High-Resolution Temperature Mapping for Cultural Heritage Conservation: A Case Study in Matera

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Abstract. In the last years, climate change is exacerbating the presence and impacts of heatwaves. The sharp rise in temperatures and the consequent increase in temperature fluctuations pose risks to the population, the environment and society, but also impact on cultural heritage. This is true throughout the territory, but even more specifically in historic centers, which are characterized by a high density of assets and where high temperatures and morphological and construction characteristics can lead to the urban heat island effect, which amplifies the implications of heatwaves. However, the lack of high-resolution heat data limits the ability to monitor these phenomena and plan conservation and mitigation strategies. Therefore, this study proposes a useful method to map the spatial distribution of temperatures and temperature excursions in a city rich in cultural heritage, Matera (Italy) characterized by particularly fragile building materials, offering a useful tool for risk assessment and heritage management.

Keywords: heatwaves · cultural heritage · climate change · spatial analysis · Matera

1 Introduction

In the last decades, the trend of world surface temperature is growing and will continue to increase, so much so that an average temperature increase of 2.7° has been predicted within the next 100 years [1]. Among the most significant consequences of climate change is the intensification of heatwaves, which are becoming more frequent, prolonged, and severe. These extreme thermal events pose serious risks at different levels: it is dangerous for air and water quality [2, 3], but also for acoustic comfort [4]; it causes increase in energy consumption [5], is a problem for the public health [6], with the following economic consequences and increases social inequalities, as the weaker social classes are also less able to cope with the effects [7], exacerbating existing environmental, social, and economic vulnerabilities.

The combination of this global warning with the resulting increase in heatwaves and the increase of the urbanization [8] produces an anthropogenic climate modification inside cities called Urban Heat Island (UHI) [9]. In this effect, temperature inside the

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urban area is higher than the surrounding suburban and country areas [10] because of the difficulties of the heat exchanges and dispersion due to the urban morphology, its material and the lack of vegetation [11].

Heatwaves constitutes also a threats for cultural heritage and its conservation is a primary target for protection by various organizations such as UNESCO and ICOMOS [12, 13]. Historical centers are affected by them [14], first of all because of its constructive characteristics and materials [15], but also for the concentration of cultural elements, as well as being themselves, in their entirety, considered cultural goods. In fact historical centers are vulnerable elements for the cultural landscape and cultural identity, they preserve as well as being a strategic point for economic activities related to it, such as tourism, or traditional socioeconomic activities.

A thorough understanding of all the aspects mentioned above, however, requires the possibility of using high-resolution temperature data, which, however, are not available free of charge or at low cost.

In this paper the goal is to propose a method for the downscaling of satellite data, in order to have high resolution datasets useful to study heatwaves temporal trends in the two last decades and footprint and return an instrument to map the potentially impacts on cultural assets, identifying an overview of the high-risk zones in a medium sized city, Matera (Basilicata, Italy).

2 The Heatwaves Effects on Cultural Heritage

Ancient buildings developed from a close connection with the natural environment.

Regulation of indoor climatic conditions was thus achieved through the use of established construction criteria that primarily exploited the geometric and positional characteristics of the building. When the external climatic conditions come to change, the ancient building will be subjected to different stresses and its response may not always be adequate.

Thermal gradients are among the aspects that concern the effects of the interaction between the building and the external environment. These in fact are of interest both from the energy point of view, in terms of heat loss, and from the conservation point of view in terms of their effects on the building's constituent matter.

First of all, a temperature of over 25° can be considered abnormal or in any case having an impacting effect on the built heritage (as well as on people and the environment), especially if prolonged over time.

In fact, these temperatures cause physical, chemical, mechanical and biological processes to intensify on it and consequently the following effects [16–20]:

- Expansion and contraction of the materials due to temperature variations with possible micro-fractures in the short term and, in the long-term problems with structural integrity.
- Acceleration of degradation processes and increased fragility due to increased water evaporation processes especially in porous materials.
- Acceleration of chemical processes leading to the formation of efflorescence and crusts.
- Increased biological growth due to heat and humidity.

- Degradation of protective coatings due to exposure to high temperatures, especially if prolonged [21].

To map the UHI footprint is consequently important to overlay it with the heritage vulnerability and to monitor these effects, in order to program intervention strategies and to mitigate them.

3 Materials and Methods

3.1 Land Surface Temperature Calculation

The main problem in heat island footprint assessment is to estimate the Land Surface Temperature (LST) at the right spatial scale. For example, for assessments concerning the built heritage or historical centre, it can be useful to have data with a high spatial resolution. However, thermal data as MODIS have an insufficient resolution (1 km). In the literature, some models are shown to estimate the temperature by exploiting previous work on the surface emissivity of objects on the earth's surface [22], according to which the emissivity can be expressed as a function of the vegetation index plotted on the pixels and then calculate the LST from the Normalized Difference Vegetation Index (NDVI). From this, an empirical model of emissivity can be applied, for example, by joining the thermal band of the data from the Landsat satellite to the NDVI elaboration [23]. Conversely, the Sentinel data, specifically, while having a very good spatial resolution and allows to calculate a highly defined NDVI, lacks the thermal channel necessary to derive with this method the LST. Another problem regarding the use of Sentinel data is that this type of temperature assessment is only valid under clear sky conditions.

For this reason, starting from the MODIS dataset, a recently introduced interpolation method has used as approach to obtain a very high resolution map of LST.

3.2 Empirical Bayesian Kriging Regression Prediction

Empirical Bayesian Kriging (EBK) is a geostatistical interpolation method that improves on the use of classical kriging. It introduces within it the ability to reduce the uncertainty in the estimation of hyper-parameters typical of interpolation, related to the variogram and thus to the relationship between variance and distance [24, 25]. This reduction of uncertainty is done by means of a Bayesian bootstrap [26, 27]. The algorithm also proved to have increased efficiency due to its ability to divide the dataset into subsets, allowing for faster interpolation [28]. Recently, EBK has been used in applications related to the mapping of chemical elements in soil [24], in studies related to public health [29], but also to improve the estimation of annual precipitation, land surface temperature [27] and groundwater [30].

While EBK predictions are made only considering the dependent variable and the estimation of the variogram (or semi-variogram), the **Empirical Bayesian Kriging Regression Prediction** (EBKRP) allows one or more additional explanatory variables to be considered through regression, whose spatial trend also influences the variable to be interpolated. The combination of the two methods, regression and kriging, combines

their own strength point: the ability of regression to capture global trends; the ability of kriging to capture local trends and relationships between points.

The mathematical basis of the EBKRP are the following: let's consider the studied variable z*(s)*, where *s* is its spatial location. It is represented as the sum of the function *m(s)*, coming from the regression model, considering the global trends, and the spatial residuals *ε(s)* (Eq. 1).

$$z(s) = m(s) + \varepsilon(s) \tag{1}$$

The regression (linear or more complex) component *m(s)* models global trends by estimating intercept β_0 and the regression coefficients $\beta_0 \ldots \beta_p$ associated to the *p* explanatory variables $X_1(s) \ldots X_p(s)$ (Eq. 2).

$$m(s) = \beta_0 + \beta_1 X_1(s) + \ldots + \beta_p X_p(s) \tag{2}$$

The spatial residuals *ε(s)* follow a Gaussian process (*GP*) with zero mean and a spatial covariance structure *C(s, s')* also called covariance function or variogram that describes how similarity between the two points in *s* and in *s'* varies with their distance (spatial autocorrelation) (Eq. 3):

$$\varepsilon(s) \sim GP(0, C(s, s')) \tag{3}$$

With kriging it is possible to obtain a weighted estimation of residuals $\varepsilon(s_i)$ in an unobserved point s_0, where weights λ_i depends on the covariance structure (Eq. 4)

$$\hat{\varepsilon}(s_0) = \sum_{i=1}^{n} \lambda_i \varepsilon(s_i) \tag{4}$$

To estimate variogram parameters (nugget, range, sill) a Bayesian approach is followed: an entire variogram distribution is followed starting from parameters that are assumed to come from an a priori distribution. For each variogram calculated, it is calculated too the probability that the observed data are generated by that variogram (likelihood). Likelihood contributes to change a priori parameters to obtain a posteriori parameters. All variograms and the parameter sets are combined in order to obtain the best parameters.

For more details about mathematical formulation see [27, 28].

4 The Case Study: The Historical Center of Matera

Matera (Basilicata, Italy) is a medium-sized city in the Mediterranean area (southern Italy) characterized by a very long settlement history. It is a perfect example of a settlement in a rocky habitat created in close harmony with the ecosystem: the sustainable use of natural resources, in particular the water collection systems, is the main feature of the urbanization of this area of the Basilicata Region, and the reason for the

recognition of the Sassi and the Murgia plateau (Natural Archaeological Park of the Rock Churches) as a UNESCO World Heritage Site since 1993 (http://whc.unesco.org/en/list/670). Defined both by ICOMOS [31] as a unicum that includes rock settlement, architectural settlement and landscape, they show various significant moments in human history. The name Sasso indicates a rock-hewn district already mentioned in documents dating back to the 13th and 14th centuries [32]. The two rock settlements that arose around the Civita (an area frequented or inhabited since the 2nd millennium B.C. [33]), developed over the centuries along the Gravina stream and were slowly transformed. Together with the Civita and then the Piano, they created a settlement system spanning more than two millennia, without spatio-temporal interruptions. The types of dwelling are: the cave; the lamione, a room with a vaulted roof; and the palaziate houses, built with the material excavated inside the cave [34]. Cultural heritage preserved in Matera is of various types: cave systems (small, dark, damp rooms with beds and cellars), millstones, oil mills, quarries, or religious places with altars, columns, vaults, domes and frescoes. The organization of the underground urban space appears on the surface only as a jumble of alleys, vicinates (small squares) and gradelle (stairways), but it is only apparently random: it was conditioned by the need to capture and channel water, to purify and store clean water for the most basic daily activities, and to drain unusable water. The cisterns collect the clean water and store it; the drainage waters follow the slopes of the terraces, cross the gullies and canals and reach the Gravina stream downstream. Thanks to a dense network of canals, wells, cisterns and divers dug into the calcarenite and made impermeable, the inhabitants of the Sassi were able to satisfy their water needs until running water arrived in the 1920s. This water management system is one of the most significant examples of the balance between human intervention and the ecosystem in an urban space. The neighbourhood called Piano developed in the 18th century at a higher level than the Sassi, with bourgeois houses, not completely excavated in the rock but built, with large windows and more comfortable, and with fine examples of Baroque religious architecture. Life here was healthier and more comfortable. In the Sassi, on the other hand, serious problems were the unhealthy conditions and the spread of endemic diseases, overcrowding, the sharing of space with animals and a high infant mortality rate. A great cultural, political and legislative mobilisation has sought to remedy these living conditions since the 1950s. Several laws were enacted (Laws no. 619/1952, 299/1958, 126/1967, 1043/1971) to relocate the inhabitants, overcome the precariousness of hygiene, economic and social conditions, and also to solve the problems of structural instability of buildings and roads [35]: town planners and sociologists designed new residential neighborhoods and rural villages: Serra Venerdì, Spine Bianche, Lanera, Borgo La Martella and Borgo Venusio. A major effort is needed to ensure mitigation measures to reduce the risk factors affecting the future of such a valuable site: an assessment of the conservation status of the settlement and the influence of environmental variables on it, in order to determine the possible factors controlling the stone degradation process was carried out in [21] (Fig. 1).

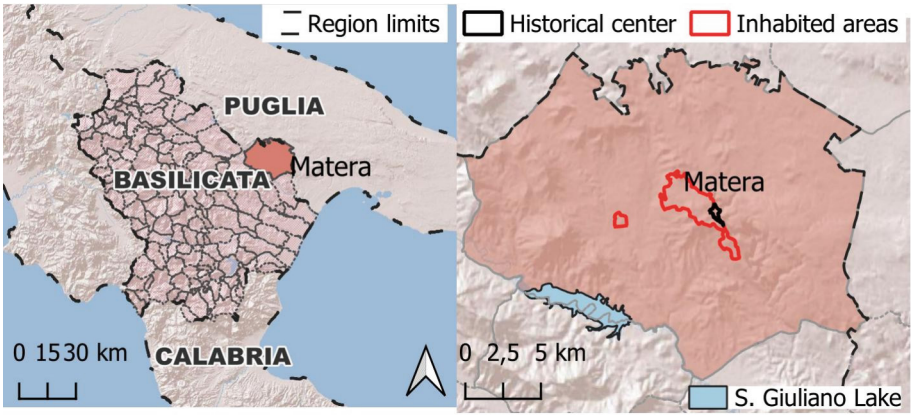

Fig. 1. Geographical overview of the study area

It can be deduced from what has been said so far that a large part of Matera's cultural heritage is characterized by calcarenites.

These materials, due to the properties they possess (high open porosity, low mechanical strength and vulnerability to degradation, the main component being calcite) are very sensitive to water, which is the main agent of deterioration, both directly and indirectly. Especially thermal variations, such as the rapid evaporation of water and its subsequent crystallization cause internal fractures and alveolization phenomena [21, 36, 37]. In temperate climates such as the one in the case analyzed, therefore, the risk factor for this material increases due to the presence of rapid and wide temperature fluctuations, even in the presence of different materials in contact. Although there are no well-documented thresholds in the literature, it is known that an increase or decrease of 20 °C causes an expansion or contraction of 0.14 mm/m [38]. For this reason, in addition to obtaining high-resolution maps of daytime and nighttime LST, it is very useful to obtain maps of the distribution of the temperature range between day and night.

5 Results

5.1 High Resolution LST Calculation

EBKRP was used to obtain LST with high resolution over all the municipality area. As input raster the thermal band of the MODIS Terra and Aqua satellite products data were used [39]. In particular it has two bands, one with the daytime and one with the nighttime Earth surface temperature. Monthly average data were downloaded with a script on GEE, a free, cloud platform, publicly released in 2010 [40].

As trend raster the elevation was used, because of different studies highlights strong correlation between temperature trends and this parameter [41, 42].

To evaluate the goodness of the result the Root-Mean-Square Error (RMSE) is calculated (Eq. 5).

$$\sqrt{\frac{\sum_{i=1}^{n}(\hat{z}(s_i) - z(s_i))^2}{n}} \tag{5}$$

where s_i is the spatial location of the considered point, $z(s_i)$ is the measured value in the s_i position, $\hat{z}(s_i)$ and n is the number of points used for the interpolation. It is useful to show how well the predicted values through interpolation models the measured values. So it must be as low as possible. RMSE values are shown in the figures, overall always low (Figs. 2 and 3).

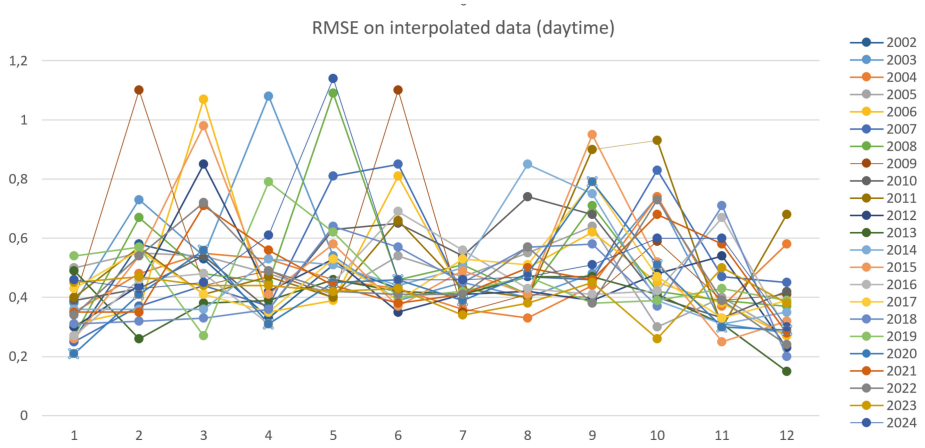

Fig. 2. RMSE values calculated from interpolated data in the daytime.

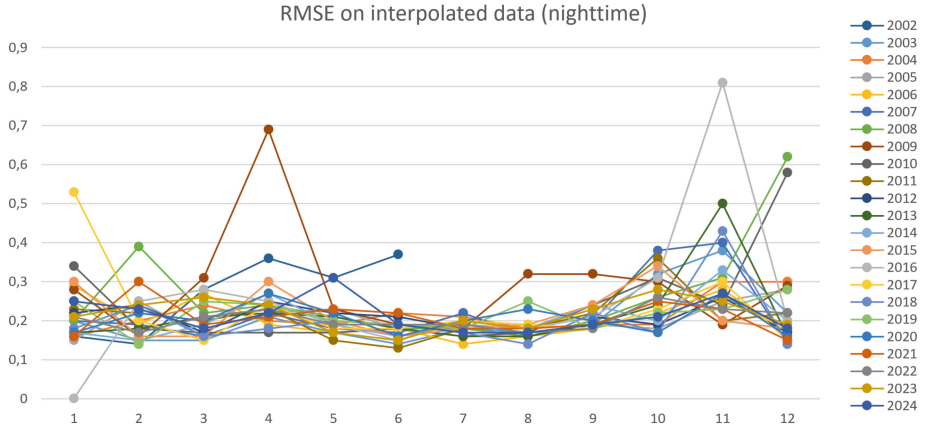

Fig. 3. RMSE values calculated from interpolated data in the daytime.

5.2 Trend Analysis and Temperature Variations

In this work, three different types of temperatures (minimum – Tmin -, average – Tmax- and maximum - Tmax) were chosen as they help to highlight different aspects in heat-waves. The minimum temperatures are useful in assessing the presence of tropical nights, i.e. temperatures above 25°, which, especially in an urban context and in the city centre, can highlight the heat island effect when not sufficiently mitigated during the night, when the heating continues to be constant despite the absence of the sun. However, minimum temperatures are not effective in showing the maximum intensity of heat waves. Maximum temperatures, on the other hand, are extremely effective in mapping the intensity of heat peaks and fully show the severity of the phenomenon during the daytime phase. The two measures are therefore complementary. Finally, average temperatures help complete the picture, showing the overall duration of the warming phenomenon through long-term trends.

In order to visualise the variation of maximum temperatures, temporal heatmaps were created in the time range considered, in three territorial bands of the Matera Co-municipality and more specifically in the rural areas (first column of heatmaps), in the historic centre (second column) and in the urban area (third column).

The first phenomenon that emerges, consistent with the current situation of climate change, is a trend of progressive growth in minimum, average and maximum temperatures and thus a brighter shade of red moving in the graphs from top to bottom (i.e. the most recent years). This upward trend is especially noticeable in historic city centres and this is a first indicator of the urban heat island effect. Heating occurs both during the day and at night, so urban areas and the historic centre have a lower cooling capacity at night.

Thus, more generally, rural areas, having a greater temperature range, thanks to the effect of vegetation, manage to maintain a cooler microclimate, despite the significant temperature peaks in some areas. This gap between rural and built-up areas is also more evident due to the marked differences between the winter and summer seasons.

Finally, in Table 1 the maxima, in the reference period, of the minimum, average and maximum temperatures in the rural area, in the historic centre and in the urban area, during the day and night are shown. The rural areas shows a Tmax higher, but also the greatest temperature excursion; this implies a strong daytime warming, probably due also to the morphology and the land cover of part of the Matera's rural areas, characterized by an extended, cultivated plain with a low density vegetation. Here, the low vegetation cover allows the exposed soil to warm up quickly and, conversely, to cool down rapidly during the night. For what concerns the inhabited area, of note are the presence of an intermediate maximum temperature and temperature range between the the rural area and the historic centre. This last shows the greatest Tmin and the lower temperature excursion that suggests its capability to maintain a stability in temperatures, again due to the urban heat island effect and thus the sparse presence of vegetation and the high density of buildings (Fig. 4).

Table 1. Maxima temperatures, in the reference period, daytime and night time in the three investigated zones.

	Zone	Tmin (°C)	Tmean (°C)	Tmax (°C)
Daytime	Rural areas	39,8	46,5	50,3
	historical center	44,3	44,6	45,3
	inhabited area	43,9	45,6	48,9
Nighttime	Rural areas	17,1	19,8	23,6
	historical center	22	22,4	22,6
	inhabited area	20,1	30,3	22,7

5.3 Spatial Distribution of Temperatures and Thermal Excursion

With the results obtained by interpolation, a series of detailed maps of the distribution of daily and night temperatures in different areas and periods of the year were obtained, with special attention paid to areas with the presence of cultural heritage and historical centres too. For the sake of brevity, in Figs. 5 and 6, the maps with the diurnal temperature variation are shown only in the period from March to October 20024 (Fig. 5 the months from March to June, Fig. 6 the months from July to October, left column), i.e. the months characterised by the presence of areas with temperatures above 20°. Moreover, in the same figures, in the right column, it is represented the distribution of the temperature range. It was decided to represent only those areas that have a temperature difference of 20 °C, a value considered significant as explained in the previous section, as it represents a critical condition for sensitive historical materials.

The maps in Figs. 5 and 6 show in detail which areas are characterised by the highest temperature rises, which for example in July and August even reach 50°, and allow us to compare these areas and those characterised by the presence of cultural heritage, so that we can better understand which heritage elements need to be monitored more because they may be particularly exposed to fluctuations.

The detailed map in Fig. 7 for the historic centre also shows in its left-hand side (Fig. 7a) the distribution of temperatures with peaks reaching 45°, while the temperature range reaches up to approx. 22.5 °C. The map depicts the most important cultural heritage elements in the historic centre, thus making it possible to understand which areas are the hottest and most exposed to temperature fluctuations, in order to prioritise conservation measures in the most critical areas and try to mitigate their effects.

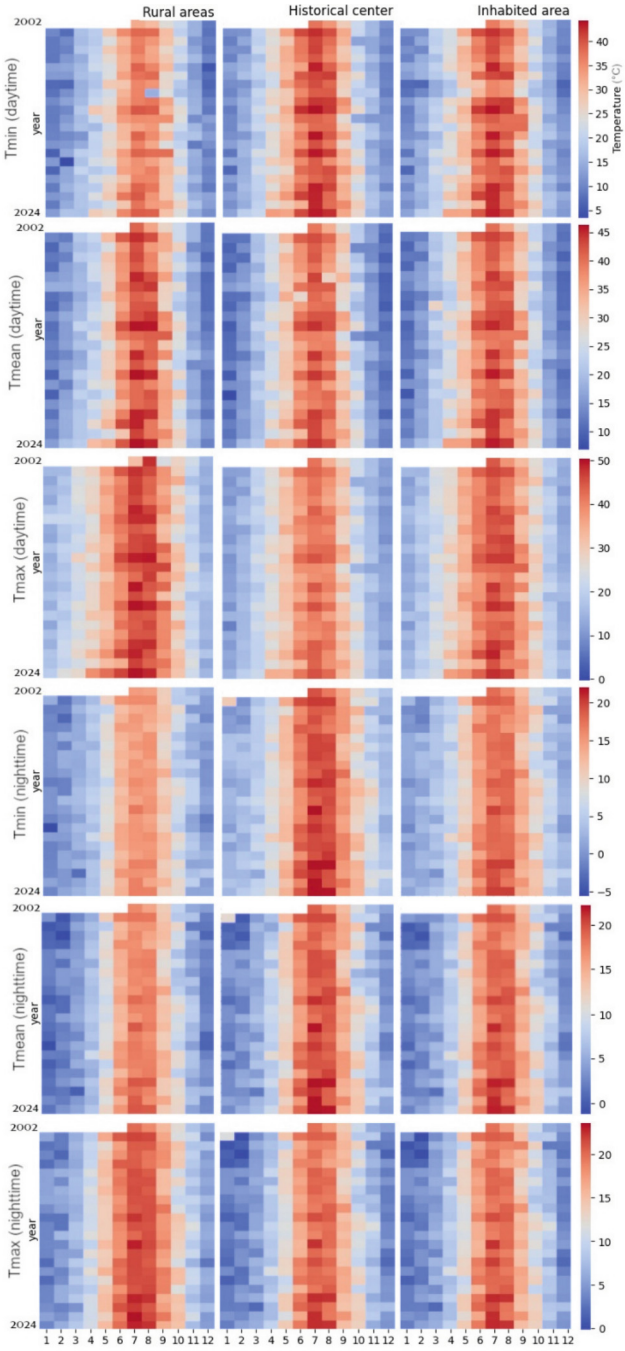

Fig. 4. Heatmaps for minimum, mean and maximum temperature (daytime and night time) in rural areas (left column), historical center (center column) and inhabited areas (right column).

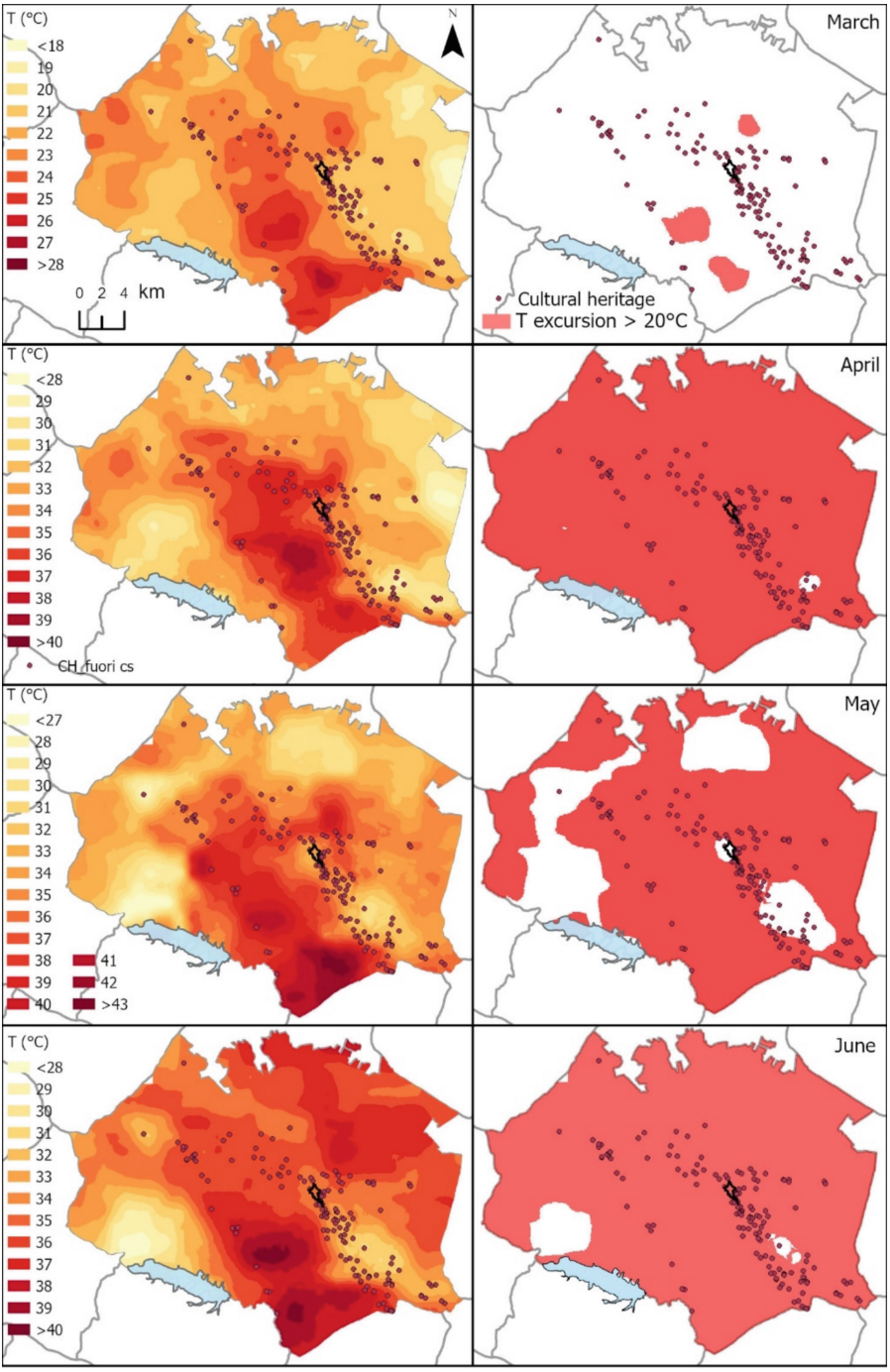

Fig. 5. Spatial distribution of diurnal temperature (left) and thermal excursion (right) from March to June and overlay with cultural heritage.

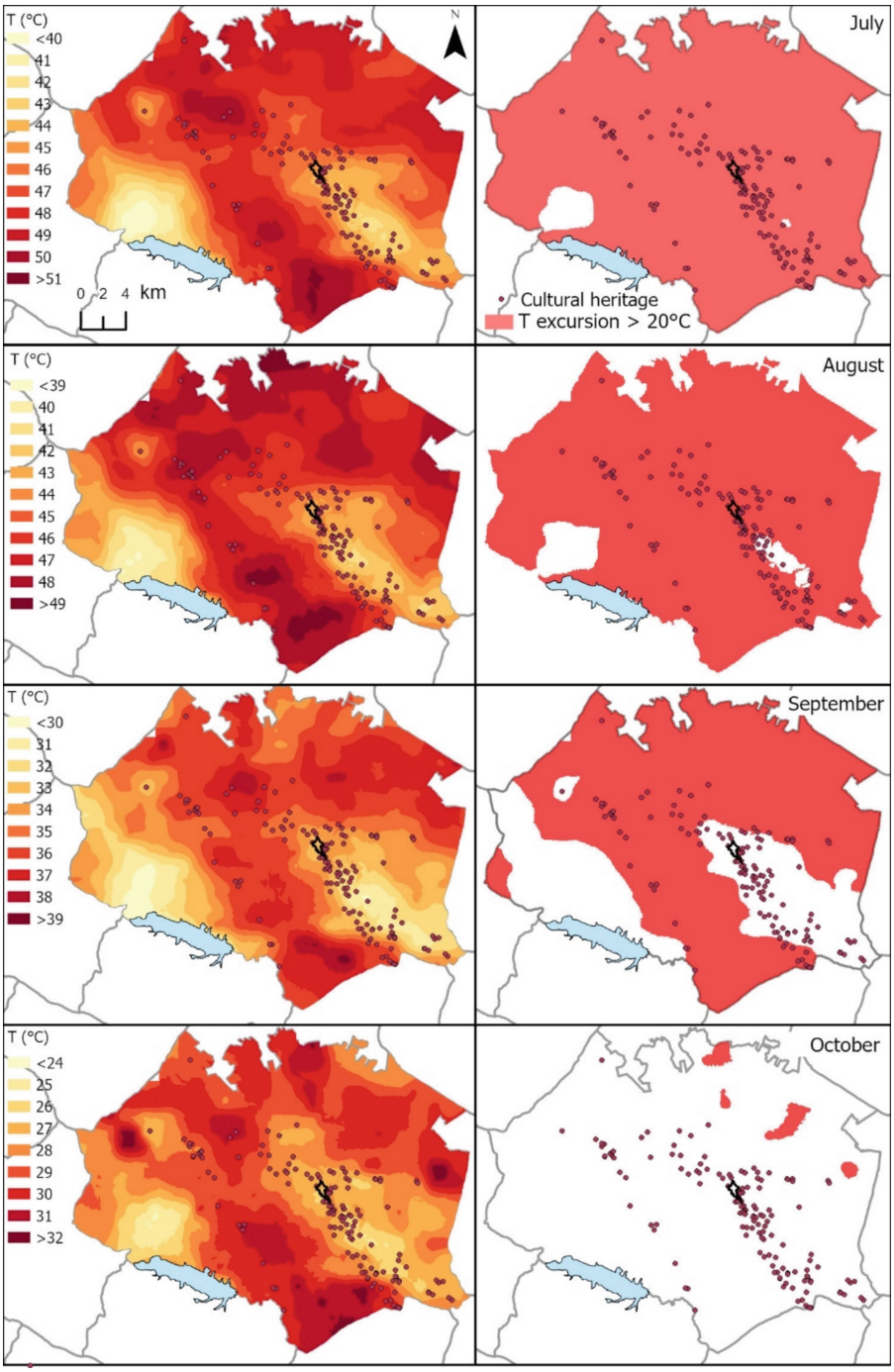

Fig. 6. Spatial distribution of diurnal temperature (left) and thermal excursion (right) from July to October and overlay with cultural heritage.

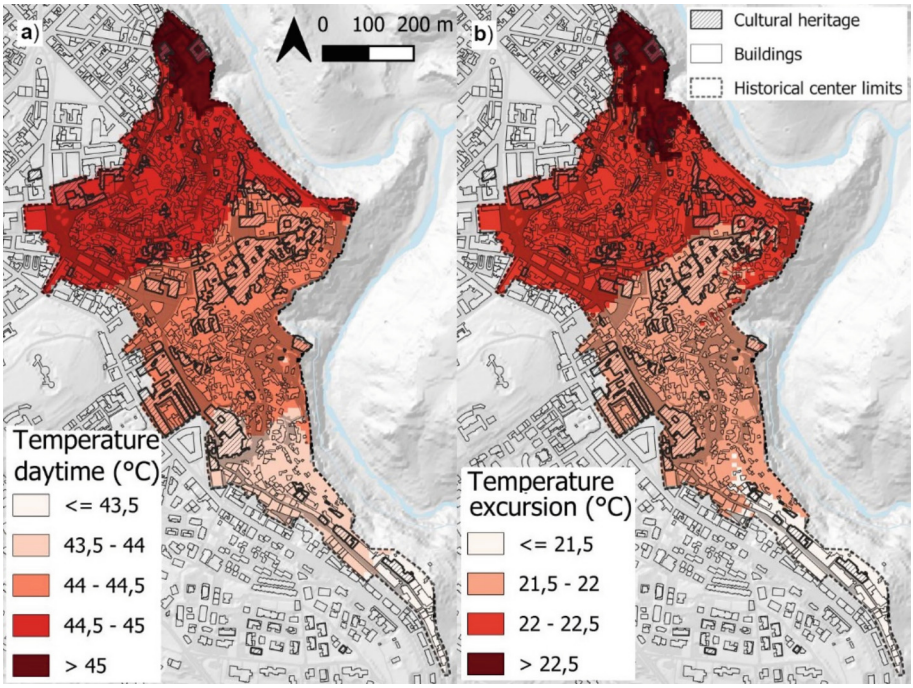

Fig. 7. Detail of spatial distribution of diurnal temperature (left) and thermal excursion (right) in the Matera historical center.

6 Discussion and Conclusion

In this study, a downscaling method was applied, based on spatial machine learning, EBKRP, which was able to return a high-resolution (10m) LST dataset from the much lower resolution MODIS data. The results were deemed reliable due to the validation performed with the RMSE index. These results constitute an important mapping tool to study the areas of greatest vulnerability and to be able to support targeted conservation and mitigation strategies for cultural heritage in general and for historic centers. The approach followed also made it possible to overcome the typical limitation of optical data, when deriving temperature using vegetation and emissivity data, consisting in the need for clean sky conditions.

In the case study of the experiment, from a statistical point of view, it was highlighted that due to higher average and minimum temperatures and a narrower day-night range, the historic center of Matera, despite its not excessively large size, is still characterized by the UHI effect. Therefore, building materials are more exposed to the risk of physical and chemical degradation of the assets present in it and, more generally, of all the built heritage present in it.

In particular, the development of detailed maps on temperatures and thermal excursions, such as those of the historic center (Fig. 7), offers a tool capable of monitoring temperature fluctuations in space and time, anticipating degradation phenomena such as cracks, detachments, and corrosion of metal elements. In this way, it also becomes

possible to identify the areas most exposed to thermal stress, where to focus predictive intervention priorities and resource optimization. These maps are therefore a useful tool for policymakers and designers whose aim is to identify strategies, solutions, and mitigation interventions at the local scale.

The protocol applied in this work, easily applicable in any geographical context, is only a starting point and presents further development possibilities, such as the integration and enhancement of initial data with IoT sensors, in order to increase temporal resolution with the aim of providing a concrete possibility to detect anomalies and intervene promptly to protect heritage. Furthermore, temperature data should be integrated with additional environmental variables, such as sun exposure, wind speed and direction, and humidity, to build a complete and detailed picture of the climatic influence on cultural heritage and historical materials.

In conclusion, in a context of increasing climate pressure, the use of combined tools, such as advanced analytical tools and satellite data represents a fundamental step to monitor elements like temperature and to enhance the resilience of cultural heritage. These data not only favor more effective conservation interventions but also help guide urban policies towards sustainable development models, in line with the recommendations of the AR5 Report by the Intergovernmental Panel on Climate Change. The ability to translate this information into concrete actions will be crucial to increase the resilience of cultural heritage and preserve historical and cultural memory for future generations.

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References

1. Parmesan, C., et al.: Terrestrial and freshwater ecosystems and their services. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2022)
2. Grimm, N.B., et al.: Global change and the ecology of cities. Science **319**, 756–760 (2008)
3. Stedman, J.R.: The predicted number of air pollution related deaths in the UK during the August 2003 heatwave. Atmos. Environ. **38**, 1087–1090 (2004)
4. Núñez-Peiró, M., et al.: Exposure and vulnerability toward summer energy poverty in the city of madrid: a gender perspective. In: Bisello, A., Vettorato, D., Haarstad, H., Borsboom-van Beurden, J. (eds.) Smart and Sustainable Planning for Cities and Regions. SSPCR 2019. Green Energy and Technology, pp. 481–495. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-57332-4_34
5. Tian, L., Lu, J., Li, Y., Bu, D., Liao, Y., Wang, J.: Temporal characteristics of urban heat island and its response to heat waves and energy consumption in the mountainous Chongqing, China. Sustain. Cities Soc. **75**, 103260 (2021)

6. Dong, X.S., West, G.H., Holloway-Beth, A., Wang, X., Sokas, R.K.: Heat-related deaths among construction workers in the United States. Am. J. Ind. Med. **62**, 1047–1057 (2019)
7. Cheng, Q., Sha, S.: Revealing the injustice and factors that affect the resilience responses of residents in the full period of heat waves. Sustain. Cities Soc. **107** (2024)
8. Tan, J., et al.: The urban heat island and its impact on heat waves and human health in Shanghai. Int. J. Biometeorol. **54**, 75–84 (2010)
9. Arnfield, A.J.: Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. Int. J. Climatol. **23**, 1–26 (2003)
10. Santamouris, M.: Cooling the cities – a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Sol. Energy **103**, 682–703 (2014)
11. Oke, T.R., Johnson, G.T., Steyn, D.G., Watson, I.D.: Simulation of surface urban heat islands under 'ideal' conditions at night part 2: diagnosis of causation. Bound.-Layer Meteorol. **56**, 339–358 (1991)
12. Colette, A.: Climate change and world heritage: report on predicting and managing the impacts of climate change on world heritage and Strategy to assist States Parties to implement appropriate management responses. Changement climatique et patrimoine mondial: rapport sur la prévision et la gestion des effets du changement climatique sur le patrimoine mondial et Stratégie pour aider les Etats parties à mettre en oeuvre des réactions de gestion adaptées
13. Markham, A., O.E., Lafrenz Samuels, K., Caldas, A.: World Heritage and tourism in a changing climate (2016)
14. Quesada-Ganuza, L., Garmendia, L., Alvarez, I., Briz, E., Gandini, A., Olazabal, M.: The risk of heat waves to historic urban areas. A GIS-based model for developing a risk assessment methodology. In: Furferi, R., Giorgi, R., Seymour, K., Pelagotti, A. (eds.) The Future of Heritage Science and Technologies. Florence Heri-Tech 2022. Advanced Structured Materials, vol. 179, pp. 47–60. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-15676-2_4
15. European, C., Cassar, M., Sabbioni, C., Brimblecombe, P.: The Atlas of Climate Change Impact on European Cultural Heritage – Scientific Analysis and Management Strategies. Anthem Press (2010)
16. Wang, Y., Zhang, H.: Preliminary study on the impact of severe heat waves on dolostone weathering: implications for deterioration of carbonate rock-hewn heritage in SE China. Environ. Earth Sci. **83** (2024)
17. Lobarinhas, R., Dionísio, A., Paneiro, G.: High temperature effects on global heritage stone resources: a systematic review. Heritage **7**, 6310–6342 (2024)
18. Quesada-Ganuza, L., Garmendia, L., Rojí, E., Álvarez, I., Briz, E., Gandini, A.: How are heat waves putting at risk historic urban areas? First steps for developing risk assessment methodologies. In: REHABEND, pp. 1114–1121
19. Grossi, C.M., Brimblecombe, P., Harris, I.: Predicting long term freeze-thaw risks on Europe built heritage and archaeological sites in a changing climate. Sci. Total. Environ. **377**, 273–281 (2007)
20. Viles, H.A., Cutler, N.A.: Global environmental change and the biology of heritage structures. Glob. Change Biol. **18**, 2406–2418 (2012)
21. Gizzi, F.T., Sileo, M., Biscione, M., Danese, M., Alvarez de Buergo, M.: The conservation state of the Sassi of Matera site (Southern Italy) and its correlation with the environmental conditions analysed through spatial analysis techniques. J. Cult. Heritage **17**, 61–74 (2016)
22. Li, Z.-L., et al.: Satellite-derived land surface temperature: current status and perspectives. Remote Sens. Environ. **131**, 14–37 (2013)
23. Sekertekin, A., Bonafoni, S.: Land surface temperature retrieval from Landsat 5, 7, and 8 over rural areas: assessment of different retrieval algorithms and emissivity models and toolbox implementation. Remote Sens. **12** (2020)

24. Samsonova, V.P., Blagoveshchenskii, Y.N., Meshalkina, Y.L.: Use of empirical Bayesian kriging for revealing heterogeneities in the distribution of organic carbon on agricultural lands. Eurasian Soil Sci. **50**, 305–311 (2017)
25. Al-Mudhafar, W.: Bayesian kriging for improved spatial heterogeneity modleing in clastic reservoirs. In: Proceedings of the 24th Formation Evaluation Symposium of Japan
26. Gribov, A., Krivoruchko, K.: Empirical Bayesian kriging implementation and usage. Sci. Total Environ. **722** (2020)
27. Krivoruchko, K., Gribov, A.: Evaluation of empirical Bayesian kriging. Spat. Stat. **32** (2019)
28. Krivoruchko, K., Gribov, A.: Distance metrics for data interpolation over large areas on Earth's surface. Spat. Stat. **35** (2020)
29. López, C.M.R., Rivera, M.M., Ochoa, A., Gallegos, J.C.P., Mendoza, J.E.G.: Geospatial situation analysis for the prediction of possible cases of suicide using EBK: a case study in the Mexican state of aguascalientes. In: Handbook of Research on Natural Language Processing and Smart Service Systems, pp. 327–346 (2020)
30. Uddin, M.S., Mitra, B., Mahmud, K., Rahman, S.M., Chowdhury, S., Rahman, M.M.: An ensemble machine learning approach for predicting groundwater storage for sustainable management of water resources. Groundwater Sustain. Dev. **29** (2025)
31. ICOMOS: WORLD HERITAGE LIST Matera No 670 (1993). http://whc.unesco.org/archive/advisory_body_evaluation/670
32. Fonseca, C.D.: Il popolamento rupestre. In: A., D.R.G.C. (ed.) Storia della Basilicata. Il Medioevo. Laterza (2006)
33. Cipolloni Sampò, M.: L'Eneolitico e l'Età del Bronzo. In: Cestaro, A.D.R., G. (ed.) Storia della Basilicata. Adamesteanu D. L'Antichità, pp. 67–136. Laterza (1999)
34. Laureano, P.: Giardini di pietra: i Sassi di Matera e la civiltà mediterranea. Bollati Boringhieri (1993)
35. Cotecchia, V., Grassi, D.: Stato di conservazione dei "Sassi" di Matera (Basilicata) in rapporto alle condizioni geomorfologiche e geomeccaniche del territorio e alle azioni antropiche. Geol. Appl. e Idrogeol **10**, 55–105 (1975)
36. Rosina, E.: Effetti delle interazioni tra edifici storici e condizioni climatiche. Efficienza energetica e patrimonio costruito. La sfida del miglioramento delle prestazioni nell'edilizia storica, pp. 145–165 (2013)
37. Guida, A.G., Bernardo, G.: Heritages of stone: materials degradation and restoration works. REUSO2015-Documentación, Conservación, y Reutilización del Patrimonio Arquitectónico, pp. 299–306 (2015)
38. Cigni, G., Codacci Pisanelli, B.: Umidità e degrado negli edifici, pp. 58–59 (1987)
39. Wan, Z.: MODIS land surface temperature products users' guide. Institute for Computational Earth System Science, University of California: Santa Barbara, CA, USA vol. 805, p. 26 (2006)
40. Moore, R.T., Hansen, M.C.: Google Earth Engine: a new cloud-computing platform for global-scale earth observation data and analysis. AGU Fall Meeting Abstracts, vol. 2011, p. IN43C-02 (2011)
41. Baldocchi, D., Ma, S.: How will land use affect air temperature in the surface boundary layer? Lessons learned from a comparative study on the energy balance of an oak savanna and annual grassland in California, USA. Tellus B Chem. Phys. Meteorol. **65**, 19994 (2013)
42. Malcheva, K., Bocheva, L., Marinova, T.: Mapping temperature and precipitation climate normals over Bulgaria by using ArcGIS Pro 2.4. Bulg. J. Meteorol. Hydrol. **2**, 61–77 (2020)