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On the effect of summer heatwaves and urban overheating on building thermal-energy performance in central Italy

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ABSTRACT

Local climate phenomena impose a serious threat to the built environment. In particular, urban heat island and heatwaves can significantly affect buildings' thermal-energy performance. The purpose of this study is to investigate summer hot periods and their impact on building thermal-energy behavior in an urban area in Italy. To this aim, the statistical analysis of the microclimate variation during monitored hot periods is performed by the analysis of local weather parameters collected from a dedicated meteorological station. Moreover, the numerical analysis of representative Italian residential buildings is carried out to determine the role of such phenomena on indoor thermal comfort and cooling energy requirements, by considering the consequences arising from heatwaves due to the indoor overheating stress. The analysis showed a strong negative correlation between temperature and relative humidity during extreme hot periods (∼−0.92). Positive correlation was noted between temperature and solar irradiance (∼0.62) and temperature and wind velocity (∼0.33). The southern winds registered in normal hot periods reduced the heat stress by cooling-down the south-facing urban surfaces. The numerical analysis demonstrated higher indoor temperature for insulated buildings, requiring more than three times the cooling requirement of traditional non-insulated buildings in extreme hot periods and exacerbating the occupants' vulnerability.

1. Introduction

Increasing outdoor air temperatures are registered year after year in urban areas, with consequent raise of the heat stress and mortality risk and non-negligible effect on buildings' thermal energy performance (Brooke Anderson & Bell, 2011; Li & Bou-Zeid, 2013; Santamouris, 2001). Such phenomenon is generated by peculiar and local microclimate events, usually identified as urban heat island and heatwaves, that can considerably affect building indoor thermal comfort conditions and cooling energy consumptions (Kikon, Singh, Singh, & Vyas, 2016; Lauwaet et al., 2016). In fact, an increased urban surface area generates turbulent airflows leading to (i) the increase of the net short-wave radiation absorption and sensible heat in buildings, and (ii) the reduction of the emitted longwave radiation, of the convective heat loss, and of the latent heat losses (Cleugh & Grimmond, 2012), therefore contributing to the urban temperatures increase.

While the definition of urban heat island seems nowadays fairly univocal and largely universally acknowledged, many different theoretical definitions may be used to describe heatwaves, since a univocal and global definition still does not exist.

Heatwaves vary in intensity, frequency, and duration according to the geographic location and type of analysis (Robinson, 2001). Even a slight modification of the different parameters used to identify heatwaves can have a large effect in terms of their impacts (Xu, FitzGerald, Guo, Jalaludin, & Tong, 2016). In most of the existing studies, heatwaves are defined as a singular microclimate condition with temperatures over a specific percentile and characterized by more than three consequent hot days (Nairn & Fawcett, 2013; Zuo et al., 2014). With the gradual increase of the earth's mean temper-

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ature and the tremendous growth of hot days' records, there was suddenly the need to modify this general definition according to the specific examined location and magnitude of temperature.

Many research studies are available not only about heatwaves characterization, but also about their effect on (i) human health risk due to indoor overheating, (ii) buildings thermal-energy behavior, and (iii) the possible mitigation strategies. In detail, many existing research studies demonstrated the non-negligible impact of heatwave on mortality and health issues (Green, Andrews, Armstrong, Bickler, & Pebody, 2016; Joe et al., 2016; Smith et al., 2016; Zhang et al., 2016). For instance, the correlation between building energy ratings and heat-related mortality and morbidity was proved by Alam et al. (2016) (Alam, Sanjayan, Zou, Stewart, & Wilson, 2016). Additionally, Xu et al. (Xu, Hu et al., 2016) demonstrated that heatwave intensity plays a relatively more important role than duration in determining heatwave-related deaths, and that the magnitude of the effect estimates varies under different heatwave definitions (threshold percentile and duration). In the same scenario, the acute health effects of heatwaves have been studied in terms of their impact on the number of visits to emergency departments in the subtropical climate of Brisbane (Australia) by Toloo et al. (Toloo, Yu, Aitken, FitzGerald, & Tong, 2014).

To countermeasure the risks related to such local microclimate phenomena, i.e. heatwaves and UHI, Touchaei et al. (2016) investigated the effect on urban climate of increasing albedo as mitigation strategy in Montreal (Canada), during a heatwave period. The reflectivity of roofs, walls, and roads were increased from 0.2 to 0.65, 0.6, and 0.45, respectively (Touchaei, Akbari, & Tessum, 2016). With the same purpose, Willand et al. (2016) performed an empirical study by linking dwelling thermal performance and indoor temperatures, finding out that increased fabric insulation is linked to increases in summer indoor temperatures and cooling energy (Willand, Ridley, & Pears, 2016). In this view, Barbosa et al. (2015) developed a methodology for assessing the relative vulnerability of thermal comfort by examining changes on both physical characteristics and occupancy of dwellings (Barbosa, Vicente, & Santos, 2015). Insulation measures and optimal ventilation were detected to significantly decrease vulnerability.

On the other hand, a few studies focused also on the analysis of the resilience of the built spaces to heatwaves, by means of weather data recorded during extreme hot season (Iddon, Mills, Giridharan, & Lomas, 2015; Palmer et al., 2013). While traditional masonry wards showed remarkable resilience to the hot weather, light-weight modular buildings were on the contrary predicted to dangerously overheat. Additionally, Guan et al. (2014) studied the climate dependence of office electricity use from sub-hourly data in Adelaide (Australia)(Guan et al., 2014). Climate dependence was detected to start at 17 °C in daytime for office buildings in Adelaide, and heatwaves were able to increase office building electricity demand by up to 50%. More in details, 1 °C warming was detected to increase annual office electricity consumption by 2%. Another work by Ren et al. (2012) investigated the heat risks in non-conditioned houses during the 2009 Melbourne heatwaves, using building simulations (Ren, Wang, & Chen, 2012). It was demonstrated that the adoption of building energy efficiency is normally effective in reducing heat risks in non-conditioned houses. The link between urban domestic heat demand and the heatwave vulnerability index was also proved by Mavrogianni et al. (2009) by using the London building stock as a case study (Mavrogianni et al., 2009).

2. Motivation

Based on the outlined research background, which highlights the large number of studies investigating the heatwaves and the possible mitigation strategies for improving building envelopes resilience to extreme thermal stresses, the purpose of the present study is to (i) characterize and correlate the meteorological conditions during extreme hot periods in a historical city in central Italy and (ii) quantify their impact on buildings summer thermal-energy performance in order to detect the key meteorological parameters driving cooling loads in both highly and poorly insulated buildings.

The present study is aimed therefore at evaluating possible dangerous phenomena, i.e. health problems, linked to the building indoor overheating occurring during heat wave events. To this aim, the energy consumption of identical buildings with different insulation level and the impact of the different meteorological factors on the buildings thermal behavior were investigated by means of dynamic simulations.

More in detail, the focus of the study is Perugia, a small size city situated in central Italy (43.1122° N, 12.3889° E) with population of about 163,000 people (Fig. 1). The year 2013 was considered as a "hot" year in Italy and in the whole Europe, and was therefore analyzed in terms of all the meteorological parameters that are continuously monitored in this work, i.e. dry bulb temperature [°C], relative humidity [%], wind speed [m/s] and direction [°], solar irradiance [W/m^2]. In fact, even if the outdoor air temperature did not reach extreme values, the general thermal discomfort experienced by the population in Perugia during summer 2013 urged the need to characterize these high temperature values as part of a heat wave event and explain their origin and dispersion. In particular, the presence of mainly northern medium speed winds in the area was demonstrated to be able to mitigate local climate, by preventing the occurrence of urban heat island in the city.

The present work is strongly connected to previous studies analyzing the impact of local boundary conditions on buildings thermal-energy performance (A. Pisello, Pignatta, Castaldo, & Cotana, 2015), where a considerable modification of the energy consumption for heating and cooling was detected by means of numerical analysis depending on the location of the building in urban, suburban, or rural area. Additionally, building upon previous results (Santamouris, 2014), who investigated the energy impact of UHI phenomenon and global warming on buildings by comparing the cooling loads of typical urban buildings and similar rural buildings in various locations, the present research is aimed at investigating the cooling loads of highly-insulated and low-insulated typical Italian houses during hot and not-hot periods affected by heatwaves.

In general, no direct association can be detected between global warming and local microclimate phenomena such as UHI and heatwaves. However, several studies demonstrated that such phenomena have a serious impact on building thermal-energy performance, since they increase the near surface ambient temperatures in cities therefore leading to local overheating phenomena and outdoor thermal discomfort, with consequent non-negligible effects on human health (Santamouris, Cartalis, Synnefa, & Kolokotsa, 2014; Santamouris, 2014). According to Santamouris (Santamouris, 2014), the cooling load in urban areas is indeed 13% higher than in rural areas and the average increase in cooling demand is equal to 23% for the period 1970–2010. Moreover, based on the study provided by Santamouris et. al (Santamouris et al., 2007), who compared the cooling loads of insulated and not-insulated non-residential buildings, an increase of 2.17 kWh/m^2 of cooling load can be registered during summer months in not-insulated building (11.02 kWh/m^2) compared to the 8.85 kWh/m^2 of the insulated one.

As a step forward, the analysis carried out in this paper focuses on (i) residential buildings and (ii) on the impact on the buildings thermal-energy behavior of specific extreme hot periods registered during the summertime, that could lead to unexpected indoor