EFFECT OF HIGH MASS TRADITIONAL BUILDINGS IN MODERATING INDOOR TEMPERATURES IN THE MEDITERRANEAN CLIMATE

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Fig 1: Traditional settlements under investigation. Images represent typical street and building configurations in three settlements of Cyprus, namely, Maroni, Pera Orinis and Askas.

WHICH ARE YOUR ARCHITECTURAL (R)SOLUTIONS TO THE SOCIAL, ENVIRONMENTAL AND ECONOMIC CHALLENGES OF TODAY?

Research summary

The present study aims at evaluating the effect of thermal mass in moderating indoor maximum temperatures in the climatic context of the Mediterranean. For this purpose, in-situ measurements in high mass traditional buildings were carried out, taking Cyprus as a case study. A total of 25 traditional spaces —located in three settlements which are characterized by different local climatic conditions— were monitored during the hot, summer period, between the 1st and 31st of August 2014. The analysis of collected data referring to environmental aspects of the spaces examined, showed that outdoor climatic variables constitute a key parameter affecting the performance of thermal mass during the hot, summer period. The effect of thermal mass in lowering indoor temperature maxima below outdoor temperature maxima significantly varied among the climatic regions under study. Traditional spaces in climatic regions which present large diurnal temperature fluctuations, demonstrated larger indoor maximum temperature reductions compared to the spaces located in climatic regions with relatively small diurnal temperature fluctuations and high night-time temperatures. Furthermore, it is found that the indoor maximum temperature in the spaces under study is affected by the combined effects of outdoor maximum temperature and outdoor diurnal temperature fluctuation. The study discusses these findings and provides a comparison with other studies dealing with the examination of the effects of outdoor climatic conditions on indoor temperature maxima.

Keywords: traditional buildings; thermal mass; Mediterranean climate; passive cooling

1. Introduction

It is well known that building envelopes with high thermal mass moderate indoor maximum temperatures in the hot, summer period, contributing to favourable thermal comfort conditions. The positive effect of thermal mass has been acknowledged and extensively used in vernacular architecture, especially in hot and arid regions. There are numerous examples of traditional buildings around the Mediterranean and the Middle East which have exploited the thermal energy storage capacity of the building envelopes. Previous studies —based on in-situ measurements in traditional buildings— conducted by Philokyprou & Michael (2012) and Martin et al (2010) confirmed the significant contribution of high mass traditional buildings in achieving indoor temperature reduction and thermal stability.

The effectiveness of thermal mass of the building envelope is related to the climatic conditions, thermophysical properties of the building envelope materials, ventilation conditions, number of occupants and their living pattern and other internal heat gains. This paper investigates the summer performance of high mass traditional buildings with respect to the outdoor climatic conditions with the aim of a better understanding of the thermal comfort conditions of these buildings. A simplified method for the computation of indoor maximum temperatures in high mass buildings with reference to the Mediterranean climate is identified. The findings of the present study can be implemented for the evaluation of the effectiveness of thermal mass as a passive cooling strategy in regions with similar climatic conditions to the examined regions.

2. Climatic classification of Cyprus

Cyprus has a Mediterranean climate which is, generally, characterized by warm to hot summers, cool to cold winters, intense solar radiation and predominantly clear skies. Fig. 2 represents the climatic classification of Cyprus into four climatic zones, i.e. coastal regions, lowland regions, semi-mountainous regions and mountainous regions. Each climatic zone possesses climatic variations depending on its proximity to the sea and altitude. The coastal regions (Climatic Zone 1) have the characteristics of a hot and humid climate. Such regions are characterized by a fairly high relative humidity throughout the year due to their proximity to the coast. For the same reason, diurnal temperature fluctuations are relatively small causing cool winters and mild summers, with moderate outdoor temperature maxima and minima. The lowland regions (Climatic Zone 2) reflect the features of a hot and semi-arid climate. At these regions, humidity is relatively lower and diurnal temperature fluctuations are big leading to more severe, cool to cold winters and hot and dry summers. The semi-mountainous regions (Climatic Zone 3) are located at a transitional zone between lowland and mountainous regions. These regions are relatively colder and wetter in winters and cooler in summers compared to lowland regions. Finally, the

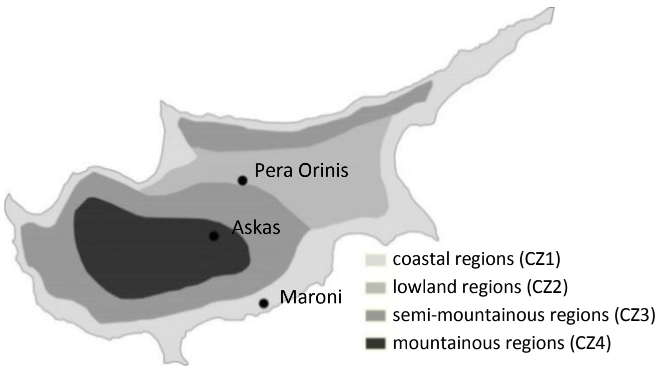

Fig 2: Climatic classification of Cyprus

climate in mountainous inland regions (Climatic Zone 4) features mild summers, cold and wet winters and lower humidity levels due to their location at high altitudes. These regions exhibit the lowest temperatures, some snowfall during winters, as well as, the highest precipitation.

3. Methodology

3.1 Selection of case studies and measurement procedures

The research methodology followed is based on a qualitative and quantitative investigation of the summer performance of high mass traditional buildings in the Mediterranean climate. For this purpose, three case study settlements, namely Maroni, Pera Orinis and Askas, located in different climatic zones in Cyprus, have been selected for further investigation (Fig. 2). Maroni is located in the coastal region (CZ1) and it is characterized by a semi-dispersed configuration, low-rise development, continuous building block massing and narrow streets. Pera Orinis is located in the transitional zone between the lowland and semi-mountainous region (CZ2/3). It shares similar planning characteristics with Maroni village but in a more compact built fabric. Askas is located in the mountainous region (CZ4). It has a very compact built fabric, mid-rise built configuration and deep and narrow streets. These spatial characteristics were partly imposed by the lack of available space due to the mountainous topography of the village.

The quantitative investigation followed includes the monitoring of indoor temperatures in various spaces inside traditional buildings in the three settlements. Traditional spaces examined are characterized by high mass masonry walls, tiled timber roof structures and relatively small and limited window openings of window-to-floor ratio not exceeding 15% (Fig. 1). Specifically, seven spaces were monitored at Maroni (CZ1), eight at Pera Orinis (CZ2/3) and ten at Askas (CZ4). In the case of the latter, five of the spaces monitored were semi-subterranean. Indoor temperatures were measured under conditions of natural ventilation and were affected by the inhabitants' daily life. However, four spaces located at Maroni (CZ1) were monitored under non-ventilated conditions in order to quantify the effect of natural ventilation on indoor temperature reductions. In-situ indoor measurements were taken in 30-minute intervals using Lascar data loggers (EL-USB-2 and EL-USB-2-LCD). Data loggers were placed 1.50 m above floor level. Recording of outdoor climatic conditions in these settlements was also undertaken using Davis weather stations (Vantage Pro2 and Vantage Pro). Weather stations were installed high above the skyline of neighbouring buildings. Indoor and outdoor temperature measurements were recorded during the hot, summer period, between the 1st and 31st of August 2014. Regression analysis was used for processing indoor temperature data by relating these temperatures to outdoor climatic variables.

3.2 Description of thermal properties

Wall thickness and thermal diffusivity were determined in order to evaluate the ability of traditional walls under investigation to reduce heat propagated through their mass. In general, a thick and low thermal diffusivity material has a larger ability to moderate indoor temperature maxima relative to outdoor temperature maxima. Table 1 presents the thickness and thermal diffusivity of the different wall material layers of the buildings under investigation. It is noted that, the selection of building materials at traditional settlements was adapted to the locally available resources. For that reason, each climatic region is distinguished by its own building materials which were mainly imposed by local geology and climate. As noted in the table limestone, adobe and volcanic stone represent the predominant construction materials used in Maroni (CZ1), Pera Orinis (CZ2/3) and Askas (CZ4) respectively (Fig 1). Adobe presents the lowest thermal diffusivity of $0.31 \cdot 10^{-6}$ m^2/s, followed by limestone with thermal diffusivity of $0.67 \cdot 10^{-6}$ m^2/s and by volcanic stone with $1.07 \cdot 10^{-6}$ m^2/s. Thermal diffusivity was determined in laboratory conditions by the authors for the needs of the present study, unless otherwise specified. Laboratory measurements were undertaken at an average temperature of 25 °C using ISOMET 2104 equipment.

Table 1: Thermal diffusivity of wall material layers

Climatic Region	Traditional Wall Composition	Thickness (m)	Thermal Diffusivity α (10^{-6} m^2/s)
CZ1	Inner plaster	0.025	0.47 (CIBSE 2006)
	Limestone	**0.2**	**0.67**
	Earth	0.05	1.00 (CIBSE 2006)
	Limestone	0.2	0.67
	Outer plaster	0.025	0.47
CZ2/3	Inner plaster	0.025	0.47
	Adobe	**0.45**	**0.31**
	Outer plaster	0.025	0.47
CZ4	Inner plaster	0.025	0.47
	Volcanic stone	**0.2**	**1.07**
	Earth	0.1	1.00
	Volcanic stone	0.2	1.07

4. Results

4.1 Thermal mass performance

Based on regression analysis, Fig. 3 shows the direct relationship between $T_{max\_d} = T_{max\_out} - T_{max\_in}$, i.e. the reduction of maximum indoor temperature relative to maximum outdoor temperature, and T_{max_out}, i.e. the maximum outdoor temperature. It is noted that the higher T_{max_out} is, the higher is T_{max_d}. It is also noted that when T_{max_out} is relatively low, there is an increase in T_{max_in} which rises above T_{max_out}, resulting in negative values in the graph (Fig. 2). The T_{max_d} of non-subterranean spaces ranges from -2 °C to 3 °C for CZ1 and CZ4 and 2 °C to 8 °C for CZ2/3 (Fig. 3). For semi-subterranean spaces (CZ4) it ranges from 1 °C to 8 °C. It is worth mentioning that in CZ1 a reduction in T_{max_in} below T_{max_out} is observed when T_{max_out} is close to 32 °C, while in CZ2/3 and CZ4 this reduction occurs at a lower T_{max_out} of about 29 °C. For semi-subterranean spaces, the T_{max_out} threshold in which T_{max_in} drops below T_{max_out} is 25 °C.

Regarding the non-ventilated spaces studied in CZ1, it is observed that these spaces presented predominantly negative T_{max_d} values (Fig. 3). This means that T_{max_in} is generally higher than T_{max_out} in such spaces. Furthermore, the shift of the line representing T_{max_d} in non-ventilated spaces of CZ1 to a position below that of the naturally ventilated spaces of the same climatic zone means that for a given T_{max_out} lower reductions of T_{max_in} are likely to be achieved in the case of the former.

The shift of the line representing semi-subterranean spaces of CZ4 in a position high above the lines indicating non-subterranean spaces means that for a given T_{max_out} higher reductions of T_{max_in} are achieved in the case of semi-subterranean spaces (Fig. 3). Fig. 3 shows that T_{max_in} in semi-subterranean spaces are 3 to 5 °C lower compared to those of non-subterranean spaces of the same climatic zone. The shift of the line representing the T_{max_d} of naturally ventilated spaces located in CZ1 to a position below the lines representing ventilated spaces of CZ2/3, CZ4 demonstrates

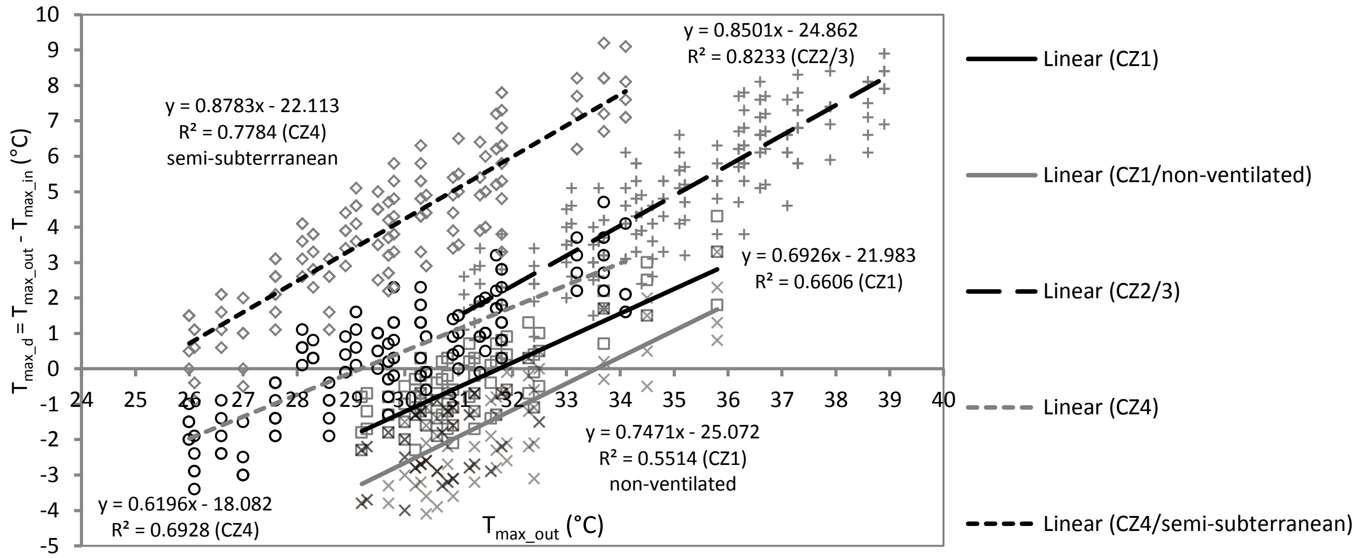

Fig 3: Correlation between T_{max_d} and T_{max_out} in monitored spaces in CZ1, CZ2/3 and CZ4

that lower reductions of T_{max_in} occur in CZ1 for a given T_{max_out} (Fig. 3). The graph indicates that T_{max_in} in the case of naturally ventilated spaces in CZ1 is roughly 2 °C above those of CZ2/3, CZ4 for a given T_{max_out}, reducing the cooling effect of thermal mass.

Results show that, semi-subterranean spaces accounted for significant reductions of indoor maximum temperatures. This is attributed to the fact that the high thermal inertia of the earth mass has the ability to further reduce indoor maximum temperatures. Regarding the non-subterranean spaces, thermal mass in CZ2/3 proved to be most effective in moderating maximum indoor temperatures followed by CZ4 and CZ1. These findings can be attributed primarily to outdoor climatic conditions and to the thermal properties of the building envelope. It is noted that some other factors such as the orientation, window-to-floor ratio and plan layout configuration have also affected indoor temperature maxima. As noted in Table 1, adobe walls used in the CZ2/3 have the lowest thermal diffusivity and thus present the greatest potential for moderating indoor temperature maxima. Additionally, it is well known that in hot and semi-arid regions such as regions in CZ2/3, which have large variations in outdoor diurnal temperature, thermal mass is highly beneficial. On the contrary, in hot and humid regions such as regions in CZ1, buildings with high thermal inertia cannot loose significant amounts of heat to the outdoors during the night due to the relatively high night temperatures reducing the benefits of thermal mass. This fact would be an explanation why despite the better ability of limestone walls (CZ1) to moderate indoor temperature maxima compared to volcanic stone walls (CZ4), the former accounted for smaller temperature reductions.

4.2 Indoor maximum temperature computation

Regression analysis based on in-situ measurements demonstrates that T_{max_d} is correlated with T_{max_out} and outdoor diurnal temperature fluctuation ($T_{max\_out} – T_{min\_out}$) (Fig. 4). Based on the regression analysis a simplified relationship for the computation of indoor maximum temperature was developed. The indoor maximum temperature is given by the following expression:

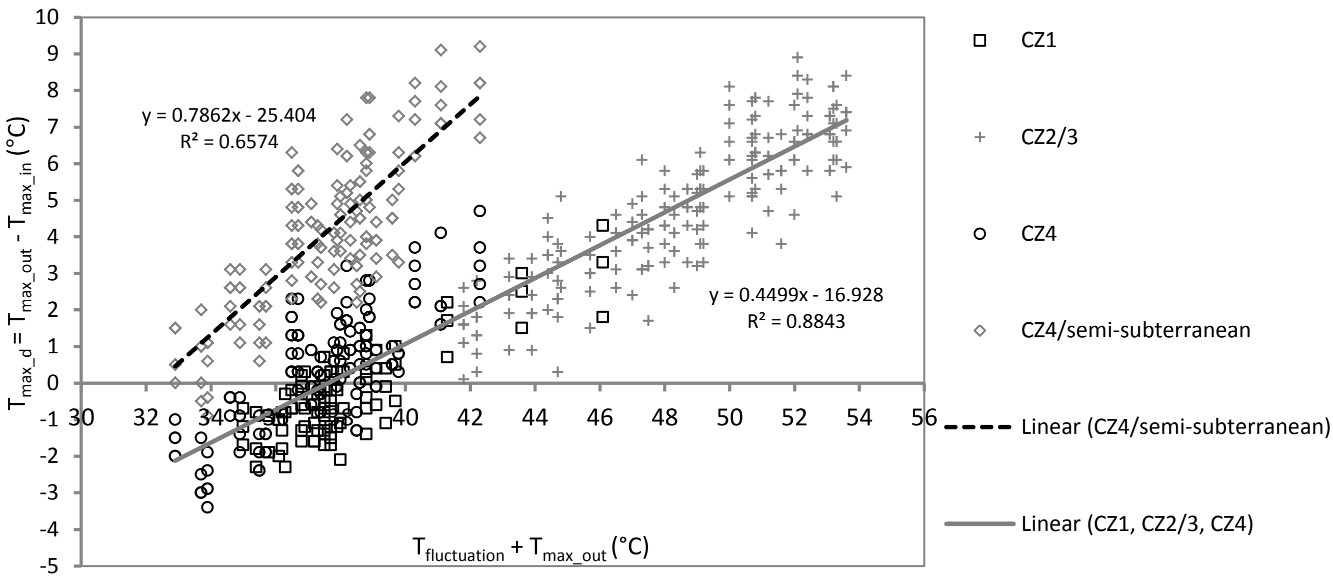

Fig 4: Correlation between T_{max_d} and $T_{fluctuation}$ + T_{max_out} in monitored spaces in CZ1, CZ2/3 and CZ4

$$T_{\max\_in} = 0.5501T_{\max\_out} - 0.4499(T_{\max\_out} - T_{\min\_out}) + 16.928;\ R^2 = 0.8843$$

where T_{max_in} is the maximum indoor temperature; T_{max_out} is the maximum outdoor temperature and $T_{max\_out} - T_{min\_out}$ is the outdoor diurnal temperature fluctuation.

Another expression has been developed for the computation of indoor maximum temperatures in semi-subterranean spaces as follows:

$$T_{\max\_in} = 0.2138T_{\max\_out} - 0.7862(T_{\max\_out} - T_{\min\_out}) + 25.404;\ R^2 = 0.6574$$

5. Discussion and comparison with other studies

Several studies devoted to the understanding of thermal performance of high mass buildings, have shown correlations of indoor maximum temperatures with outdoor maximum temperatures and diurnal temperature fluctuations (Table 2). Specifically, in-situ measurements undertaken by Givoni (1998) in high mass test chambers in Pala, South California showed that there exists a relationship between maximum indoor temperature reduction and outdoor diurnal temperature fluctuation. Based on these findings, the author proposed a formula for the prediction of indoor maximum temperature as follows:

$$T_{\max\_in} = T_{\max\_out} - 0.31(T_{\max\_out} - T_{\min\_out}) + 1.6$$

Another field study carried out by Ogoli (2003), in high mass test chambers in Nairobi, Kenya confirmed the findings of Givoni (1998) and arrived at a new equation:

$$T_{\max\_in} = T_{\max\_out} - 0.488(T_{\max\_out} - T_{\min\_out}) + 2.44;\ R^2 = 0.63$$

Shaviv et al (2001), based on simulation studies in high mass buildings in different climatic regions of Israel, confirmed the findings of Givoni (1998) and Ogoli (2001). Shaviv et al (2001), tested three different modes of night ventilation, i.e. no night ventilation (2 ach), natural night ventilation (5 ach) and forced night ventilation (20 ach), and obtained the following equations:

Table 2: Present and other studies dealing with the computation of indoor temperature maxima in high mass spaces

	Present study	Givoni (1998)	Ogoli (2003)	Shaviv et al (2001)
Location	Maroni-CZ1, Pera Orinis-CZ2/3, Askas-CZ4, Cyprus	Pala, South California, USA	Nairobi, Kenya	Israel
Case Studies	actual buildings	test chambers	test chambers	actual buildings
N^{o} of rooms	7 (CZ1), 8 (CZ2/3), 10 (CZ4)	-	4	1
Experiment	warm period	warm period	warm period	warm period
Wall composition	see Table 1	natural stonework	200 mm natural stonework	plaster, 100 mm concrete blocks, plaster
Mode of ventilation	natural ventilation	natural ventilation, forced night ventilation	no ventilation (0.5 ach)	night ventilation (2 ach, 5 ach and 20 ach)
Climate	Mediterranean	Mediterranean	temperate	hot and humid
Method	in-situ measurements	demo-project measurements	demo-project measurements	software simulations

$T_{\max\_in} = T_{\max\_out} - 0.599(T_{\max\_out} - T_{\min\_out}) + 1.436$; 2 ach

$T_{\max\_in} = T_{\max\_out} - 0.697(T_{\max\_out} - T_{\min\_out}) + 1.722$; 5 ach

$T_{\max\_in} = T_{\max\_out} - 0.810(T_{\max\_out} - T_{\min\_out}) + 1.627$; 20 ach

Fig. 4 shows the degree of correlation between field-measured and model-computed indoor temperature maxima. Model-computed results were obtained using the equations of Givoni (1998), Ogoli (2003) and Shaviv et al (2001), as well as, the expressions developed in the present study. The figures show a good correlation between measured and computed values using the expressions of this study. The differences in computation of indoor maximum temperatures between this study and other studies can be explained by the parameters presented in Table 2. These are: (a) previous studies were carried out in different climates; (b) studies from Givoni (1998) and Ogoli (2003) were carried out in test chambers while the present study was carried out in actual buildings; (c) previous studies were undertaken in controlled ventilation modes while in this study ventilation was dependent on the human factor and that (d) previous studies have used different types of thermal mass and wall thicknesses compared to this study. Finally, this study has used a larger sample of case studies.

6. Conclusions

In-situ measurements demonstrated that spaces in the hot and humid region presented a smaller ability in moderating indoor temperature maxima compared to those in hot and semi-arid region. It is therefore indicated that the application of thermal mass in climates with small diurnal temperature fluctuations and high night-time temperatures constitutes a less effective cooling strategy, whereas in climates with large diurnal temperature fluctuations it is highly beneficial. It is also indicated that semi-subterranean spaces accounted for the greatest reduction of indoor temperature maxima. This fact highlights the advantage that earth provides to further dampen external thermal inflows.

The results obtained from this study are in line with other studies which proved that sensitivity of thermal mass on the performance of indoor temperatures significantly varies with outdoor climatic variables. In high mass spaces with similar characteristics to those of the case studies and within similar climatic context, the

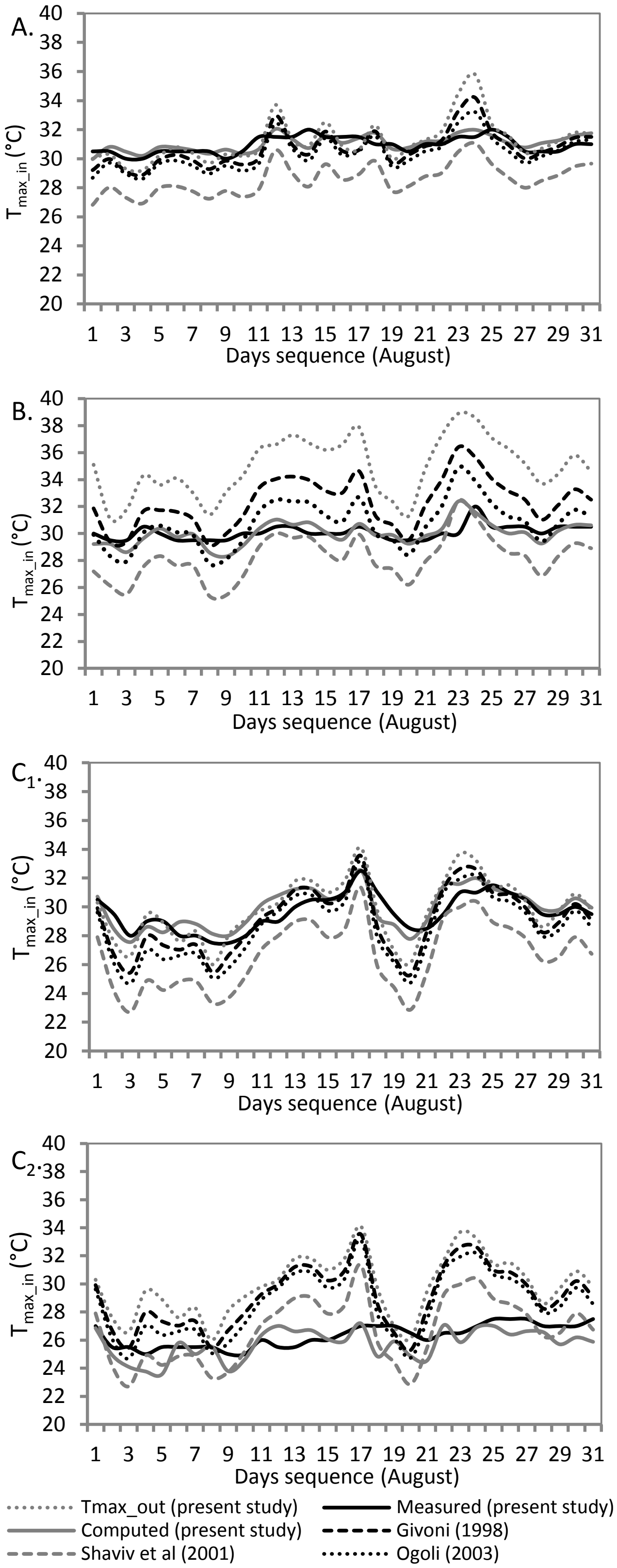

Fig 4: Measured and computed indoor maxima in A. CZ1, B. CZ2/3, C_1. CZ4 and C_2. CZ4 semi-subterranean spaces

summer indoor temperature maxima can be computed by the expressions developed in the present study. The proposed expressions are intended to propose a simplified method to compute indoor temperature maxima rather than to propose a standard formula. The set of data refers to a small range of case studies and to a specific seasonal period. Further research, taking into account a larger sample of buildings will enable the validation of these results.

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