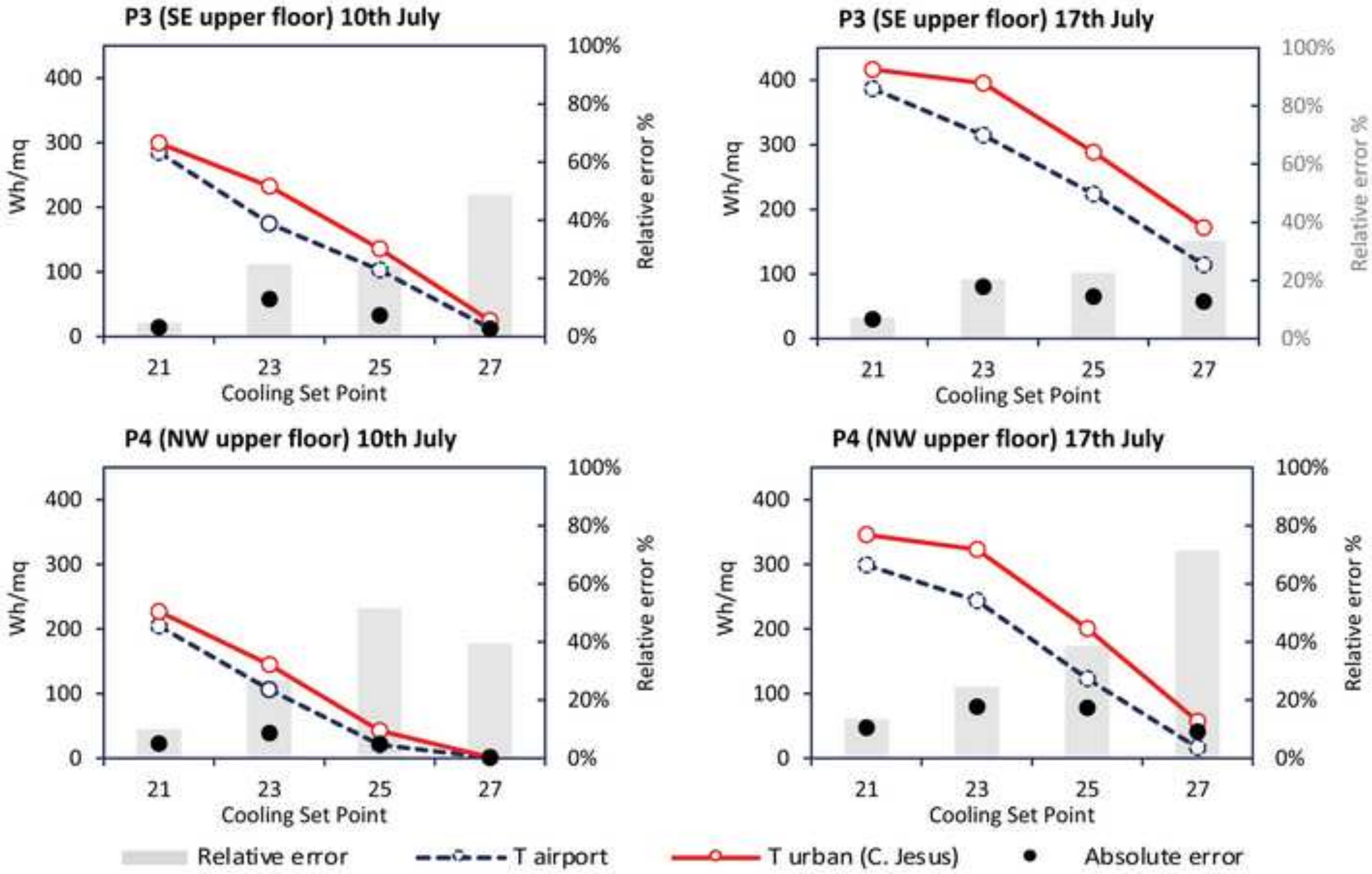

P1 (SE lower floor) 10th July
P1 (SE lower floor) 17th July
P2 (NW lower floor) 10th July
P2 (NW lower floor) 17th July
Wh/mq
0
100
200
300
400
Relative error %
0%
20%
40%
60%
80%
100%
21
23
25
27
Cooling Set Point
Relative error
T airport
T urban (C. Jesus)
Absolute error

FIG16.TIFF


P3 (SE upper floor) 10th July
P3 (SE upper floor) 17th July
P4 (NW upper floor) 10th July
P4 (NW upper floor) 17th July
Wh/mq
400
300
200
100
0
Relative error %
100%
80%
60%
40%
20%
0%
21
23
25
27
Cooling Set Point
Relative error
T airport
T urban (C. Jesus)
Absolute error

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Month	Avg Temp [°C]	Avg Maximum [°C]	Avg Minimum [°C]	Avg Precip [mm]	Days with Precip >1 mm
Jan	9.2	13.6	4.7	37	3.7
Feb	9.9	14.3	5.4	35	4
Mar	11.8	16.1	7.4	36	4.5
Apr	13.7	18	9.4	40	5.1
May	16.9	21.1	12.8	47	4.7
Jun	20.9	24.9	16.8	30	3.6
Jul	23.9	28	19.8	21	1.8
Aug	24.4	28.5	20.2	62	4.5
Sep	21.7	26	17.4	81	5.2
Oct	17.8	22.1	13.5	91	6.3
Nov	13	17.3	8.6	59	5.1
Dec	10	14.3	5.7	40	4.4
Year	16.1	20.3	11.8	588	53.3

Table 1: Monthly climate data series for Barcelona city. Data refer to observations at "El Prat Airport" weather station over the period 1981-2010 (2- column fitting table)

Weather Station	Sensor	Accuracy	Range	Height a.s.l.	Height above surface level	Resolution	Period
Raval	Platinum resistance thermometers PT100	±0.3 °C at 0 °C	from -200 to +850	33 m	1.5 m (from roof)	Hourly data	Year 2014
Gracia	Two Platinum wire thermistors	± 0.5˚C	from -45˚ to +60˚C	78 m	4.5 m (from roof)	Hourly data	Year 2014
El Prat	08181 WMO station	-	-	6 m	2 m (from ground)	Hourly data	Year 2014

Table 2 Characteristics of the temperature sensor at the urban weather stations and consistency of the data (two- column fitting table)

Canyons	Sensor	Accuracy	Range	Height a.s.l.	Height above surface level	Resolution	Period
Raval	portable thermometer	±1 °C	from -10 to +50 °C	From 5 to 15 m	1.5 m (from ground)	Every two hours	4th, 10th and 17th of July 2014
Gracia	portable thermometer	±1 °C	from -10 to +50 °C	From 60 to 90 m	1.5 m (from ground)	Every two hours	4th, 10th and 17th of July 2014

Table 3 Position and characteristics of the thermometers used for the air temperature measurements at street level (two- column fitting table)

MODEL ASSUMPTION
65 sq.m. (two bedrooms flat)
Store height: 3.3 m
OCCUPANCY:
Density = 0.03 (people/sq.m.)
Schedule: 00:00-09:00 and 16:00-24:00
ENVIRONMENTAL CONTROL:
Cooling set point = 21,23, 25, 27°C

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Cooling set back = 28°C
Cooling operation = 07:00-09:00 and 16:00-23:00
Natural ventilation: on
Outside air: 2 ac/h
Operation = occupancy scheme
CONSTRUCTION
Infiltration: Constant rate: 0.5 ac/h
Wall: masonry type, U-value: 1.3 W/sq.m. K
Glazing ratio: 30%
Glazing U-value: 4.5 W/sq.m. K
Shading: None

Table 4 model assumption (single column table)