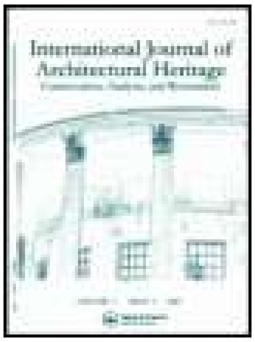

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ABSTRACT
Most of the artistic heritage in the Mediterranean basin is hosted in rupestrian hypogeum whose peculiarity is given by the presence of at least one open side, which makes them particularly sensitive to meteorological conditions. This makes mandatory the monitoring of both indoor and outdoor environmental parameters to analyze the cause–effect relationship between microclimatic inside and outside the hypogeum. The paper proposes a spatial and temporal multi-scale methodological approach applied to a rupestrian church in Matera, which hosts precious wall paintings, particularly vulnerable to the effects of environmental parameters. The approach is based on the analysis of data acquired by three platforms: indoor, close-range outdoor, and outdoor data from a meteorological station and weather forecast from the COSMO 5 model. The method allowed to characterize the relationships between the indoor and outdoor parameters at different spatial and temporal scales. The results showed a significant correlation between the parameters, thus opening new opportunities for the monitoring of the rupestrian heritage based on the use of data systematically available, such as those from meteorological stations and meteorological forecast.

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Conservation; environmental parameters; frescoes; microclimate; rupestrian architecture

1. Introduction

The safeguard of architectural and artistic heritage implies planned maintenance, preventive conservation, and restoration. To model and quantify the decay over time and to devise *ad hoc* conservation actions and strategies, the safeguard implies the systematic monitoring of a number of physical parameters, including the environmental ones.

The monitoring of environmental parameters emerged as a critical issue for protecting cultural heritage since the 1970s, thanks to the studies focusing on the works of art preserved in museums (Thompson 1978). A fundamental impulse to the development of procedures and technologies has been given by Camuffo, who in particular stressed the importance of the monitoring of the environments which host works of art (Camuffo 1983, 1986, 1998, 2014). Technologies and procedures today used for the monitoring of thermo-hygrometric parameters rise from the technical-cognitive development matured in other different scientific areas such as natural sciences, atmospheric investigations, physics, and meteorology (Camuffo 1998, 2014; Filippi 1996; Thompson 1978). They are regulated by a number of international and national technical standards (for example, UNI 10829 1999; CEN TC 346; UNI EN 15757 2010, UNI EN 15758 2010, D.M. 10 maggio 2001), and object of analysis and technological development thanks to a number of research projects dedicated to preventive conservation decision support system (e.g. www.collectioncare.eu).

The monitoring technologies and procedures have been used in various operational scenarios, from planned conservation to safety measure of works of art exposed in museums (Accardo et al. 1980; Bernardi et al. 1985; Camuffo et al. 2001; Litti and Audenaert 2018), historical palaces and churches (Aste et al. 2019; Bonacina et al. 2015; Fabbri, Pretelli, and Bonora 2019; García-Diego and Zarzo 2010; Gysels et al. 2004; Muñoz-González et al. 2018; Sileo, Gizzi, and Masini 2017), and natural sites (Bernardi, Todorov, and Hiristova 2000; Di Tullio et al. 2010).

In the last two decades, a growing attention has been paid to the safeguard of rupestrian works of art and architecture, especially after that a number of rupestrian sites were included in the World Heritage List, such as Cueva de las Manos (Argentina), Longmen (China), Cappadocia (Turkey), Valle Camonica and Matera (Italy), the latter designed European Culture Capital in 2019. In the Mediterranean basin, a significant part of the cultural heritage is conserved in rupestrian hypogea which are the result of a long-lasting life choice in

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human history (Fonseca 1972). Rupestrian cultural heritage consists of wall paintings, graffiti, sculptures and architectural elements, particularly fragile because exposed to several deterioration factors, primarily microclimatic conditions and their variations.

Wall paintings are exposed to numerous pathologies such as capillary rise (Di Tullio et al. 2010), infiltration by permeability (Accardo, Cacace, and Rinaldi 1984) and biological attacks (Caneva et al. 2019; Nugari et al. 2009; Rosado et al. 2014; Zucconi et al. 2012). The peculiarity of the rupestrian hypogea with respect to other hypogeum environments (i.e. crypts of churches), is given by the presence of at least one open side, which makes these spaces particularly sensitive to (outdoor) meteorological conditions. Therefore, in order to analyze the cause–effect relationship between the two environments, it is mandatory to monitor both indoor and outdoor parameters.

The outdoor monitoring is usually performed using a dedicated weather station close to the site of cultural interest (e.g., Camuffo 1987, 2001; Camuffo and Schenal 1982; Nguyen, Schwartz, and Dockery 2014). However, in order to both understand indoor and outdoor microclimatic interdependence mechanisms and foresee short-term risk scenarios, it is fundamental to extend the environmental data collection to a wider spatial scale.

To this end, a multi-scale monitoring-based approach (MMA), which integrates indoor and outdoor platforms for measuring temperature (T) and relative humidity (RH), is herein proposed and applied to a rupestrian site (RS) in Matera (Basilicata, Southern Italy). The outdoor monitoring is performed by i) two weather stations, one dedicated and installed close to the RS, the second located about 6 km away from RS (belonging to the network of the meteorological stations of regional civil protection); ii) weather forecast from the Cosmos 5 model available from National Civil Protection at 5 km spatial resolution. (downloaded from https://simc.arpae.it/arkiweb/). Moreover, the indoor monitoring includes CO_2 measurements, and the analysis of the impact of the touristic presence.

The rupestrian site, selected to test the MMA, has been the well-known *Cripta del Peccato Originale* in Matera (in English Crypt of the Original Sin, see sections II.1 and III.3), which hosts precious wall paintings (particularly sensitive to the effects of environmental parameters), for which significant data related to past restorations are available.

The proposed MMA has been aimed at the statistical characterization and correlation between indoor and outdoor (temperature and humidity) parameters, herein considered at different spatial and temporal scales.

2. The case study

2.1. Geographic and geological settings of the area

The *Cripta del Peccato Originale* is located in the Basilicata Region (Southern Italy), south-west of Matera in the upper portion of the ridge that limits the deep incision of the “Gravina di Picciano” river (Figure 1).

Geologically, Matera and the Murgia Materana Natural Park (Southern Italy) are located between the Foreland and Foredeep domains of the Apennine system. In this area, the main stratigraphic units are the Upper Cretaceous Altamura Limestone and the Pleistocene succession consisting of the Gravina Calcarenite, Subappenine Clay and the regressive medium to coarse-grained clastic deposits.

The *Cripta del Peccato Originale* was dug inside a bank of friable limestone rock of Gravina Calcarenite (Upper Pliocene—Lower Pleistocene). This geological Formation rests in discordance on more ancient and consistent deposits that belong to the Altamura Limestone formation (Cretaceous, Senonian) (Ciaranfi et al. 1983; Pieri, Sabato, and Tropeano 1996). The Calcarenite is made up of calciclastic formation typical of the Apulian foreland, which is considered as the basal unit of the Pleistocene transgressive succession on the Cretaceous limestone. It is overlaid by pelagic clays, the Subappenine Clay Formation, that filled the Bradanic Trough and partially covered the Apulian foreland (Pieri, Sabato, and Tropeano 1996). Scientific studies about physical and mechanical characteristics of the Calcarenite show its high susceptibility to the absorption of water by permeability and capillary rise (Andriani and Walsh 2000, 2003; Caputo, Quadrato, and Walsh 1996; Radina and Walsh 1972), features which have caused particular conditions of hygrometric stress in the crypt.

The presence of the Calcarenite has been crucial for man’s ability to settle in Matera area since the Palaeolithic era. From the natural caves that appeared with the retreat of the sea, more and more complex and evolved rock habitats were subsequently obtained both in the slope near the city of Matera and along the ravines as well as in other neighboring towns.

2.2. The discovery and the first restoration works

The topographic position of the *Cripta del Peccato Originale*, close to the “Gravina di Picciano” river, has kept this place hidden for a long time (De Ruggieri 1966).

The crypt was discovered by local scholars in 1963 (local cultural association “La Scaletta”). However, already half a century before another local scholar mentioned the presence of paintings portraying St. Michael, St. Gabriel and St. Raphael in a cave quite close to

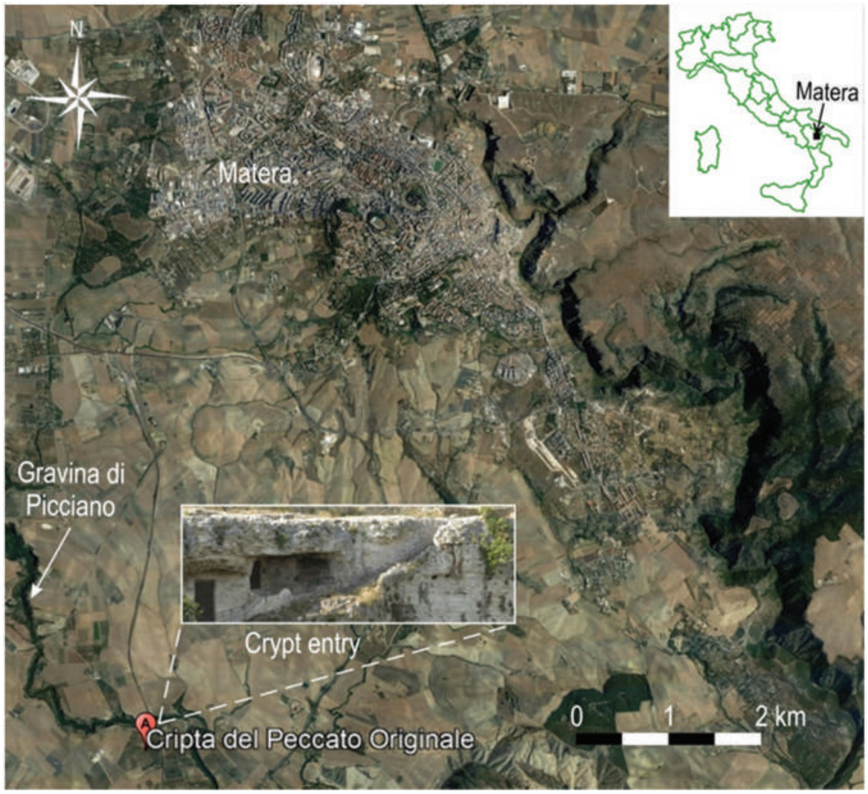

Figure 1. Location of the study area.

Matera town (Ridola 1912). This fits well with some oral sources related to shepherds, who referred to a "cave entirely painted, with the images of a hundred saints" (Bertelli & Mignozzi 2013).

As the discovery, also the first study on the Crypt was performed by scholars belonging to the cultural association "La Scaletta". The study was the first attempt to analyze the frescoes in the artistic context of medieval paintings in Southern Italy (Demetrio 2014). In the 2000s, the Zetema Foundation, after having purchased the property of the cave, commissioned the first restoration, directed by Michele D'Elia. The restoration, carried out between April and December 2004, relied on the results of multidisciplinary investigations performed by ICR (Central Institute of Restoration) aimed at mapping and understanding the cause of wall paintings decay.

Prior to this intervention, in 1994, the geological survey of the site and the analysis of pigments through X-ray fluorescence technique were commissioned to ENEA (at that time the National Body for Alternative Energy) (ENEA).

All information relating to investigations performed in the Crypt are summarized in Table 1.

2.3. The frescoes and the history of the crypt

The Crypt is a Benedictine rupestrian monastery characterized by a post-Carolingian pictorial cycle of the

Table 1. Studies, surveys, diagnostic investigations and interventions carried out on the *Cripta del Peccato Originale*.

Date	Type of investigation
April 1994	Geological survey, study on the state of conservation of the frescoes, investigation on pictorial pigments
September 2000	Description of frescoes and state of preservation
December 2001	Investigations and planning of the works aimed at the restoration and defense of humidity
January-March 2002	Diagnostic indications on biodeterioration and indications for weeding works
June 2002	Photometric measurements
December 2003	Chemical and biological investigations (intermediate report)
March 2004	Chemical and biological investigations (second Report)
January 2005	Restoration report
November 2008	Maintenance program
July 2010	Maintenance and control intervention
October/December 2017	Maintenance and control intervention

Beneventan school with oriental decorative influences, dated to the Lombard period (8th-9th centuries). The architecture space is based on a trapezoidal plan characterized by three apses facing East and a ceiling about 3 m high, probably obtained by regularizing a pre-existing karst cavity. Outside one can see the signs of ancient tombs long desecrated. The preparatory layers of the frescoes consist of a curl made from «rhinestone, of brown color and of different thicknesses overlaid by a lighter plaster » (C.B.C.—Roma, 2005) The frescoes are laid out on two layers: the first of lime and gypsum with the addition of inert materials typical of rock, carbonates and quartzes of coarser grinding and the second are similar but it is finer (C.B.C.—Roma, 2005; De Ruggieri 1966). The mortar was used to even out the wall of the rock and on this was laid out the line of the design and finally the color, always diluted in lime water. The cycle visible today presents frescoes on the eastern wall, in the three small apses and in the upper band, and along the southern wall.

In the first apse, on the left, St. Peter is depicted between St. Andrew and St. John the Evangelist. In the central apse, the Virgin is represented according to the iconography of the Odegitria, characterized by a sumptuous dress and a hair on the model of the Roman one of the early Middle Ages. Next to it, there are St. Lucentia and a saint of difficult identification (Figure 2a). In the third apse, the three archangels Michael, Raphael and Gabriel are represented. Finally, in the remaining frescoed areas scenes taken from the Old Testament are painted (Bertelli and Mignozzi 2013) (Figure 2b).

The crypt presented the typical problems of hypogeal environments. In particular, the walls showed localized phenomena of plaster detachment, extensive areas affected by salt efflorescence and crusts. The frescoes were also covered by molds and patinas (bright green, greenish-black, and pink) caused by mosses, lichens, cyanobacteria and actinobacteria.

Two are the primary causes of the fresco degradation (Imperi et al. 2007; Pacini and Caneva 2003-04, 2002; 2003-04; Padula 2000). The first is the increase in humidity following the construction of a dam (Dam of St. Giuliano) and the consequent artificial lake formation in the 1950s, at about 3 km west of the crypt. The second was the addition of soil above the cave for agricultural aims, which increased the humidity of the rocky banks, thus contributing to accelerating the chemical and biological aggression on the frescoes.

The first restoration works took place in the early 2000s (Table 1) and concerned the safety of the cave. In September 2003, the soil and vegetation covering the wall surfaces were removed. Other preventive conservation measures were also performed. In particular, the surface area overlying the Crypt was coated with bentonite to reduce percolation from the upper layers of the ceiling (Caneva et al. 2019). Subsequently, the first conservation treatments based on biocides and mechanical cleaning were mad with a minimal reintegration of pictorial surface aimed to improve the visibility of some artistic details.

The scientific investigations and interventions performed represented a best practice project for the restoration of rupestrian paintings and architectures. It led to grow the awareness to develop both a protocol to be used as a scientific reference model (see, for example, Nugari et al. 2009) and a code of good practices valuable for future interventions based on the systematic assessment of the conservation status of the frescoes and architecture through a constant monitoring of environmental parameters. This aspect was also stressed in a recent study on changes in biodeterioration patterns carried out within the Crypt and performed by Caneva et al. (2019). The work highlights the need for continuous long-term monitoring of environmental parameters, which is the cause of the development of some biological patterns that develop in

Figure 2. Crypt of the Original Sin, eastern wallsecond apse: Madonna Queen between two Saints (a).Third apse: the Archangel Michael between the archangels Gabriel and Raphael (b) © Zetema Foundation.

the crypt; in particular, biological materials were sampled and studied from the wall before a scheduled maintenance intervention at the end of 2017. The results of this research highlighted the change in the types of biological colonization due to variations in the internal microclimate that occurred after restoration works during the period 2001–2003. These variations, although present in a less widespread manner than in previous years, indicate that the microclimatic conditions inside the crypt modified by internal biocide and external waterproofing interventions had positive effects, but the induced changes gave rise to changing in biological colonization so as to make need to perform further monitoring (Caneva et al. 2019).

3. Methods

The methodological approach is based on a multiscale and multiparametric monitoring system divided in different platforms of data: 1a) indoor data, including, temperature (T), relative humidity (RH), and CO_2; 1b) one close-range weather station; 2a) one weather meteorological station at 6 km from the Crypt, 2b) and weather forecasts from the Cosmos 5 model.

3.1. Indoor platform and close range weather station

The acquisition of microclimatic data was carried out through the use of non-invasive and barely visible sensors having dimensions of 25 × 10 mm. The mobile instrumentation was inserted in strategic points of the fresco: on three different internal walls and inside small pre-existing cavities to make them almost undetectable by naked eye (see Figure 3).

In order to evaluate the frescoes microclimatic conditions of the crypt, the main thermo-hygrometric parameters were collected, analyzed, and correlated. The monitoring was performed by an integrated communication system that allows the simultaneous acquisition of environmental parameters inside and outside the crypt. The system consisted of a network of sensors/transducers connected to a central node (Gateway) in Wireless mode to allow the transmission of the recorded information to a server for the collection, data processing, and publication. The LOng-RAnge wireless communication technology (LORA) has been used to connect the sensors to the gateway, which forwards the data from the sensors to the server (that makes them usable through the Web interface).

The indoor-measured physical parameters are (i) temperature and humidity, surveyed both in the center of the crypt (T5, RH4) and near the frescoes (T1-T3, RH1-RH3), (ii) temperature at contact with the wall close to frescoes and nearby the sensors 2 and 3; (iii) degree of illumination, (iv) CO_2 concentration (see Figure 3). The sensors 1 and 2 are close to the paintings showed in Figure 2a and 2b, respectively.

All the sensors meet the minimum characteristics required by UNI 10829:1999 standard (ASHRAE 2003, 2011; UNI EN 15757:2010, 2010), which indicate the

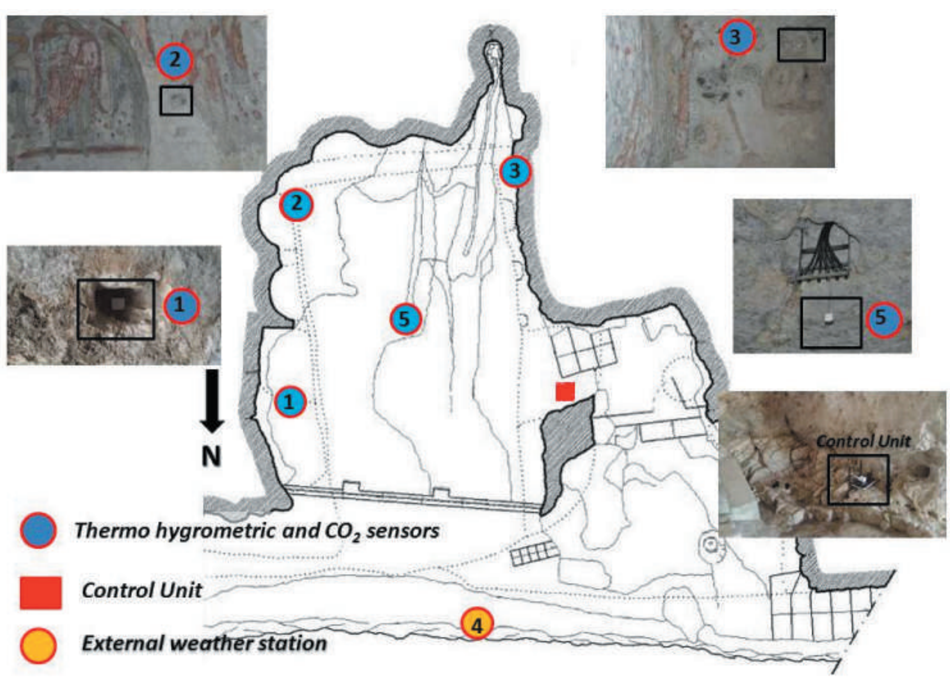

Figure 3. Plan of the Crypt. The figure also reports the sensor localization scheme of the monitoring system. Sensors 1 and 2 measure T, RH and CO_2 close the paintings showed in Figure 2.

environmental conditions of conservation, the measurement and analysis criteria to be followed for assets of historical and artistic interest.

All the collected data can be accessed in real time via a dedicated web interface through which it is also possible to visualize and download the historical time series. The indoor data integrated with the data recorded by the outdoor sensors, to understand the influence of weather conditions on the internal microclimate. Figure 3 shows the position of the different sensors inside and outside the crypt.

The monitoring aims to evaluate the presence of critical indoor thermo-hygrometric conditions and identify potential water infiltration or condensation on the frescoed walls. The presence of an excessive amount of water and humidity inside the crypt was already reported by Massari (2002), although he analyzed a short period characterized by lacking of rain events. In particular, Massari highlighted that most of the water and humidity in the crypt derived from the infiltrations caused by the permeability of the Calcarenite. After the external and internal waterproofing works of the crypt concluded in 2004, Nugari et al. (2009) highlighted the need to continue microclimatic monitoring to evaluate the conservation conditions of the frescoes that can be treated by the presence of biological pathogens. The multi-scale and multi-parametrical system, herein devised for the Crypt, well fits these monitoring requirements. To this aim, one indoor thermo-hygrometric and five surface temperature sensors were installed in strategic points close to the painted walls.

The internal parameters, available from 14 July 2017 (date of the complete installation of the system) were correlated with those obtained from an external microclimatic station that acquired the local values of atmospheric temperature and humidity. Furthermore, starting from 15 December 2017, a sensor for the detection of CO_2 concentration was installed into the crypt, while from 20 March 2018 some sensors at contact with frescos were also installed.

The period herein analyzed is a whole annual cycle, from July 2017 up to July 2018. The monitoring was carried out in four different places inside the crypt (see 1, 2, 3, 5 in Figure 3) so that the indoor measurements were compared and analyzed jointly with outdoor data (from the external weather station, sensors T4 and RH4).

3.2. Outdoor platform

The outdoor platform includes:

(i) data acquired by two external weather stations:

- one close the crypt (T4/RH4 and precipitation), and the other is the meteorological station located close the Professional School in Matera (MT_T/RH/rainfall), about 6 km away from the Crypt, provided by the Civil Protection of the Basilicata region;

(i) weather forecast from the Cosmos 5 model, at 5 km resolution, related to the location of the Crypt (C_Crypt — T/RH) as well as the location of the meteorological station (C_- T/RH).

The indoor data were correlated with those of the weather forecasts of Cosmo_5M_ITA model related to the Crypt (LAT = 40.6205649 N—LON = 16.5633306 E) and to the Weather meteorological Station located in Matera (LAT = 40.65972222 N—LON = 16.59527778 E —475 meters above the sea level). Both meteorological data and Cosmo 5 forecasting were downloaded from the Civil Protection website https://simc.arpae.it/arkiweb/ in an automatic mode. Cosmo 5 model provides forecasting, with a resolution of about 5 km (corresponding to 0,045°) and a range of 72 hours, updated every 12 hours (run 00:00 UTC and run 12:00 UTC) and made available 5 hours after the run. Cosmo 5 forecasting is selected using a customized tool ad hoc developed to select the point of interest, the level and the time range of the variables to be downloaded (in a file grid in .txt format of small size).

4. Results and discussion

4.1. Temperature trend analysis

Figure 4 shows the temperatures measured by indoor sensors (in all figures, the temperatures "T" are measured in °C) (T1, T2, T3 and T5), close-range outdoor sensor (T4), the weather station (MT_Tav), and, finally, the temperature obtained from Cosmo 5 data platform (C_T Crypt). The graph shows that the trends of indoor and outdoor temperatures are similar. Furthermore, analyzing the air temperature trend (T5), it can be observed that the amplitude of the indoor daily thermal cycles is shorter than the outside one (T4), due to the thermal inertia of the Crypt walls.

The contact temperatures (T1, T2, and T3 of Figure 3) exhibit trends similar to the outdoor and indoor air temperature, but their daily range is shorter, as expected. Furthermore, T1-T2, and T3 trends do not show abrupt and significant changes also when the outdoor temperature was higher (July–August 2017 and April–May 2018).

Figure 5 shows the comparison between the average values of the indoor and outdoor temperatures. The trends suggest a slight thermal inertia of the crypt

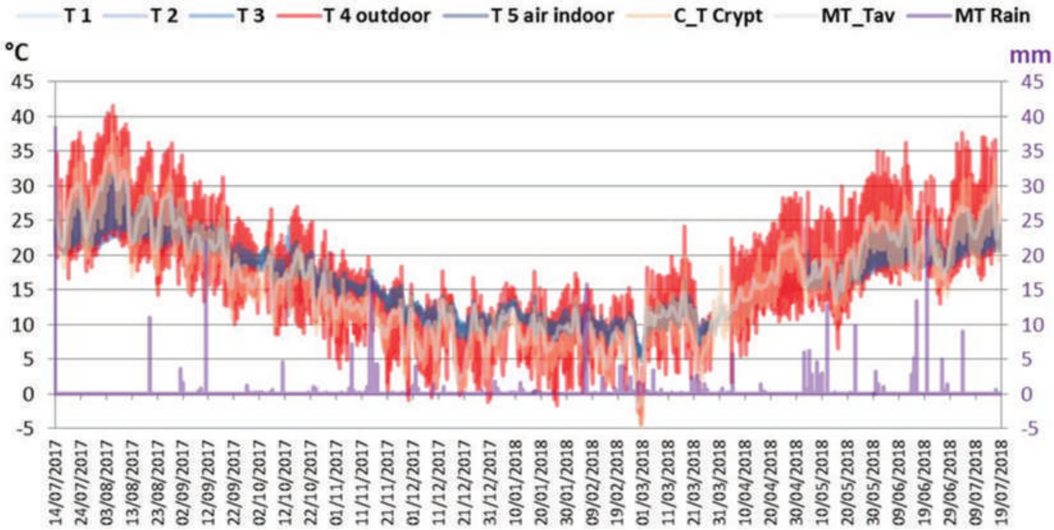

Figure 4. Graphs of indoor (T1, T2, T3 and T5 in °C) and outdoor temperatures (close the crypt (T4 in °C), from the weather station (MT_Tav in °C), and Cosmo 5 data platform (C_T in °C) (MT Rain in mm of rain).

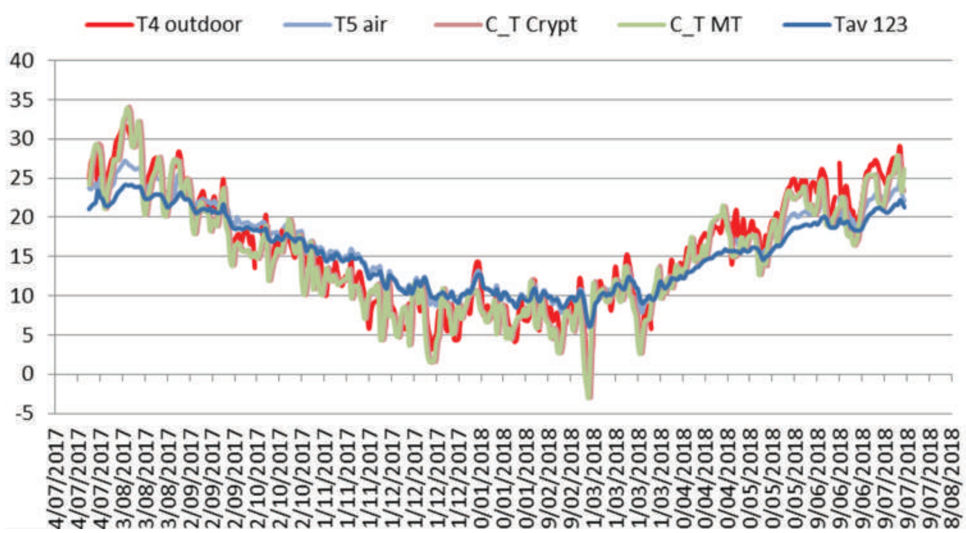

Figure 5. Average temperatures indoor (Tav 123), inside the Crypt (T5 from the center of the Crypt), and outdoor (T4, see figure 3 for position) and C_T MT (from weather station of Matera) and C_T Crypt (in correspondence with the crypt) calculated from Cosmo 5 data platform.

structure: the indoor air temperatures generally show a pattern that follows the external one, but with some differences throughout the year; the differences in values are shown in Figure 6. In particular, in the spring-summer period, the external temperature is always greater than the internal one (Tav 123 is the average of three temperature of sensors 1,2,3) of around +2 to +4° C. In autumn-winter, the internal temperature is higher than the external of around 4°C to 6°C (Figure 6) (C_T MT, temperature from weather station of Matera; C_T Crypt, temperature in correspondence with the crypt calculated from Cosmo 5 data platform).

Table 2 summarizes the temperature excursions in the year cycle of the maximum, minimum and average, indicated as Tmax, Tmin, and Tav. The table evidences greater values of excursion of Tmax respect to T min and T average, as expected for all the sensors. Comparing the indoor and outdoor temperatures, the greater excursions were recorded for the outdoor temperatures (T4 is the temperature outside the Crypt, MT_T is the temperature from weather station of Matera; C_T crypt is the temperature in correspondence with the crypt calculated from Cosmo 5 data platform) than the indoor one, for Tmax, Tmin and T av. As regards the three indoor sensors (1, 2, and 3), set close to the frescos, we notice a greater excursion of T3 (in particular the max value) respect to T1 and T2.

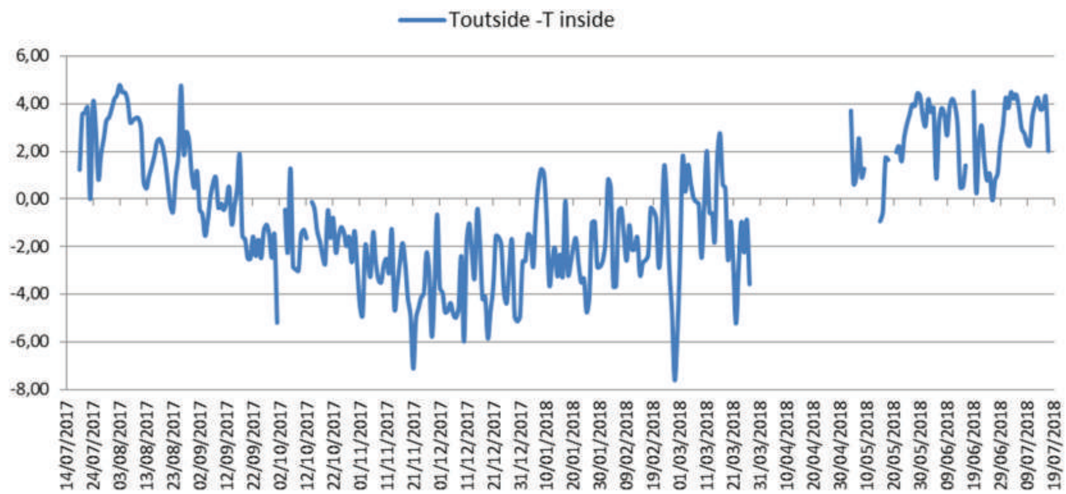

Figure 6. Temperature differences from outside-inside of the Crypt (in the graph the lack of data refers to an interval in which the transmission of the data has failed).

Table 2. Temperature excursion in annual cycle in °C (July 2017-July 2018).

	T 1	T 2	T 3	T4 outdoor air	T5 indoor air	MT_T	C_T crypt
Exc T min	0,26	0,06	0,20	1,31	0,42	0,50	0,60
Exc T max	2,81	5,59	8,90	20,75	8,35	16,20	14.6
Exc T av	1,26	1,01	1,47	11,55	3,28	8,79	4,70

Table 3. Daily temperature excursion on monthly average.

T daily excursion	T1	T2	T3	T4 outdoor air	T5 indoor air
July 2017	1,71	1,30	1,40	15,29	5,60
August 2017	1,78	1,33	1,47	14,94	5,60
September 2017	1,12	0,67	0,92	11,70	2,90
October 2017	1,25	1,22	2,55	11,01	2,90
November 2017	1,11	0,65	1,39	9,60	1,99
December 2017	1,10	0,63	1,57	9,43	2,22
January 2018	1,02	0,55	1,39	9,51	2,23
February 2018	1,04	0,72	1,36	8,45	2,18
March 2018	1,29	0,89	1,27	9,99	2,92
April 2018	1,41	1,19	1,46	13,23	3,20
May 2018	1,31	1,26	1,33	13,15	3,84
June 2018	1,15	1,30	1,31	12,33	4,00
July 2018	1,47	1,74	1,72	14,98	5,17

Table 3 shows the daily temperature excursion computed on monthly average. The comparative analysis of the three indoor sensors close to the frescoes (1, 2 and 3) put in evidence the following:

(i) sensor 1, near the window, shows a low and constant daily excursion (1.02 to 1.78),
(ii) sensor 2 exhibits on average lower values than sensor 1, but they are much more variable because of its position in the frescoed wall facing upstream (see Figure 3),
(iii) sensor 3 exhibits the highest excursion recorded in October 2017. This result is in accordance with the annual excursion reported in Table 2. Such values indicate that the western side of the wall is the most exposed to decay,
(iv) the periods characterized by the highest excursion, particularly for sensors 1 and 2 (close to the fresco on the east side wall) are the summer months (July–August 2017, July 2018).

4.2. Relative humidity trend analysis

Moving on the analysis of relative humidity, Figure 6 shows the average value of RH computed for indoor and outdoor measurements. We observe a great variability over the year inside the crypt (see, Figure 7). In particular, RH average values range between 40% and 55% in August 2017 and 99% in January 2018, which was a period characterized by strong and persistent rains and the highest values were reordered in autumn (see curve of millimeters of Rain (Rain mm) in Figure 7).

In a monitoring activity the measure of the excursion, in particular, the daily one is crucial because it is the cause of significant stress on the frescoed surfaces.

Table 4 shows the daily RH excursion on monthly average. The comparative analysis of the indoor sensors close to the frescoes (1, 2 and 3), indoor air and outdoor sensors (5 and 4, respectively) put in evidence the following:

(i) the sensors (1, 2, 3) close to the frescoes show an excursion ranging from 6% to 22%. The highest RH excursion is related to sensor 2 and is equal to 22%
(ii) sensor 5, measuring the indoor air RH, exhibits an excursion ranging from 14% to 30%.

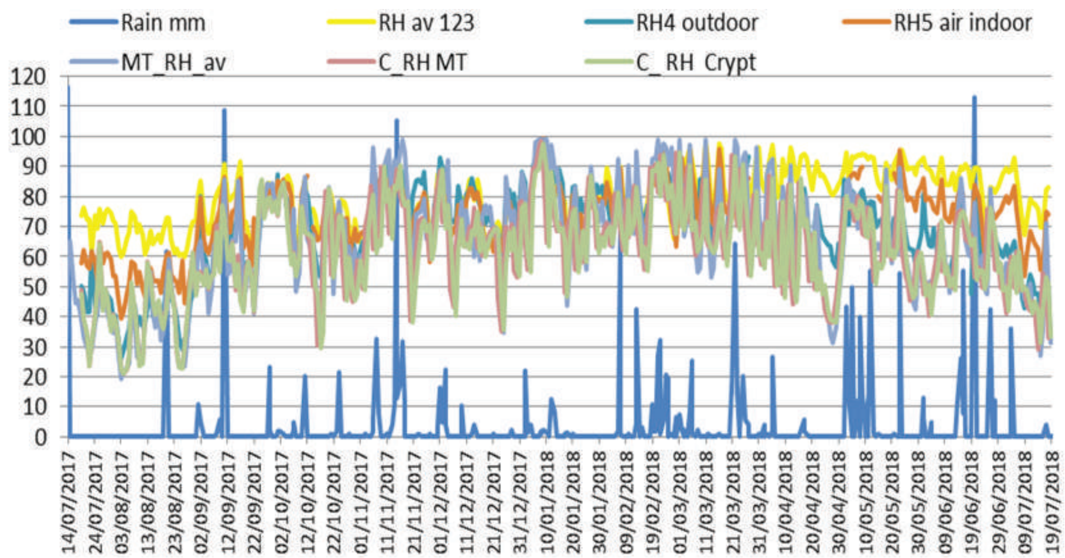

Figure 7. Average Relative Humidity indoor (RH1-3 from the wall of the Crypt and RH5 from the center of the Crypt) and outdoor (RH4, see figure 3 for position) and C_RH MT (from weather station of Matera), Rain in millimeters and C_RH (in correspondence with the crypt) calculated from Cosmo 5 data platform (the values of RH are measured in % of relative humidity).

Table 4. Daily relative humidity excursion on monthly average. The maximum values are highlighted in bold.

	RH exc 1 indoor	RH exc 2 indoor	RH exc 3 indoor	RH exc 4 outdoor	RH exc 5 indoor
July 2017	11,09	19,81	15,39	42,53	28,61
August 2017	13,28	21,78	17,48	37,12	29,65
September 2017	9,18	15,85	12,75	43,50	28,88
October 2017	10,64	15,60	16,13	39,47	26,38
November 2017	6,88	12,47	12,08	29,59	16,80
December 2017	6,79	13,27	11,72	30,37	15,51
January 2018	7,46	11,43	12,96	26,30	14,16
February 2018	6,38	12,77	12,34	28,25	15,15
March 2018	6,78	11,37	12,81	30,77	18,46
April 2018	7,27	11,32	11,91	42,94	18,23
May 2018	5,53	9,30	9,59	40,95	17,43
June 2018	8,75	14,25	13,94	41,44	22,80
July 2018	10,83	16,98	17,15	45,47	28,18

(iii) The highest RH excursion for indoor and outdoor sensors (1–5) is related to summer months (July and August 2017, July 2018)

(iv) As already observed for the temperature, also trend in relative humidity follows the outdoor pattern (RH outdoor) (Figure 7) and is inversely proportional to the temperature fluctuations.

4.3. Thermo-hygrometric data analysis

Thermo-hygrometric analysis has been performed computing the mixing ratio (MR, by the ratio between the mass of water vapor and the mass of dry air, UNI EN 16242 2013) and the dew point (DP) (is a meteorological parameter that indicates the temperature at which, at constant pressure, the air becomes saturated with water vapor, UNI EN 16242 2013).

The mixing ratio (the ratio between the mass of water vapor and the mass of dry air) has been evaluated considering the data recorded in sensor positions n.5 and drawn in Figure 7, which shows the following:

(i) a relatively high variability of MR characterized the whole monitoring period;

(ii) very high values were in the spring-summer period, and the MR values decrease in the end of autumn-winter periods;

(iii) from May 2018 the value of MR increased greatly due to the higher air moisture that reached the maximum values in July 2018 and September 2017.

This trend is in direct correlation with the variations of absolute humidity of the external environment of the crypt and depends on the weather conditions (Figures. 4, 7, 8).

The differences in T and RH found between inside and outside throughout the analyzed period suggest a medium-low thermal inertia of the Crypt, which generally happens for semi-closed systems (Cardinale and Ruggiero 2002) such as caves and crypts. In this case, the low inertia is also due to the openings present (grate always open even during visits) as opposed to ancient buildings or monuments which, due to their construction and insulation characteristics, may present greater inertia also due to the considerable mass of air they contain inside them (Aste et al. 2019).

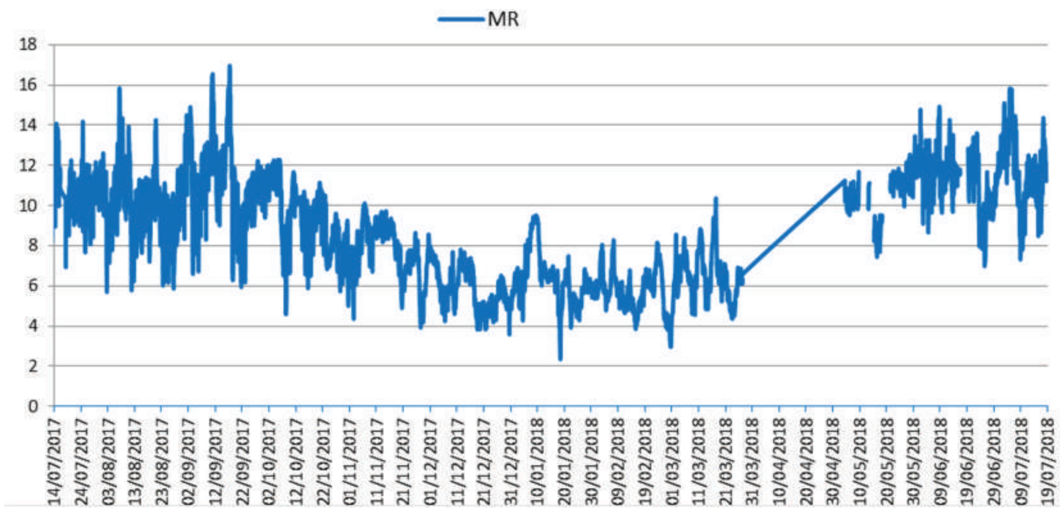

Figure 8. The mixing ratio trend of the indoor air of the Crypt.

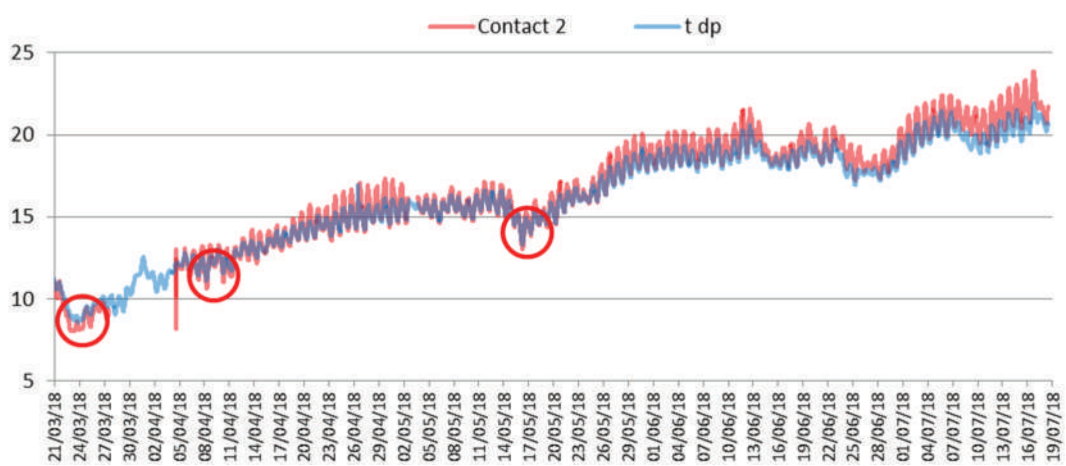

Figure 9. Red color curve indicates the trend of the temperature in °C measured by the contact sensor 2; while blue color curve is the trend of the DP in °C (Dew Point, defined as the temperature to which air is saturated with water vapor) computed according to the formula by UNIEN 16242 2013), red circles correspond to risk of condense.

Figure 9 reports the trends of daily temperature variations of contact sensors 2 and 3 (red-colored curve) near the fresco and the dew point (Dp, defined as the temperature to which air is saturated with water vapor).

The analysis of daily temperature variations of contact sensors 2 and 3 allowed us to identify the episodes when sensors went into saturation due to condensation. This is a very feared problem especially in presence of a significant content of soluble salts (as in our case) which can cause the risk of strong decay due to crystallization of salts and formation of efflorescence and sub-efflorescence.

In fact, starting from March 2018 two contact sensors were installed to measure temperatures near the ends of the main fresco on the South wall (in position n.2 and 3 see Figure 3). To identify the occurrence of condensation events on the fresco surface, the theoretical curves of dew point (DP, that is the temperature to which air is saturated with water vapor) were calculated for all the frescoed walls, adopting the formula recommended by UNIEN 16242 2013.

Analyzing the two curves of temperature measured by sensor in contact and the computed values of DP three episodes evidence of condensation in the period of March–May 2018 (Figure 9). Such events indicate a real risk of long-term wall degradation.

4.4. Incidence of visitors and CO_2 analysis

The incidence of visitors on changes in indoor parameters was also evaluated, correlating the total daily visits of the crypt with changes in indoor T and CO_2 (Figure 10). The visits last not more than 30 minutes for groups of visitors of around 20–30 people. Observing Figure 10, one can argue that there is no direct correlation between temperature increase and inflow inside the crypt.

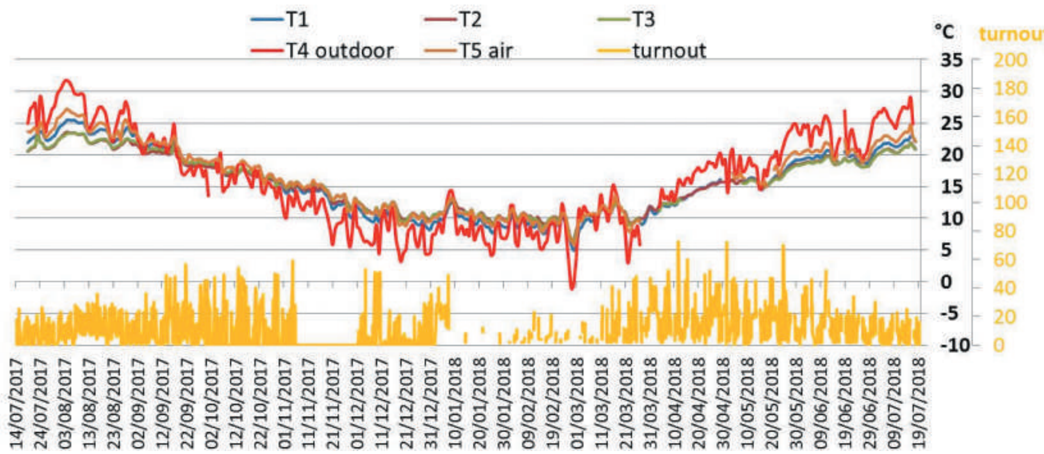

Figure 10. Incidence of visitors on changes in temperature. The curves indicates indoor and outdoor temperature (range scale −10/35°C) and visitor turnout (range 0/200).

Analyzing the CO_2 data in relation with the daily shift, it is clear that the internal concentrations are low on average and can be correlated with the typically external atmospheric values. However, an inflow of more than 50 people can lead the exceeding of the limit parameter set at 1000 ppm (Figure 11). From the analysis of the data collected, it can be observed that the presence of people, has a temporary effect on the local microclimate as also suggested by the literature (e.g. Aste et al. 2019). That is mainly due to the small air volume of the Crypt, as well as its small thermal mass and the very slow rate of air exchange.

In order to counteract this phenomenon, the access to the crypt should be limited and staggered, fixing the maximum number of people at 50.

4.5. Indoor and outdoor parameter correlation

Finally, the analysis of correlation between indoor, close-range outdoor and outdoor environmental parameter has been done (see Figure 12).

As a whole, the best correlation values have been obtained for the temperature (see Table 5).

In particular, the correlations between the indoor temperature close to the frescoes (T1, T2, T3) and the air temperature (T5) are almost equal to 1 (see Figure 12a).

Whereas the correlation between indoor and close range outdoor is equal to 0,9388 (see Figure 12c, and 12d), and between indoor and forecasted outdoor is 0,8511 (see Figure 12e). These values are very important because demonstrate a good fit not only between indoor sensor and outdoor sensors, ad hoc installed for the Crypt monitoring (as expected) but also between indoor data and forecasted temperatures (see Table 5). Considering that today higher spatial resolution forecasting is free available it is possible to use these data also for a rough evaluation of temperature in the case of lacks of measurements due to instrument failure or absence. A very good fit could be also observed between close range outdoor temperature and forecasted outdoor temperature and is equal to 0,9375 (see Figure 12g).

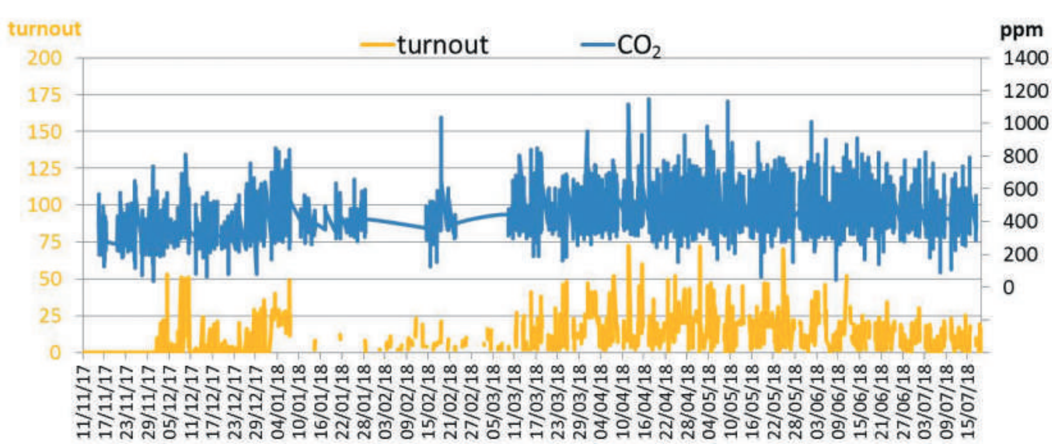

Figure 11. Incidence of visitors on changes in CO_2. The curves indicate CO_2 (range on the right −200/1200 ppm) and visitor turnout relation (range 0/200).

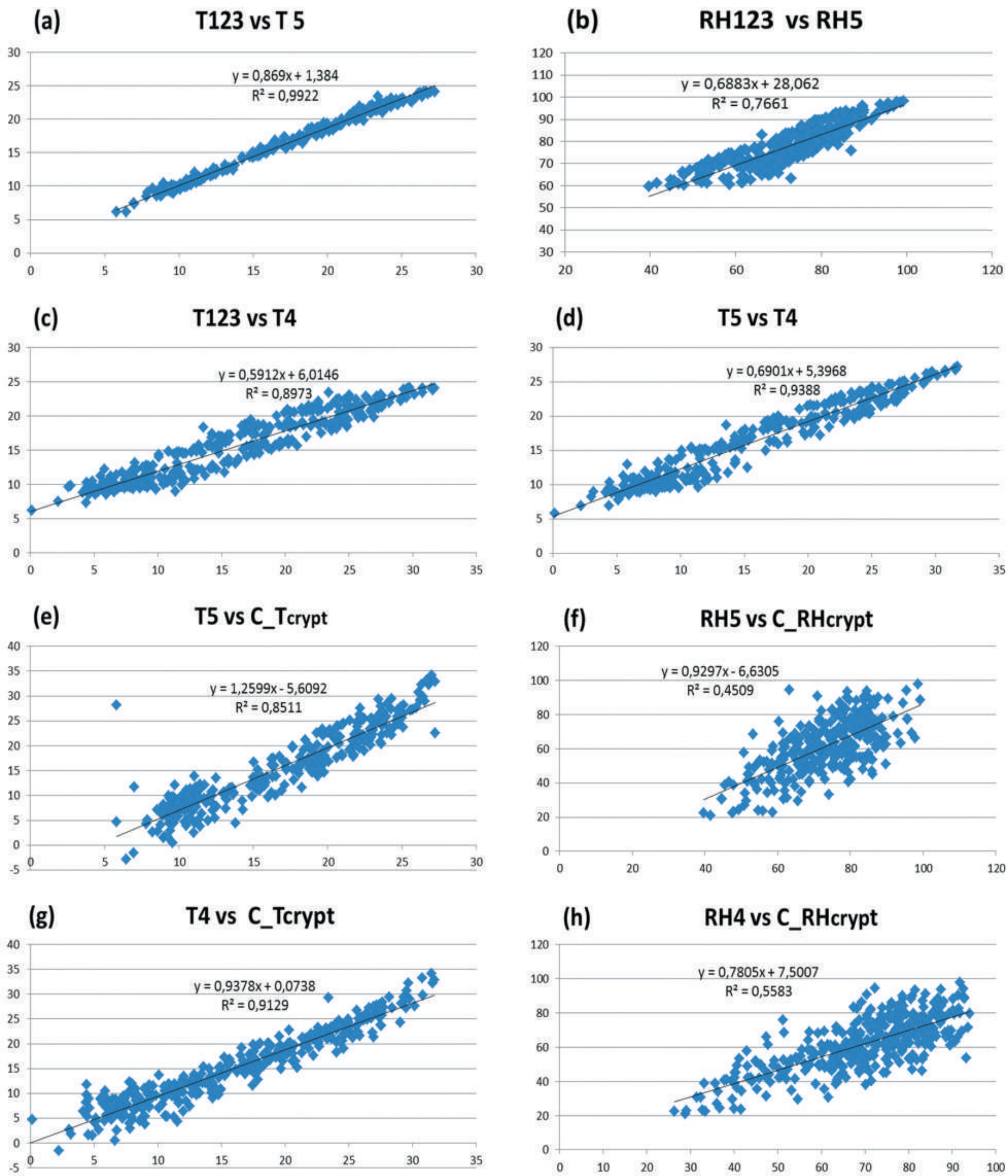

Figure 12. (a) Correlation between the average of T1, T2 and T3, measured close to the fresco, and T5 measured in the middle of the crypt (see Figure 3). (b) Correlation between the average of RH1, RH2 and RH3, measured close to the fresco, and RH5 measured in the middle of the crypt. (c) Correlation between the average of T1, T2 and T3,, and the T4 (close range outdoor) (see Figure 3). (b) Correlation between T5 measured in the middle of the crypt and T4. (e) Correlation between T5 measured in the middle of the crypt and the forecasted temperature from Cosmo 5 (C_Tcrypt). (f) Correlation between RH5 measured in the middle of the crypt and the forecasted humidity from Cosmo 5 (C_RHcrypt). (g) Correlation between T4 (close range outdoor) and the forecasted Temperature from Cosmo 5 (C_Tcrypt). (h) Correlation between RH4 (close range outdoor) and the forecasted humidity from Cosmo 5 (C_RHcrypt).

As regards the relative humidity, the correlation between indoor and close range outdoor is equal to 0,6622, whereas the correlation between indoor and forecasted outdoor is 0,4509. Finally, the correlation between close range outdoor RH and forecasted outdoor RH is equal to 0,5583 (see Figures 12f and 12h).

Table 5. Correlation values obtained between indoor, close-range outdoor and outdoor parameters (T and RH).

			Correlation of T	Correlation of RH
Indoor	*Vs*	*Indoor*	0,9922	0,7661
Indoor	*Vs*	*Close range outdoor*	0,9388	0,6622
Indoor	*Vs*	*Outdoor*	0,8511	0,4509
Close range outdoor	*Vs*	*Outdoor*	0,9375	0,5583

These correlation values lower than those observed for the temperature are expected because RH is characterized by a higher variability in space and in time respect to temperatures.

These values need to be confirmed with future longer-term measurements and analyses, but to date, they support the idea that forecasting data can be useful for large-scale monitoring of sites like the Crypt, which are not always easy to monitor, in order to find combinations of temperature and humidity (see, for example, the period of condensation) in the Crypt that can be useful to identify risk conditions in early stages. The next efforts can be addressed to the identification of critical conditions and their mapping over time and space to support risk mitigation strategies and preventive interventions particularly for the conservation of very fragile sites as the *Cripta del Peccato originale* is.

One of the most important results for the case of the Crypt is the evidence and understanding that the condensation on the walls was generated in the periods of heavy rain >55 mm/day, RH >85% within a day and temperature <10°C.

5. Final discussion and outlooks

We proposed a spatial and temporal multiscale methodological approach for the monitoring of wall paintings in rupestrian environments. It is based on four diverse platforms of sensors and data: i) indoor, with sensors measuring T, RH and CO_2 close to the fresco and in the air, ii) close range outdoor (the sensors measure T, RH and rain precipitation); iii) long-range outdoor, including a weather station measuring T and RH, provided by the Civil Protection of the Basilicata region; iv) weather forecast data from Cosmos 5 model.

The integration of data from the *ad hoc* monitoring system (i and ii) with the data from other platforms (iii and iv) has been fruitfully employed, exploiting different spatial and temporal scales, to analyze the relationship of the meteorological conditions and forecasts with indoor microclimatic changes, and, consequently, the variations of the conservation state of the wall paintings to suitably support preventive conservation maintenance.

The outputs from our preliminary analyses clearly pointed out the importance of devise future systems for the internal regulation of temperature and humidity, to set up the best conservation conditions of the frescos. Moreover, the meteorological forecasting data from Cosmos 5 model showed great potentialities for large-scale monitoring of sites as the Crypt and similar cultural properties. In the future, additional efforts will be addressed to the identification of critical thresholds of the monitored parameters for early warning. Considering that most of the water and humidity in the crypt derives from the infiltrations caused by the permeability of the Calcarenite, the need of making measurement of humidity in the inner bank, is also relevant for its conservation. The high thermal inertia of the crypt, evidenced by the data analysis, showed that the problems related to the indoor microclimate are mainly linked to the humidity. This, especially during persistent rain period, determines condensation on the walls, which is very dangerous for the long-term conservation status of the frescoed walls. Therefore, an internal air regulation system needs to be envisaged in the future, to make the condensation risk lower.

The correlations of indoor and outdoor parameter (in particular for the temperature) provided promising results. This confirms the usefulness to enlarge the spatial of outdoor monitoring up to include free available data from meteorological stations and short-term forecasting, as has been done in this work. This suggests the opportunity to apply the same approach to other test sites in order to characterize the hygrothermic behavior, using the obtained correlations to model and link the indoor and outdoor parameters.

In the future, outdoor monitoring will be enriched by satellite data as MODIS (Recondo et al. 2013) for temperature and humidity data, PRISMA (Spinetti et al. 2017) which provide data of pollution (in particular CO_2, NOx, etc., at 30 m resolution), along with Sentinel 5 (https://sentinel.esa.int/web/sentinel/missions/sentinel-5) with daily global coverage for climate, air quality, and ozone/surface UV applications which will enable to expand the monitoring on a macroscale level to support conservation strategies.

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Author contributions

N.M. and M.S. conceived, directed the investigations and coordinated the drafting of the paper; F.T.G. contributed to the drafting of the paper and results validation; F.F.contributed to the historical research, A.D. contributed to the technological applications; R.L. revised the whole paper and contributed to the multiscale approach. All authors have read and agreed to the published version of the manuscript.

Disclosure statement

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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