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Thermal Assessment of Traditional, Partially Subterranean Dwellings in Coastal and Mountainous Regions in the Mediterranean Climate. The Case of Cyprus

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Fully, or partially, subterranean dwellings have developed as a distinctive building type from the prehistoric to pre-industrial era in the Mediterranean region, often serving specific purposes. The energy benefits of such spaces are well documented mainly through the investigation of numerous examples found in vernacular architecture. Despite their environmental potentials, subterranean structures remain limited in contemporary design practices. The present paper reports on the findings of a systematic research that examines partially subterranean traditional dwellings in the coastal and mountainous regions of Cyprus, an island in the Eastern Mediterranean. The study focuses on the environmental assessment of these spaces, through the monitoring of air temperature and relative humidity, and on a brief demonstration of various passive strategies for indoor microclimate improvements. Although these structures are not very common in the vernacular architecture of the island, their scientific examination produces useful knowledge in terms of energy savings. This can inform contemporary design applications and form a basis for the drafting of environmental refurbishment guidelines, applicable for this particular building typology. The research indicates favourable temperatures and significant cooling effects in partially subterranean spaces during the hot summer period, especially in mountainous regions. Temperatures in such spaces during the cold winter period are found to exhibit higher values compared to the temperatures of above-ground spaces, although they remain below comfort limits. High indoor humidity is found to be a major problem, in both the summer and winter period, in the coastal regions of the island. It is highlighted that, although partially subterranean spaces have many environmental benefits, as earth offers thermal insulation and heat storage, generalizations should be avoided since a number of varying parameters, such as the local climate, geology, natural ventilation conditions and building materials used, influence considerably their environmental performance.

KEYWORDS: partially subterranean dwellings, Mediterranean climate, vernacular architecture, coastal and mountainous regions, environmental design.

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Introduction

Fully, or partially, subterranean dwellings exhibit various typologies based on the characteristics of the natural environment such as the topography, geology and available building materials, as well as on factors related to human behaviour, such as the need for protection and privacy. Such structures can be divided into two general types: the cliff-cut dwellings built into the sides of slopped terrain and the pit-like dwellings arranged around sunken courtyards normally found on plateau-located land (Vegas et al. 2014). Subterranean dwellings have a rich history around the Mediterranean area; they are encountered in the island of Santorini, Greece, Matera in Italy, Granada, Almazora and Guadix in Spain etc. (Vegas et al. 2014). These structures incorporate many environmental advantages, such as considerable time lag, dampening of daily and seasonal temperature fluctuations, especially during cold or heat waves, and noise protection (Malaktou et al. 2016). Considering the environmental potential of subterranean buildings, it may be argued that the protection, preservation and refurbishment of such spaces, and their introduction in contemporary architecture, promote a sustainable design approach.

Since subterranean structures on the island are mostly associated with vernacular domestic architecture, this research focuses on the environmental performance evaluation of representative traditional partially subterranean dwellings from two distinctly different climatic regions of Cyprus; i.e., a mountainous and a coastal region. A significant number of publications investigate the environmental sustainability of vernacular architecture of Cyprus, including aspects of outdoor and semi-outdoor microclimatic conditions assessment (Savvides at al. 2016; Thravalou, 2015); lighting performance evaluation (Michael et al. 2015); natural ventilation potential (Michael et al. 2014); energy consumption (Florides et al. 2001); passive heating and cooling design strategies inherent in vernacular architecture (Lapithis 2004; Serghides 2010; Philokyprou et al. 2013; Philokyprou et al. 2015) and evaluation of indoor thermal conditions (Philokyprou and Michael 2012; Michael et al. 2013). Despite related research interest on environmental performance issues of the local vernacular architecture, quantitative thermal investigations still remain very limited in partially subterranean typologies. The aim of this research is to highlight the environmental potentials of such structures, namely their ability to create favourable thermal comfort conditions and, at the same time, to discern their weaknesses and deficiencies, in order to identify potential future prospects.

Background

Research interest in the environmental behaviour of subterranean buildings —including thermal comfort conditions, daylight levels and energy consumption— has grown noticeably in the last decades. Meir and Gilead (2002) carried out onsite measurements of air temperature and relative humidity during the hot, summer period on selected dwellings in three distinctly different climatic regions of Israel and provided evidence that subterranean spaces achieve significant reduction of temperatures and thermal stability. The same study however, reports issues related to inefficient natural ventilation and daylight, as well as high indoor humidity levels in the examined region that feature high ambient relative humidity. Similar results, i.e. significant temperature reductions, constant indoor temperatures and high humidity levels were found by Canas and Martin (2005) in their study of traditional wine cellars in Spain. A case study performed in Iraq (Kharrufa 2008) showed that the subterranean space average temperature on a July hot, summer day was 33.6°C, i.e. 4.5°C lower than the temperature of the space above-ground (38.1°C). Another study by Al-Temeeni and Harris (2004), discusses the advantages and disadvantages of subterranean structures in hot and arid climates. The advantages reported relate to minimum maintenance, enhanced noise protection, stability to earthquakes and better thermal behaviour compared to above-ground structures. It was further indicated, that subterranean structures are often the result of the hilly or mountainous topography, which makes them perfectly adapted to the landscape. Among the disadvantages reported is the lack of sufficient natural ventilation and lighting, as well as the limited visual connection with the outdoors, due to the absence of windows. A study by Zhai and Previtali (2010), on the environmental evaluation of vernacular architecture in different locations and climates around the world, reveals that fully or partially subterranean dwellings are more frequently observed in cold climates, occasionally in hot climates and never in humid climates.

Subterranean Structures in Cyprus

Partially subterranean dwellings in Cyprus have appeared since the prehistoric period. Building units of irregular plan at the Neolithic settlement of Ayios Epiktitos–*Vrysi* constitute distinctive examples of partially subterranean construction on the island (Wright 1992; Philokyprou 1998). This building configuration was favoured due to the settlement location on a steep sea cliff. However, other factors, such as camouflage from the intemperate environment or human aggression, have also led to this subterranean architecture concept (Wright 1992). Quite different cases are observed at the Neolithic site of Philia–*Drakos* (Philokyprou 1998) and at the Chalcolithic sites of Kalavassos–*Ayious* and *Kokkinoyia/Pampoules* (Wright 1992). In these sites, numerous pits created spaces for various purposes. Some of them seem to have been hearths or ovens, while others were probably used for storage. The larger ones seem to have been used for some form of occupation (Wright 1992). Apart from domestic architecture, a number of burial monuments of antiquity, such as the Hellenistic necropolis of the Tombs of the Kings in ancient Paphos, also exhibited an organisation of subterranean rooms. Such structures were often configured by underground peristyle courts and burial chambers carved on natural rock. During the medieval period, these burial monuments were often modified to accommodate domestic uses (Hadjisavvas 2012) while, at the same time, many newly-built dwellings incorporated subterranean spaces. According to Enlart (1987), the use of basement spaces in the summer was usual during that period, since these spaces offered protection from solar heat.

In the subsequent historical periods, partially subterranean spaces became assimilated in the rural vernacular architecture of the island, mainly in mountainous and occasionally in coastal settlements located on hilly landscapes. These rooms were mainly utilised as storage spaces, pantries and stables (Kizildere and Ozsoy 1995). In the context of coastal settlements, the single-space room with a wide façade, called *monochoro platymetopo*, is most commonly used either as above ground or partially subterranean room. Its length usually covers twice, or more, its width resulting in a shallow plan layout room. In the context of mountainous settlements, more compact configurations, such as the single-space room with a narrow façade, called *monochoro stenometopo* and the double-space room, called *dichoro* were preferred to be used either as above ground or subterranean rooms. *Monochoro stenometopo* features a narrow facade and a deep plan layout, while *dichoro* resembles more a square space with a relatively deep plan layout.

Research Methodology

In the framework of this research, the thermal behaviour of partially subterranean buildings in different climatic regions of the island, i.e. coastal and mountainous regions, was examined in depth. Specifically, representative partially subterranean spaces were selected for a detailed analysis in the coastal traditional settlement of Maroni, located in the south coast of the island, and in the mountainous traditional settlement of Askas, located in the central highlands, in Troodos mountain area. Although Cyprus is divided into four distinct climatic regions, i.e. the coastal region (CZ1), the lowland region (CZ2), the semi-mountainous region (CZ3) and the mountainous region (CZ4), the present analysis focuses on coastal and mountainous regions for in depth investigation. This is mainly due to the fact that buildings in the lowland region rarely incorporate subterranean spaces, while buildings in semi-mountainous regions share typological and constructional features with the ones located in the mountainous region.

Climatic and Geological Context

Cyprus has a Mediterranean climate. However, different regions of the island feature diverse climate subtypes (Table 1). Specifically, the coastal region (Maroni) features high relative humidity throughout the year due to its proximity to the sea. As a result, diurnal temperature fluctuations are moderated, causing cool winters and relatively mild summers. The climate in the mountainous region of the central highlands (Askas) features cold and wet winters and mild summers due to its high altitude. Snowfall occurs frequently during the winter period. In terms of geology, Table 1 briefly indicates that the South coast region, in which Maroni village lies, is composed

Table 1

Climatic and geological characteristics of the two regions under examination

	Coastal Region (Maroni)	Mountainous Region (Askas)
Altitude (m)	70	900
Distance from the sea (km)	2	50
Climatic Context		
Mean T_{min}–T_{max} for the coldest month (°C)	6.1–17.6	3.0–10.4
Mean T_{min}–T_{max} for the hottest month (°C)	20.0–33.6	20.2–30.9
Mean RH_{min}–RH_{max} for the coldest month (%)	34–100	12–99
Mean RH_{min}–RH_{max} for the hottest month (%)	22–92	7–92
Mean annual precipitation (mm)	384	699
Geological Context		
Building materials	sedimentary stones, i.e. calcarenites	silica-rich soils, igneous stones, i.e. gabbro, diabase
Thermal Properties of Building Materials		
Thermal conductivity, λ (W/mK)	0.99	1.82
Thermal diffusivity, α (m^2/s)	$0.67*10^{-6}$	$1.07*10^{-6}$

T_{min}, mean min temperature; T_{max}, mean max temperature; RH_{min}, mean min relative humidity; RH_{max}, mean max relative humidity

mainly of sedimentary stones i.e. calcarenites, while the central highlands where Askas village is located consists of igneous stones, i.e. gabbro and diabase. These locally available building materials have been extensively used in local traditional building construction. Based on laboratory measurements, the thermal properties of stones, from the locality of the Troodos mountain area and the South coast region, are presented in Table 1. As seen in Table 1, these two regions have so diverse climatic and geological conditions that it would be inappropriate to assess their potentials for subterranean construction in a uniform manner. Since the hygrothermal properties of soil and building materials, as well as the climate, determine the environmental behaviour inside subterranean structures to a great extent, each geographical location requires a separate examination.

Selection of Case Studies

Based on a survey of a total of 30 traditional dwellings in each settlement under study, it is established that partially subterranean dwellings account for a significant 93% of the mountainous settlement of Askas, while they appear at a more limited rate of 13% in the coastal settlement of Maroni. This is in line with related literature documenting that partially subterranean dwellings are most commonly found in the mountainous settlements of the island. Onsite measurements were conducted in five representative traditional dwellings (Table 2); two located in the coastal region (C_A and C_B) and three in the mountainous region (M_A, M_B and M_C). In each case study building, environmental data recordings were made for one partially subterranean space, i.e. C_{A1}, C_{B1}, C_{B2}, M_{A1}, M_{B1} and M_{C1}, and one above-ground space, i.e. C_{A2}, C_{B3}, C_{B4}, M_{A2}, M_{B2} and M_{C2}, for comparative analysis. In case study C_B, measurements were taken in two partially subterranean spaces and two above-ground reference spaces.

The case studies are representative of the prevailing traditional building materials and cover a variety of typologies, as well as spatial configurations applied on the vernacular architecture of the island (Table 3). The partially subterranean spaces under study in the coastal region of Maroni

Table 2

Maps of Maroni and Askas settlements presenting case study buildings. Sections and images of case study partially subterranean spaces

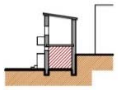
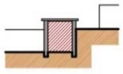
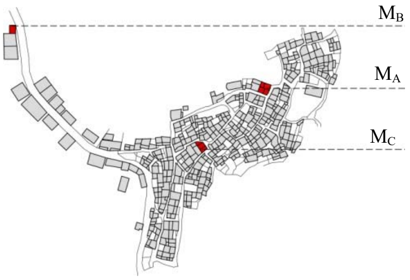
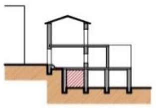
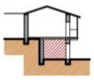
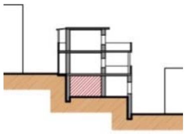
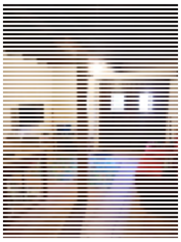
Coastal Region (Maroni)	C_{A1}	C_{B1}	C_{B2}
			
			
Mountainous Region (Askas)	**M_{A1}**	**M_{B1}**	**M_{C1}**
			
			

Table 3

Typological, spatial and constructional details of partially subterranean spaces

	Typology	Or.	Window		Masonry	Roof Type	R*
			Type	Configuration			
Coastal Region (Maroni)							
C_{A1}	double-space	NE	low + shutters	single-sided	sedimentary stones & mud in-between	decked by upper storey	2.0
C_{B1}	single-space	E–W	low & top + shutters	double-sided		decked by upper storey	1.6
C_{B2}	single-space	E–W	top	double-sided		flat	1.9
Mountainous Region (Askas)							
M_{A1}	single-space	-	-	-	igneous stones & mud in-between	decked by upper storey	2.1
M_{B1}	single-space	E	-	-			1.9
M_{C1}	double-space	NE	fenestration on door	-			1.7

*Area of building envelope which has contact with soil to floor area ratio

settlement comprise thick stone-built masonries (0.5 m thick) constructed by local, almost rectangular, sedimentary stones and by a limited number of window openings (**Table 3**). Case study C_{A1} is a representative example of the double-space (*dichoro*) typology while case studies C_{B1} and

C_{B2} are representative of the wide façade single-space (*monochoro platymetopo*) typology which generally prevails among the Maroni built stock. The three case studies host main daily activities. The partially subterranean spaces under study in the mountainous region of Askas settlement are constructed by local igneous stone, approximately 0.5 m thick. Case studies M_{A1} and M_{B1} are representative of the narrow façade single-space (*monochoro stenometopo*) and wide façade single-space (*monochoro platymetopo*) typology respectively, while M_{C1} features the double-space (*dichoro*) typology. The entrance doors are the only means of fenestration in the selected case studies. Case studies M_{A1} and M_{B1} have preserved their original use as storage spaces while case study M_{C1} has been converted into a main living space.

Onsite Measurements and Data Analysis

Environmental data, i.e. air temperature and relative humidity, was recorded during the hot, summer period (18th to 31st July 2014) and cold, winter period (13th to 22nd January 2015) to provide an environmental performance evaluation of the partially subterranean spaces, during both extreme climatic conditions. For the environmental monitoring of indoor spaces, Easylog data loggers, were placed 1.5 m above floor level and recordings were made at 30-minute intervals. Outdoor measurements were taken with VantagePro weather stations in each of the settlements under examination. The collected microclimatic data, i.e., mean average, minimum and maximum values of temperature and relative humidity and mean temperature fluctuations, are presented in comprehensive tables for comparative analysis. In addition, a regression analysis method was used to relate indoor temperature data to outdoor temperatures.

Results

Thermal Performance during the Hot Summer Period

The analysis of the onsite recordings in partially subterranean spaces for coastal and mountainous regions during the hot, summer period is presented below.

The monitoring results in the coastal region during the hot summer period show that maximum temperatures in partially subterranean spaces remain significantly lower compared to the temperatures of the above-ground reference spaces and the outdoor environment. More specifically, mean maximum temperature ranges from 27.4 to 29.1°C in partially subterranean spaces, from 29.2 to 33.1°C in above-ground reference spaces while the mean maximum temperature in the outdoor environment is 30.4°C (Table 4). Measurements in partially subterranean spaces, during the hottest day of the monitoring period, indicate a significant reduction of the maximum outdoor temperature (between 3.4 and 4.9°C). Mean diurnal temperature fluctuations range between 0.1 and 0.7°C, indicating that temperatures in partially subterranean spaces remain fairly constant. On the other hand, relative humidity in all three case study spaces remains stable, —i.e. with small fluctuations from 2 to 7%— exhibiting high values nevertheless. Specifically, relative humidity within the acceptable limits of 40–70% is observed only for 52%, 6% and 18% of the registered data in spaces C_{A1}, C_{B1} and C_{B2} respectively (Table 4). In contrast, the above-ground reference spaces present sufficient performance in terms of perceived humidity; all the registered data in cases A_{C1} and B_{C3}, as well as 84% of the registered data in B_{C2}, remains below the 70% upper acceptable limit. In general, although partially subterranean spaces achieve significant reductions in terms of maximum temperatures, relative humidity exceeds acceptable levels and thus creates uncomfortable conditions.

Regarding the mountainous regions, it is established that the mean maximum temperatures in partially subterranean spaces range between 24.4 and 25.7°C during the hot, summer period. Mean outdoor maximum temperature for the same period is 28.3°C, while mean maximum temperatures vary between 28.2 and 29°C in above-ground reference spaces. These results indicate that mean maximum temperature in partially subterranean spaces remains significantly lower compared to above-ground spaces and the outdoor environment. During the hottest day of the

Table 4

Summary of registered environmental data during the hot, summer period

	Mean air temperature (°C)				T_{max_out}-T_{max_in} in hottest day (°C)	Temp. limits (°C)	Mean RH (%)			% of data in which RH = 40–70%	RH limits (%)
	avg	max	min	fluct			avg	max	min		
Partially Subterranean Spaces – Coastal Region (Maroni)											
Out.	26.8	30.4	23.1	7.3	32.4*	21.6–32.4	74	87	61	-	39–93
C_{A1}	29.0	29.1	29.0	0.1	3.4	29.0–29.5	70	71	69	52	68–73
C_{B1}	27.9	28.0	27.8	0.2	4.4	27.5–28.5	73	74	72	6	69–80
C_{B2}	27.0	27.4	26.7	0.7	4.9	25.5–27.5	75	78	71	18	60–86
Partially Subterranean Spaces – Mountainous Region (Askas)											
Out.	**24.3**	**28.3**	**20.6**	**7.6**	**31.3***	**17.3–31.3**	**53**	**75**	**33**	**-**	**23–92**
M_{A1}	23.9	24.4	23.4	1.0	6.3	23.0–25.0	55	62	46	99	36–68
M_{B1}	24.3	24.7	23.8	0.9	5.8	23.0–25.5	58	61	54	100	50–63
M_{C1}	25.5	25.7	25.3	0.4	5.3	25.0–26.5	57	59	54	100	51–66
Above-ground Reference Spaces – Coastal Region (Maroni)											
C_{A2}	31.2	33.1	29.5	3.5	-1.6	29.0–34.0	59	61	56	100	52–63
C_{B3}	28.7	29.8	27.7	2.1	1.4	26.5–31.0	65	69	62	84	49–74
C_{B4}	28.8	29.2	28.4	1.2	2.9	28.0–29.5	66	67	65	100	62–69
Above-ground Reference Spaces – Mountainous Region (Askas)											
M_{A2}	27.0	28.2	25.7	2.5	1.3	25.0–30.0	46	51	41	91	36–57
M_{B2}	27.4	29.0	25.8	3.1	0.3	25.0–31.0	52	58	46	99	35–66
M_{C2}	27.4	28.6	26.3	2.4	0.8	25.5–30.5	50	52	48	100	46–62

T_{max_in}, maximum indoor temperature ; T_{max_out}, maximum outdoor temperature;
RH, Relative Humidity; * highest outdoor temperature

monitoring period, the indoor maximum temperature reduction in partially subterranean spaces ranges from 5.3 to 6.3°C. Despite the relatively large mean diurnal temperature fluctuation of the external environment, i.e. 7.6°C, mean.

temperature fluctuations in partially subterranean spaces are limited to 0.4–1.0°C indicating great thermal stability. Relative humidity in partially subterranean spaces remains stable, i.e. with variations from 5 to 16%, and within the acceptable comfort limits of 40–70%. In terms of both summer temperatures and perceived humidity during the summer period, partially subterranean spaces generally create favourable conditions.

In an attempt to investigate whether the area of the building envelope in contact with the soil affects indoor temperatures, the ratio R, i.e. the area of the building envelope which has contact with soil to floor area ratio (Table 3), was correlated with mean maximum temperatures in partially subterranean spaces. It is noted that when ratio R of a space increases, the mean maximum temperature decreases, resulting in cooler temperatures. Deviations from the trend-lines occur in the case of C_{A1}. The influential variables that may be related to this deviation are the orientation, ventilation conditions, window-to-floor area ratio and exposure of the building envelope, i.e. external walls and roof, to ambient conditions. Along with ratio R, the above variables constitute important factors that affect temperatures in partially subterranean spaces. It is noted that the set of data correlating ratio R to indoor temperatures refers to a small number of case studies and for this reason it is not possible to validate these results.

Thermal Performance during the Cold Winter Period

The analysis of the onsite recordings in partially subterranean spaces in coastal and mountainous regions during the cold, winter period is presented below.

Based on the onsite recordings, mean maximum temperatures in the partially subterranean spaces of coastal regions are found to be low, ranging between 14.4 and 15.1°C during the cold winter period, whereas outdoor mean maximum temperature is 16°C. Mean maximum temperature in the spaces under study remains lower compared to the outdoor environment (**Table 5**). However, mean maximum temperatures in partially subterranean spaces remain higher than the temperatures of the above-ground reference spaces, which range from 13.5 to 14°C. Mean diurnal temperature fluctuations in partially subterranean spaces are limited to 0.1 to 0.2°C. Due to their high thermal stability, partially subterranean spaces present a beneficial thermal effect during night-time hours when temperatures are minimal. Specifically, mean minimum temperature in partially subterranean spaces ranges from 14.2 to 15°C, from 12.2 to 13°C in above-ground reference spaces while the mean minimum temperature in the outdoor environment is 10.2°C. During the monitoring period, 96%, 5% and 0% of the registered relative humidity data in partially subterranean spaces C_{A1}, C_{B1} and C_{B2} respectively remains below the 70% upper acceptable limit. Based on the above results, it is established that case study $C_{A1,}$ which is the warmest space, remains

Table 5

Summary of registered environmental data during the cold, winter period

	Mean air temperature (°C)				T_{min_in}-T_{min_out} in coldest day (°C)	Temp. limits (°C)	Mean RH (%)			% of data in which RH = 40–70%	RH limits (%)
	avg	max	min	fluct			avg	max	min		
Partially Subterranean Spaces – Coastal Region (Maroni)											
Out.	**12.9**	**16.0**	**10.2**	**5.8**	**8.3***	**8.3–17.9**	**76**	**87**	**63**	**-**	**51–91**
C_{A1}	15.0	15.1	15.0	0.1	6.7	15.0–15.5	65	66	64	96	57–71
C_{B1}	14.3	14.4	14.2	0.2	5.7	14.0–15.5	75	76	73	5	69–80
C_{B2}	14.4	14.5	14.3	0.2	6.2	14.0–15.0	78	79	77	0	72–82
Partially Subterranean Spaces – Mountainous Region (Askas)											
Out.	**7.1**	**9.7**	**5.0**	**4.7**	**2.6***	**2.6–16.3**	**81**	**93**	**67**	**-**	**9–95**
M_{A1}	8.2	8.4	8.0	0.4	4.9	7.0–9.5	73	75	70	15	61–77
M_{B1}	8.2	8.5	8.0	0.5	4.9	7.0–9.5	75	77	74	7	65–79
M_{C1}	9.8	9.9	9.7	0.2	6.9	9.5–11.0	60	61	59	100	56–64
Above-ground Reference Spaces – Coastal Region (Maroni)											
C_{A2}	12.9	14.0	12.2	1.8	5.7	11.5–16.5	72	74	71	8	68–76
C_{B3}	13.2	13.9	12.7	1.3	5.7	12.0–15.0	73	74	72	16	68–78
C_{B4}	13.2	13.5	13.0	0.5	5.2	12.0–14.5	75	77	75	4	69–83
Above-ground Reference Spaces – Mountainous Region (Askas)											
M_{A2}	5.7	6.4	5.1	1.3	1.9	4.0–8.5	82	83	80	0	77–85
M_{B2}	6.3	7.0	5.7	1.3	3.4	4.5–9.5	79	80	79	0	76–82
M_{C2}	7.1	7.8	6.5	1.3	3.9	5.5–10.5	72	73	71	0	70–77

T_{min_in}, minimum indoor temperature; T_{min_out}, minimum outdoor temperature;
RH, Relative Humidity ; * lowest outdoor temperature

drier compared to the other two examined partially subterranean spaces. At the same time, relative humidity in above-ground reference spaces satisfies comfort limits for only 8%, 16% and 4% of the registered data in the case of C_{A2}, C_{B3} and C_{B4} respectively. The analysis indicates that some environmental limitations occur in partially subterranean spaces during winter due to high relative humidity and low temperatures.

Regarding the partially subterranean spaces of mountainous regions, the monitoring results indicate that mean maximum temperatures remain lower, or slightly above, the mean maximum temperature of the outdoor environment during the cold, winter period (Table 5). Specifically, the partially subterranean spaces under study exhibit a range of mean maximum temperatures of 8.4–9.9°C when outdoor mean maximum temperature is 9.7°C. Nevertheless, mean maximum temperatures in partially subterranean spaces remain higher than the temperatures of the above-ground reference spaces (6.4–7.8°C). Mean diurnal temperature fluctuations in the partially subterranean spaces under study are limited to 0.2–0.5°C. It is worth mentioning that partially subterranean spaces exhibit higher mean minimum temperatures (8.0–9.7°C) compared to the above-ground reference spaces (5.1–6.5°C). It is also demonstrated that 15%, 7% and 100% of the registered relative humidity data remains within the acceptable comfort limits for the partially subterranean spaces M_{A1}, M_{B1} and M_{C1} respectively. This indicates that case study M_{C1}, which is the warmest space, remains drier compared to the other partially subterranean spaces. Relative humidity in the above-ground reference spaces always falls outside the acceptable limits. Overall, high humidity levels (recorded in two case studies), and low temperatures inside partially subterranean spaces, result in cold and wet indoor conditions during winter.

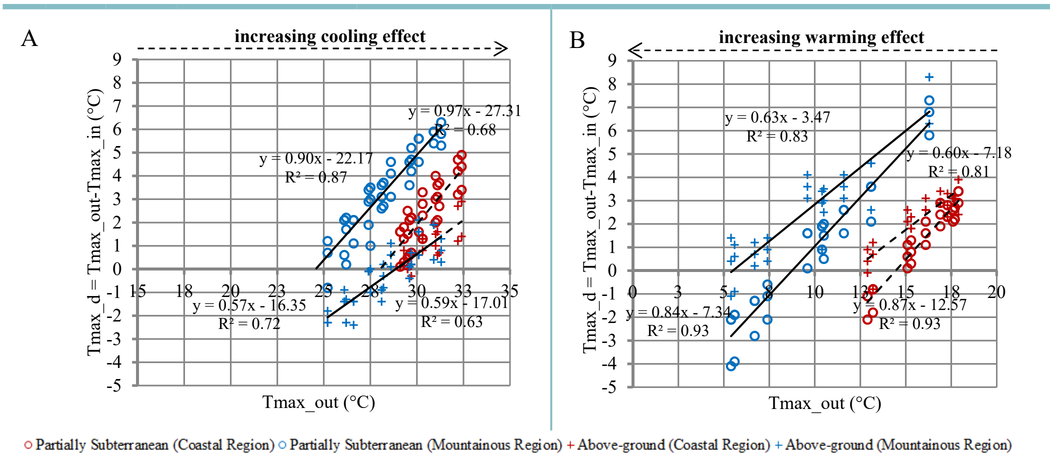
Cooling and Warming Effect Estimations

A further quantitative analysis of the cooling and warming effects of partially subterranean spaces during the summer and winter period is also performed (Table 6 & 7). Table 6A indicates that during the summer period, maximum temperatures (T_{max}), recorded in partially subterranean and above-ground spaces, present a linear correlation with the difference between the maximum ambient air temperature and indoor maximum temperature ($T_{max\_d} = T_{max\_out}-T_{max\_in}$). The analysis shows that ambient maximum air temperature affects the level of cooling inside the rooms – the higher the ambient maximum air temperature the stronger the cooling effect is. The steeper slope of the graph-line representing partially subterranean spaces, as opposed to above-ground spaces, confirms that the cooling effect in the former case is stronger. More specifically, if the maximum outdoor temperature increases by 1°C, it is predicted that the cooling effect values will be enhanced by 0.9–1.0°C for partially subterranean spaces and by 0.6°C for above-ground spaces. It is worth mentioning that maximum temperatures inside partially subterranean spaces in the coastal region fall below outdoor maxima when outdoor temperature exceeds 28.2°C while, in above-ground spaces, the maximum temperature falls below the relative outdoor whereby the outdoor temperature equates to 28.8°C. Correspondingly, in the mountainous region the temperature threshold is estimated to 24.6°C for partially subterranean spaces and 28.7°C for above-ground spaces.

During the winter period, maximum temperatures (T_{max}) inside the case study rooms also present a strong linear correlation with the difference between the maximum ambient air temperature and indoor maximum temperature (T_{max_d}) (Table 6B). The results indicate that outdoor maximum air temperature values affect the warming effect inside the examined indoor spaces; the lower the outdoor maximum temperature the stronger the warming effect is. Applying the resulted regression, when outdoor maximum temperature decreases by 1°C, the average warming effect values are estimated to be enhanced by 0.8–0.9°C for partially subterranean spaces and by 0.6°C for above-ground spaces. Maximum temperatures in partially subterranean spaces, located in the coastal region, rise above maximum outdoor temperature, when maximum outdoor temperature

Table 6

Linear regression results for partially subterranean and above-ground spaces. Regression is performed between T_{max_in} and T_{max_d} (T_{max_out}-T_{max_in})



	Summer				Winter			
	b	R^2	T_{max_out} lower limit in which $T_{max\_d} \geq 0$	Cooling effect for every 1°C increase of T_{max_out}	b	R^2	T_{max_out} upper limit in which $T_{max\_d} \leq 0$	Warming effect for every 1°C decrease of T_{min_out}
Partially Subterranean Spaces								
C	1.0	0.68	28.2	1.0	0.9	0.93	14.4	0.9
M	0.9	0.87	24.6	0.9	0.8	0.93	8.7	0.8
Reference Above-ground Spaces								
C*	0.6	0.63	28.8	0.6	0.6	0.81	12.0	0.6
M	0.6	0.72	28.7	0.6	0.6	0.83	5.5	0.6

*C_{A2} was excluded from the correlation analysis of the summer environmental monitoring data;
b, slope; *R^2*, correlation coefficient

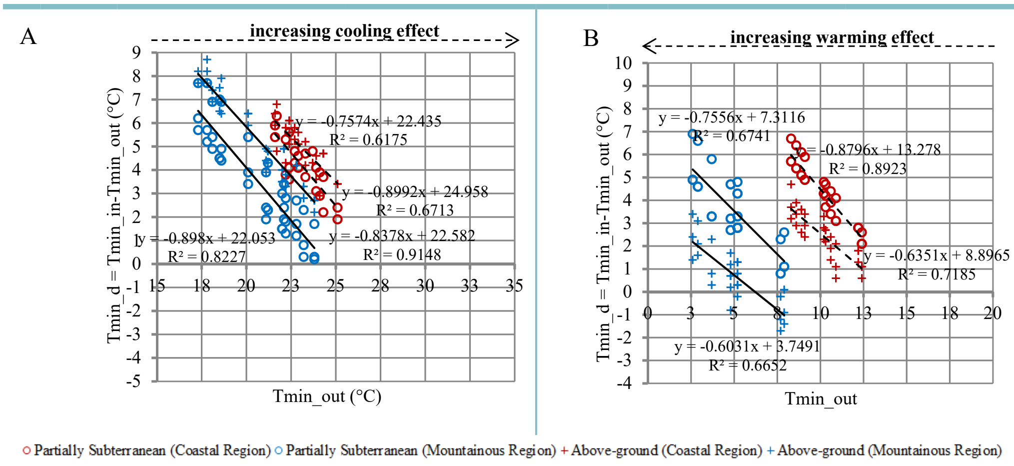
is equal to, or lower than, 14.4°C. The temperature threshold for above-ground spaces is estimated to 12.0°C. Similar relations are observed for mountainous regions whereby the temperature threshold is estimated to be 8.7°C and 5.5°C for partially subterranean spaces and above-ground spaces respectively.

Results of the regression analysis using the daily values of the minimum air temperature are given in **Table 7**. It is shown that the minimum air temperatures (T_{min}) of the examined spaces present a good inverse correlation with the difference between the minimum indoor temperature and minimum ambient air temperature ($T_{min\_d} = T_{min\_in}$-T_{min_out}) during the summer period (**Table 7A**). The higher the minimum outdoor temperature the stronger the cooling effect inside the examined spaces is. The cooling effect patterns appear more intense in partially subterranean spaces than in above-ground spaces, i.e. for every 1°C increase of outdoor minimum temperature the average cooling effect is estimated to be 0.9°C and 0.8°C for partially subterranean spaces and above-ground spaces, respectively. Furthermore, the shift of the lines representing partially subterranean spaces below the lines of above-ground spaces indicates that lower minimum temperatures generally occur in the case of the former.

During the winter period, minimum temperatures (T_{min}) inside the examined spaces are inversely correlated with the difference between minimum indoor temperature and minimum ambient air temperature (T_{min_d}). **Table 7B** indicates that the warming effects of indoor spaces are strongly associated with colder days, i.e. with lower minimum temperatures. In addition, the warming effect

Table 7

Linear regression results for partially subterranean and above-ground spaces. Regression is performed between T_{min_in} and T_{min_d} (T_{min_in}-T_{min_out})



	Summer				Winter			
	b	R²	T_{min_out} lower limit in which $T_{min\_d} \leq 0$	Cooling effect for every 1°C increase of T_{min_out}	*b*	*R²*	T_{min_out} upper limit in which $T_{min\_d} \geq 0$	Warming effect for every 1°C decrease of T_{min_out}
Partially Subterranean Spaces								
C*	-0.9	0.67	27.8	0.9	-0.9	0.89	15.1	0.9
M	-0.9	0.82	24.6	0.9	-0.8	0.67	9.7	0.8
Reference Above-ground Spaces								
C	-0.8	0.62	29.6	0.8	-0.6	0.72	14.0	0.6
M	-0.8	0.91	27.0	0.8	-0.6	0.67	6.2	0.6

*C_{A1} was excluded from the correlation analysis of the summer environmental monitoring data;
b, slope; *R^2*, correlation coefficient

of the above-ground spaces is found to be weaker than in partially subterranean rooms. Based on the resulting regression, when the minimum outdoor temperature decreases by 1°C, the average warming effect enhances by 0.8–0.9°C for partially subterranean spaces and 0.6°C for above-ground spaces. Indoor minimum temperatures in partially subterranean and above-ground spaces in coastal regions remain above outdoor minimum temperatures when outdoor minimum temperature is equal to, or lower than, 15.1°C and 14°C respectively. In the case of mountainous regions, these values are estimated to reach 9.7°C and 6.2°C in partially subterranean and above-ground spaces respectively. These results indicate that partially subterranean spaces achieve minimum temperatures higher than those of the ambient environment for a greater outdoor temperature range than above-ground spaces.

Discussion

The environmental analysis presented in the current study indicates that partially subterranean spaces have a high environmental potential in the Mediterranean climatic context. It is here demonstrated that during the summer period, in both the coastal and mountainous regions of Cyprus, partially subterranean spaces cause a considerable dampening effect of the external thermal inflows. Compared to above-ground reference spaces, partially subterranean spaces provide significantly lower temperatures, improving thermal comfort conditions. The better performance of partially subterranean spaces in terms of perceived air temperatures is attributed to the thermal mass of the earth which has the ability to further regulate indoor microclimate. Additionally, the earth that surrounds partially subterranean structures is cooler during the hot period, compared to the ambient air to which above-ground spaces are exposed. This means that earth acts as a heat sink for cooling. The temperatures results obtained for the summer period in the present study are in line with the results reported in other previous studies (e.g. Canas and Martin 2005). In terms of humidity levels, partially subterranean spaces in mountainous regions were found to have the capacity of regulating indoor humidity within acceptable levels. In contrast, the spaces under study in the coastal region exhibit high humidity, which has a negative impact on comfort conditions. This may be attributed to the proximity to the sea, the poorly drained soil, as well as to the poor ventilation of indoor spaces. These results are in line with findings reported in other studies (Meir and Gilead 2002; Canas and Martin 2005). The environmental limitations resulting from high humidity might explain why traditional partially subterranean spaces rarely appear in humid climates as stated in related literature (Zhai and Previtali 2010). The enhancement of air movement through natural ventilation constitutes a passive design strategy, which could significantly minimize dampness. Moreover, the architectural design of traditional dwellings i.e. the shallow plan layouts and wide façades, as well as the double-sided window arrangement, which form typical characteristics of vernacular architecture in coastal regions of Cyprus, offer potentials for sufficient natural ventilation.

The onsite monitoring results during the winter period show that the thermal comfort conditions of partially subterranean spaces, in both coastal and mountainous regions, are unsatisfactory. Several reasons could explain the low temperatures observed within these spaces. For instance, the thick, high mass building envelopes, and the small and limited window openings, block solar penetration, which would allow passive heating. However, despite their insufficient performance, partially subterranean spaces exhibit higher temperatures than those of the above-ground spaces confirming the positive contribution of high thermal inertia and insulating properties of the earth. The earth mass, that is warmer in winter than ambient air, serves as a passive source for heating. Humidity levels prove to be high above acceptable limits in both coastal and mountainous regions. The relative rise of outdoor humidity during the winter period, as in the case of mountainous regions, may have resulted in increased dampness in the indoor spaces under study.

The regression results obtained for the partially subterranean spaces under examination highlight their stronger cooling and warming effect patterns in the summer and winter respectively, compared to above-ground spaces. More specifically, the analysis reveals that when the outdoor temperature during the summer becomes higher, the cooling effect becomes stronger. Similarly, when the outdoor temperature during the winter becomes lower, the warming effect becomes stronger. This interrelation has also been reported by Givoni (1998), Shaviv et al. (2001) and Ogoli (2003) in high mass indoor spaces and by Tsiros and Hoffman (2014) in semi-outdoor spaces during the summer period. This confirms that maximum control over outdoor temperature extremes may be achieved through the incorporation of subterranean rooms. Research results also indicate that the surface area of the building envelope in contact to the soil affects indoor thermal conditions; the greater the contact of the building envelope with soil, the greater the potential for moderation of outdoor temperature extremes in the indoor space.

The assessment of thermal performance of the spaces under study was obtained using air temperature and relative humidity recordings. Wind speed and mean radiant temperature were not recorded during the experimental period. This limitation does not permit the calculation of operative temperature and by extension, the evaluation of human thermal comfort conditions in the indoor spaces under study.

Conclusions

In an attempt to explore partially subterranean spaces in terms of their thermal behaviour in diverse climatic contexts, onsite air temperature and relative humidity measurements were carried out. It is presented herein that in different climatic regions of Cyprus that lay in a relatively small geographical area, partially subterranean spaces present different thermal behaviour. This highlights that partially subterranean spaces cannot be treated in a uniform manner in different contexts since, a number of varying parameters, such as the local climate, local soil properties, the architectural layout, the openings arrangement and natural ventilation conditions form determining factors of the spaces' actual thermal performance.

Concerning the air temperature recordings, partially subterranean spaces were found to function as positive climatic elements in the Mediterranean climate of Cyprus during summer. Mean reductions in indoor maximum temperatures compared to the ambient environment were found to reach up to 3.0°C in the coastal and 3.9°C in the mountainous regions. In contrast to partially subterranean spaces in the mountainous region, relative humidity in the coastal region exceeded the acceptable 70% upper limit threshold for a large part of the monitoring period. This creates uncomfortable conditions which result to unhealthy effects for the occupants. The winter performance of partially subterranean spaces proved to be the most challenging one. Mean maximum temperatures inside these spaces remain up to 1.5°C and 1.3°C lower than the outdoor temperature maxima in the coastal and mountainous regions respectively. However, it is worth noting that, partially subterranean spaces exhibit higher temperatures compared to above-ground spaces. In terms of humidity levels, partially subterranean spaces in both regions suffer from humid indoor conditions.

In conclusion, the current study provides a basis for the formulation of a site-specific design strategy to improve thermal conditions and achieve energy conservation within subterranean constructions in diverse geographical locations. Understanding and analysing the thermal behaviour of these spaces is the first step towards this strategy. The quantitative analysis reveals the various challenges faced and opportunities provided by subterranean structures and contributes to informing current design policies. Further studies should focus on the effects of other parameters on thermal comfort, such as the wind speed and mean radiant temperature. This would allow a precise evaluation of the thermal comfort conditions inside partially subterranean spaces by using established indoor environmental indices and standards.

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