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Climate change and indoor temperature variation in Venetian buildings: the role of density and urban form

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Abstract. Although the influence of urban form on microclimate and building thermal processes has been acknowledged, few studies have addressed the influence of overheating mechanisms on heterogeneous urban fabrics for existing historical cities. This study investigates the impact of changing urban climate on indoor temperatures by focusing on three Venice morphological patterns. Through microclimate modelling techniques, outdoor and indoor temperatures are simulated in 2020 and 2050 scenarios. Results show that the compactness of the urban fabric contributes to reducing indoor building temperatures. The analysis suggests that the increased density of shadow areas can mitigate the outdoor temperature values and reduce direct radiation on façades. When comparing the two climate scenarios 2020 and 2050, average indoor temperatures increase in the latter. However, the analysis highlights that the absence of insulation and the relatively high thermal mass of typical Venetian envelopes plays a crucial role in the building thermal processes preserving indoor comfort in a warmer climate future.

1. Introduction

The predicted increase of average global temperatures and heat wave frequency is challenging climate conditions for historical cities that aim to transition towards a low-carbon and sustainable future. Among others, Venice is one case of a city that needs to cope with drastic changes. Besides global warming pushing sea levels higher, between 2000 and 2018, Venice had a 1.2°C increase in temperature when related to the 20th-century average. This trend challenges the adaptive capacity of the city and sets the urgency for investigating the complex interactions between projected changes and the urban environment. Measures of energy retrofitting of existing and historical cities would require a deep understanding of how and to what extent climate change impacts local microclimates, affecting the energy demand of large stocks of old and antique buildings, their indoor comfort and human wellbeing.

Over the last decades, researchers have acknowledged and demonstrated that overheating phenomena, such as heatwaves and Urban Heat Island (UHI), significantly impact energy needs for space cooling. By reviewing previous studies, Santamouris et al. [1] find that electricity consumption increases between 0,5%

and 8,5% for each degree of temperature rise, while Li et al. [2] show that only the UHI effect could increase energy demand to a median value of 19%. However, these studies 1) generally neglect the spatial distribution of urban climate phenomena that lead to significant temperature variations within areas, and 2) observing the influence of high built compactness on thermal processes in Venice, with its complex morphological characteristics, is challenging. In the study of strategies for Venice decarbonization, the development of morphological approaches and models allows an understanding of heat intensity levels and warming mechanisms within city specific areas. This is studied by linking air and surface temperature variations to numerical parameters describing land cover and density of urban patterns.

Previous parametric studies in other contexts have demonstrated a complex trade-off between thermal, aerodynamic processes and form factors at the building and district scale [3]. Among others, significant correlations have been found between solar irradiation and Space Matrix indices [4], UHI intensity and average building height, building façade, and coverage density [5], as well as between wind potential capacity and characteristics of rugosity, porosity, and compactness [6,7]. Such types of interdependencies are assumed as critical to the understanding of the influence of outdoor microclimate and consequently on their effect on building thermal behavior.

Despite the higher spatial resolution, most of these studies have analyzed typical buildings or 'generic' urban patterns, overlooking existing heterogeneous fabrics. The majority normalize the urban form characteristics by selecting homogeneous areas or employing theoretical typologies resulting from the repetition of a building type. As a result, very little research is discussing climate warming effects in a specific and topologically heterogeneous urban fabric such as the Venetian one.

Given these coordinates, this study bridges the gap by investigating the impact of urban microclimate on indoor temperatures for existing morphological patterns with different density levels, water and green coverage. Focusing on three areas in Venice, the study analyses building summer indoor temperatures through large stocks modelling techniques in the actual scenario (2020) and the projected scenario 2050.

2.   Methodology

For this study, three areas representative of Venetian fabrics were selected. Secondly, microclimate simulations were carried out in ENVI-met to model local outdoor and indoor temperatures in two climate scenarios (S2020 & S2050). Finally, detailed statistical analyses at different aggregation levels (district, buildings) were performed on the three samples' indoor building temperatures.

2.1.   Case study description

The selected case studies of S.Polo, S.Maria Formosa, and Garibaldi are representative of the three types of Venetian fabric systems [8]. The so-called 'archipelago city' based on the dominance of water ways [9], is organized in island systems (S.Polo). The quadrangular 'campo' with church, aristocratic houses and collective courtyard all served by water docks, constitutes a typical roman structure (till the X-XI) [10]. The 'spine' type (S.Maria Formosa), specific of the Gothic period, is structured by parallel canals and streets distanced by secondary orthogonal elements such as calli, courtyard buildings and palaces. Finally, the 'fondamenta' type (Garibaldi), where walking paths following waterways, serves as a structure for rows of buildings, which represents the typical Renaissance and modern structure (sec. XVI-XVIII).

Moreover, a quantitative morphological method was applied to verify that the cases represent different density levels. Three squared shape areas of equal size (240m by 240m) were chosen for the analysis. The calculation of Ground Space Index (GSI) and Floor Space Index (FSI) [11] shows that building coverage and building intensity are the lowest in Garibaldi (GSI=0,43; FSI=1,22), medium in S.Polo (GSI=0,57; FSI=2,29), the highest in S.Maria Formosa (GSI=0,67; FSI=2,70).

2.2.   Microclimate Simulations

ENVI-met, a three-dimensional prognostic microclimate model designed to simulate the interaction between surfaces, plants and air in an urban environment is used to perform a microclimate simulation for the three selected areas. Digital spatial models were built using a grid resolution of 2 m (x) by 2 m (y) by 3

m (z). As shown in Table 1, the horizontal domain dimension was kept constant (240 m x 240 m), while the vertical domain dimension was defined according to the maximum height of the existing buildings.

Table 1: Domain dimensions for each key selected Venice Area

	Model Area 1 (S.Maria Formosa)	Model Area 2 (S.Polo)	Model Area 2 (Garibaldi)
Domain (m)	240.0 × 240.0 × 60.0	240.0 × 240.0 × 69.0	240.0 × 240.0 × 51.0
Grid Size	120(x) x 120(y) x 20(z)	120(x) x 120(y) x 23(z)	120(x) x 120(y) x 17(z)

To build the digital models, building geometry and land cover characteristics were derived from the open dataset "Atlante della Laguna". Additionally, building and surface material data were retrieved through surveys. Their thermo-physical properties were modelled according to literature sources. A User Database (Table 2) was created to include the streets' locally used quarried stone (Trachite Euganea), the exposed brick walls and plastered brick walls for building envelopes, and shallow water for the canals (1.0 m deep).

Table 2: Material database

Materials	Absorption	Reflection	Emissivity	Specific Heat (W/m·K)	Thermal Conductivity (W/m·K)	Density (kg/m³)
Plaster	0.50	0.50	0.90	850	0.60	1500
Masonry	0.65	0.35	0.90	840	0.90	1850
Brick-burned	0.60	0.40	0.90	650	0.44	1500

Exposed Brick Wall: brick-burned (10cm), masonry heavyweight (25 cm), plaster (2 cm) Plastered Brick Wall: plaster (2 cm), masonry heavyweight (40 cm), plaster (2 cm)

	Roughness	Albedo	Emissivity
Trachite Euganea	0.01	0.5	0.9
Canal Water	0.01	0.04	0.96

The vegetation occupies a large area in Garibaldi. The uneven green mass is made of different species (Tilia europaea, Celtis australis, Quercus ilex, Picea abies) that vary in height (7 m to 26 m) and in canopy dimension (spherical or conic form). The irregular disposition of trees has been modeled accordingly: spherical or conic, medium trunk, sparse, tall/medium height, dense foliage, and they are all characterized by the albedo estimated in the range 0.25-0.40.

After creating spatial models and material dataset for the Venice case studies, climate boundary conditions were set for two climate scenarios, and applied with a simple forcing method. An average hot day with clear sky (19/08/20) was selected from the Venice standard EPW file, and used as contemporary

climate reference for scenario 2020 (S20). For scenario 2050 (S50), the same day was projected according to the IPCC scenario A1B. The Meteonorm Weather Generator was used for the purpose. With the combination of Meteonorm's current database 1961-90, the interpolation algorithms and the stochastic generation typical years can be calculated for any site, for different scenarios and for any period between 2010 and 2200. Literature shows [12] that this is a relatively simple method to enhance the spatial and temporal resolution, compared to downscaling methods based on regional climate models.

Finally, microclimate simulations were performed to estimate outdoor and indoor temperatures. ENVI-met provides modelling of the heat and humidity transfer of buildings, in addition to a prognostic calculation of walls [13] and indoor temperatures. Indoor spaces are treated as empty air volumes with uniform temperature (no heat capacity given by inner partition and furniture). This allows a rough estimation of the building energy balance (heating/cooling load if the indoor air temperature should remain constant) and the indoor air temperature amplitude [14] The tool does not account for the indoor reflection of the shortwave, and has limitations in accounting for thermal interactions between inside/outside environments [15]. The simplified method estimates the indoor air temperature as a prognostic variable, and the evaluation must still be regarded as only a rough evaluation [13]. However, such simplification fits within the scopes of generalization needed when a large stock of buildings are studied.

3.   Results

Simulation results for daytime outdoor (OutT) and indoor temperatures (IndT) were analysed at the district and building scale. At the district level, a first comparison between air temperature values in the two scenarios suggests that despite the exponential increase of outdoor temperatures in 2050, the Venetian fabric can maintain relatively low indoor temperatures. As shown in Figure1a, all the areas see an increase in average OutT of around 6 degrees in S50, reaching 30°C. However, the average IndT in the same scenario registers a maximum increase of only 0.7 degrees, reaching 21.35 °C. More in detail, S.Polo is the district with the lowest IndT difference between S20 and S50 (0.30 °C), followed by S.Maria Formosa (0.5°C) and Garibaldi (0.7°C). Additionally, in S50 a higher standard deviation is observed among the cases (Figure 1c), suggesting that the overall rising in OutT increases the values' variability of IndT.
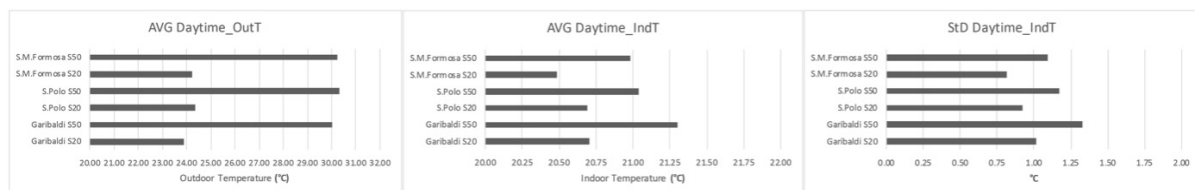

Figure 1: Comparison between outdoor and indoor temperature in S20 and S50

The mapping of maximum IndT in 2020 (Figure 2) shows that the frequency of buildings with high temperatures increases according to the fabric's density. Garibaldi, followed by S.Polo, have a predominance of buildings that reach 24°C, while S.Maria Formosa presents a homogeneous distribution of maximum IndT values (22°C - 23°C). However, in all three areas, buildings that reach 24°C have similar characteristics. These low-rise buildings are generally enclosed incompact surroundings and have exposed brick envelopes. Thus, the combination of reduced heat dissipation due to low wind speed, and the high albedo are major factors of indoor overheating.
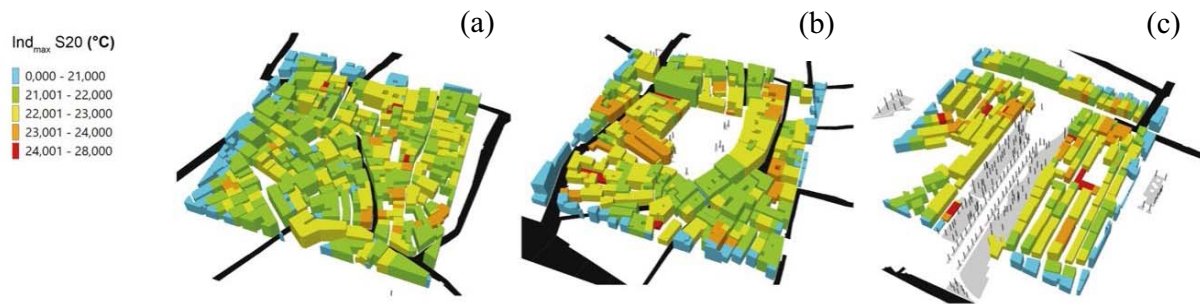
Figure 2: Maximum indoor temperature in S20: S.M.Formosa (a), S.Polo (b), Garibaldi (c)

In scenario 2050, the maximum IndT increases in a range of 2°C. As shown in Figure 3, buildings in S.Polo, given their larger size (grain), have the lowest increase of IndT (1.2 °C). By contrast, Garibaldi sees the most significant rise in maximum IndT 2.1°C. This city fabric has the lowest built compactness (GSI=0,43) among the three, and is crossed by a green wooded area, while S.Maria Formosa and S. Polo are featured by high compactness (GSI=0,57 & 0,67). Thus, these results indicate that the cooling effect of greenery on IndT decreases with the rise of outdoor temperatures. High density and high building size (footprint area>250m^2), on the opposite, contribute to mitigating overheating, confirming the importance of shadowing measures and building compactness (surface-to-volume ratio).
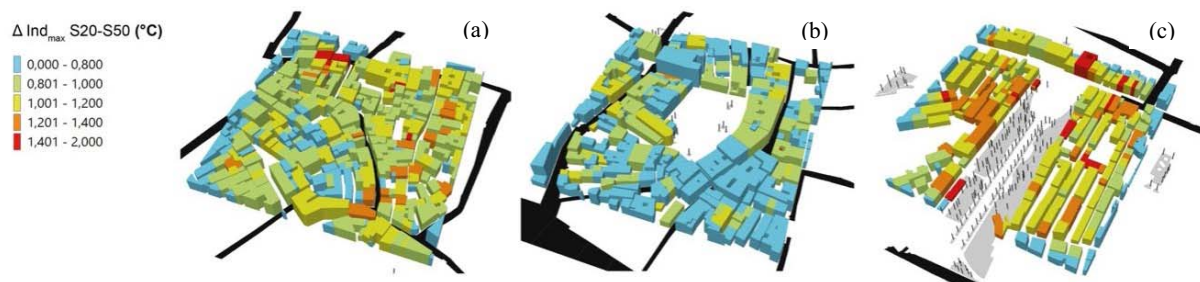

Figure 3: Variation of maximum indoor temperature between S20 and S50: S.M.Formosa (a), S.Polo (b), Garibaldi (c)

Moreover, at the building level, regression analysis shows that a linear relation exists between actual IndT temperatures (S20) and the variations between S20 and S50 (Figure 4). This constant pattern in the three areas suggests that the higher IndT in S20, the higher the temperature variation in S50. Despite this significant relation, Figure 4 also confirms that compared to S.Polo and S.Maria Formosa, buildings in Garibaldi see much higher ΔmaxIndT between S20 and S50.
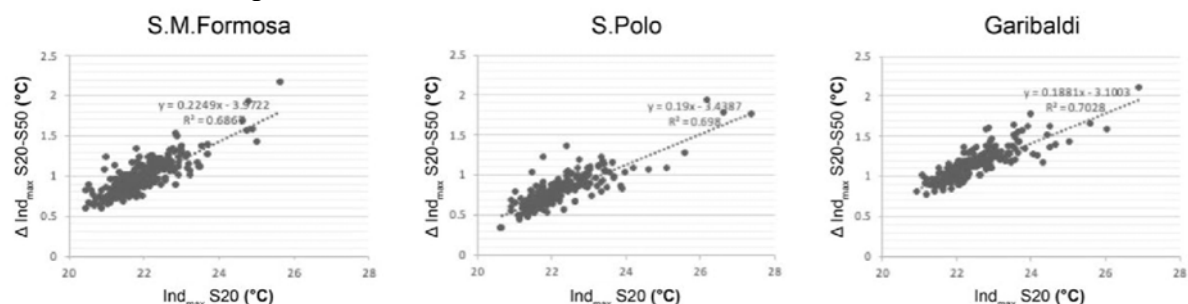

Figure 4: Correlation between maximum indoor temperature in S20 and increase of maximum indoor temperature in S50

4.   Conclusions

This study investigates the impact of Venetian's morphological characteristics on urban microclimate and daytime indoor temperatures. Three existing form patterns with different density levels, water and green coverage were modeled with ENVI-met, in the actual (2020) and future climate scenario (2050). The analysis at the district scale indicated that Venice fabrics are highly resilient to climate warming. Despite the significant increase in average outdoor temperatures in 2050 (avg. 6°C), all the fabrics maintain relatively low indoor temperatures (avg 0.7°C, range 2°C). This result suggests that the high thermal mass of construction systems and the large presence of light-color stone materials contribute to maintain a good level of indoor thermal comfort also in a warmer climate future. Additionally, the density of the urban fabric is observed to influence the distribution of indoor temperatures values: the higher the urban fabric compactness, the lower the frequency of high indoor temperatures. High density (GSI>0,5) and high building size (footprint area>250m^2) also contribute to mitigating indoor overheating (S.Polo, S. Maria Formosa) in the warmer climate scenario, while by contrast, the cooling effect of greenery decreases with the increase of outdoor temperature (Garibaldi). The role of water on climate processes is not addressed in this study. Further investigations need to study the meso-scale climate effect of the sea breezes and the influence of water elements.

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