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Article

Sustainability of Traditional, Historical Roofs in the Mediterranean: A Rediscovered Opportunity for a Carbon Neutral Future

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Abstract: As the world grapples with the effects of climate change, there is an urgent need for sustainable solutions to help reduce carbon emissions. Historic urban centres can indicate one possible way forward, and this is because of the way traditional buildings (in this paper centring on the Mediterranean) are built. Their materials and technologies are usually well chosen and adapted to hot climates, while the layout of historic centres, often with quite narrow, winding streets, provide shading and frequently also appropriate direction of cooling winds, especially in marine locations. These often result in these urban cores being cooler than more modern city centres. Traditional roofs, in particular, have over the centuries proved to be reliable and sustainable (when given appropriate maintenance), with layers of porous materials providing inbuilt breathable (evaporative) properties. These lead to a degree of passive cooling and ultimately to less energy consumption (less use of air conditioning for example), thus creating a smaller carbon footprint for each building, and hence also for the urban centre when a number of these buildings are present. This paper is based on a three-year pilot study, where an innovative methodology using a combination of remote data (obtained from Unmanned Aerial Vehicle (UAV) and satellite) with in situ measurements, allows for the remote identification of traditional and modified roofs, as well helping understand the thermal behaviour of such roofs, with this study concentrating on historic centres in the Island of Malta, in the Mediterranean. Ultimately aimed at promoting preservation of these traditional roofs, this study provides data to help address, at least in part, current climatic concerns, whilst also potentially providing some adaptation strategies to address climate change (in particular increased ambient temperatures). Our studies on the behaviour of traditional *deffun* mortar roofs have shown that they are effective in protecting the internal environment from the external one. This can lead to a reduction in carbon emissions and help create a more carbon-neutral future over an entire historic centre. Therefore, in the long term, with the right management policies in place, traditional roofs on traditional buildings can provide an excellent and cost-effective way of moving towards carbon neutrality in historic urban centres.

Keywords: Mediterranean; traditional roofs; porous materials; evaporative properties; passive cooling; historic city centres; carbon neutrality

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1. Introduction

Traditional flat roofs of vernacular and historic buildings found in many Mediterranean historic town and village centres have long been considered as being well adapted to the location and climate where they were built [1], especially with regard to the materials and technology used. Depending on the design and layout of such buildings (including courtyards and covered terraces, but also thick walls, high ceilings and shuttered windows) and of the wider urban centre itself [2–5], traditional roofs can produce an evaporative (cooling) effect when the porous layered materials which make up the roof are moist (such as after rain or heavy dew occurrences), and the sun appears—an effect which, however, has never been quantified. This paper presents the results of a three-year pilot project (EO4HBCS, funded through the MCST Space Research Fund 2019) during which a select number of traditional roofs in the Mediterranean Island of Malta have been studied, and their behaviour compared to modified traditional roofs and more modern roof types, with the aim of utilising the knowledge gained to potentially promote the better maintenance, and retention of these traditional roofs.

In many historic urban centres, policies and regulations are in place to preserve the streetscape, often for aesthetic, historical and/or touristic reasons, but the roofing materials themselves are rarely part of a holistic way forward. As a result, owners and occupants of such traditional buildings can remove and replace original roofing materials with more "watertight" materials; this is often a consequence of lack of readily available information on original roofing materials, their behaviour and their maintenance, and aggressive marketing of more modern replacements such as membranes and other water-resistant coatings. Such changes, which often happen on a wide scale, not only upset the "breathability" of the whole building but may also lead to a localised increase in the Urban Heat Island (UHI) effect when several of these buildings occur in the same historic urban core—an effect which is expected to increase under a changing, warmer climate. Addressing the behaviour and hence the maintenance and retention (or even reinstatement) of such roofs would therefore help target not only greater (passive) occupant comfort now and in the future, but also help reduce the carbon footprint of the building resulting from internal heating and cooling, and eventually of the historical urban core itself.

Natural ventilation in individual buildings is key to occupant comfort. This is promoted in traditional Mediterranean buildings by the presence of internal courtyards, sometimes with fountains and vegetation, windows with wooden louvres (or mashrabiyas) which allow in air but not heat, and shaded terraces which help promote air circulation inside the building. This is most appreciated during the night, where overnight cooling in hot climates is needed, whilst also addressing security issues—most of these features prevent intruders from gaining access whilst cool night air is still let in. Learning how to include and use these ventilation/cooling mechanisms will promote and enhance the passive cooling effect, an effect which can be supplemented by the presence of traditional evaporative roofs.

There is also a direct relationship between a traditional building, its roof, and the UHI in its immediate surroundings. Studies show that there is a clear synergy between the temperature at ground level and the nature and layout of the surrounding streets—the organic development/urban design of the old city centres over time results from external requirements which occurred over the centuries [6]. This is closely related to not only the individual buildings, but also their arrangement in relation to one another, as well as the number, size and location of public spaces. If we take the characteristic old city centres of historic towns on both northern and southern shores of the Mediterranean, the narrow winding streets characteristic of such areas came about primarily for reasons of security but also in many cases benefited from the shading which buildings offered each other, and also the exploitation of cooling sea breezes in often torrid climates. Important historic centres include those of Toledo in Spain, Palermo in Italy, Mdina in Malta, and the Medinas of many North African countries. During the morning hours, the narrow streets exhibit a phenomenon where their walls and road surfaces, possessing significant thermal inertia, maintain a lower temperature compared to the surrounding air [7]. This cooler air, being denser and heavier, tends to linger within the streets, especially in the absence of wind. The close-knit arrangement of buildings in this urban setting minimises the number of surfaces directly exposed to sunlight, allowing the structures to cast shade upon each other. As a result, solar heat absorption by the building envelope is reduced.

A 2016 paper by Achour-Younsi and Kharrat specifically studied the impact of the geometry of an urban street canyon on outdoor thermal comfort, focusing on the Mediterranean subtropical climate of Tunis, Tunisia. The conclusions were that "the deepest streets are the most comfortable" and also "demonstrated the importance of the prospect of the street and its orientation in the creation of a comfortable environment" [8].

A direct study on the Urban Heat Island of the coastal Mediterranean city of Kyrenia, Cyprus was carried out by Atak et al. [9]. This concluded that whilst "the old town is warmer at night-time than the rural areas . . . during the daytime, the rural area is warmer than the urban area because the sunlight directly affects the ground and surrounding area". This was attributed to the fact that in "the urban area during the daytime, the sunlight is unable to directly reach the ground with the result that the temperature is lower than the rural area. In the narrow street, the buildings create shade for each other."

2. The Urban Heat Island Effect and the Contribution of Overheating Buildings

The concept of the UHI was initially proposed in 1818 to describe a phenomenon where the air and surface temperature in a particular area exceeded that of its neighbouring surroundings [10]. Urban areas, in general, experience temperatures that are 3.5–4.5 °C higher than their immediate suburban and rural surroundings, and this temperature difference is expected to continue to increase by approximately 1 °C per decade when considering overall environmental change [11]. Factors that trigger the UHI effect can include the use of low-albedo construction materials (such as concrete, tar, dark roof tiles, black membranes), extensive impermeable dark surfaces such as road asphalt, lack of urban vegetation, and increased energy consumption in buildings. To identify, evaluate, and monitor UHI, it is essential to estimate primarily the land surface temperature (LST) since UHI is closely related to it.

The increased temperatures caused by UHI can adversely affect the thermal comfort of residents, potentially resulting in heat strokes, respiratory problems, heat cramps, dehydration, and even heat-related mortality. This impact is particularly severe for vulnerable populations such as children, the elderly, and those with underlying health conditions [12]. UHI may exacerbate the negative health effects during heatwaves, bushfires, and other periods of elevated temperatures in the summer season. Furthermore, elevated temperatures at night can also contribute to heat stress. The resultant increase in domestic electricity demand has been estimated to be about 1.4% on average for every increase of 1 °C in temperature [13]. Peak loads during summer afternoons in large buildings also increase significantly, adding to a greater demand for electricity and leading to potential power outages of highly vulnerable power infrastructure.

Therefore, reducing the UHI effect can have a significant positive impact on energy savings and achieving zero net emissions. By improving, amongst other things, building insulation (where several challenges occur in the case of traditional and historic buildings) and the use of energy-efficient roof technology, we can lower the energy demand for cooling especially during hot weather. Such an approach reduces the demand for fossil fuels, leading to a reduction in greenhouse gas emissions and can help move towards a more sustainable and resilient future with zero net emissions. The presence of fully functional evaporative cool roofs, such as traditional roofs, can partly help reduce the UHI effect by keeping their surfaces, and the underlying rooms, cooler than the ambient temperature.

Satellite remote sensing has become a powerful tool in mapping out the extent and monitoring of UHI. Various environmental satellite sensors are being used to monitor LST [14,15]; among them, the LANDSAT program (Thematic Mapper, Enhanced Thematic Mapper Plus, and Thermal Infrared Radiometric Sensor) are renowned for their high-resolution satellite data and reliable accuracy. In a nutshell, satellite remote sensing data can effectively record the development and evolution of UHIs and related indices and provide large quantities of timely and accurate spatial information to link to changes in urbanisation. For example, Cassar et al. [16], showed how the land surface temperature of the Maltese Islands estimated from a LANDSAT 8 satellite overpass showed various hot spot areas, which ranged from a temperature of 30–36 °C, to the hottest areas (up to 42 °C) located further inland.

2.1. Detection of Current Thermal Hotspots over the Maltese Islands

The Maltese Islands have a total surface area of 316 km^2 and in order to instantaneously geolocate thermal hotspots, satellite infrared imagery acquired from orbiting satellites were utilised. For this study, the technique used to estimate the Land Surface Temperature was based on the Split-Window Algorithm Becker and Li (1990), as described by Galdies and Lau (2020) [17,18].

Cloud-free LANDSAT OLI/TIRS overpasses covering the entire Maltese Islands were acquired on 25 July 2020 at 11:36 am local time, and downloaded from USGS [19]. Atmospheric disturbance was removed from the satellite image. The format of the data derived from the Optical Land Imager and the Thermal Infrared Sensor was L1T; hence, further geometric correction of the images to be transformed as image maps was not needed. Based on radiative transfer theory, for a cloud-free atmosphere under thermodynamic equilibrium, the channel radiance $B_i(T_i)$ on Top Of the Atmosphere (TOA) was approximated using the latest LANDSAT data product [20].

Information about the emissivity was obtained by calculating the Normalized Difference Vegetation Index (NDVI) for which bands 2 to 5 of the LANDSAT 8 OLI were used [21]. From LANDSAT 8 metadata, the LST was calculated as follows (for coefficients see Skokovic et al. 2014) [22]:

$$LST = TB_{10} + C1\,(TB_{10} - TB_{11}) + C_2\,(TB_{10} - TB_{11})^2 + C_0 + (C_3 + C_4W)\,(1 - \varepsilon) + (C_5 + C_6W)\,\Delta\varepsilon \quad (1)$$

where:

LST: Land Surface Temperature (K).
C_0–C_6: Coefficient values of SW.
TB_{10} & TB_{11}: Brightness Temperature (K) of Bands 10 and 11.
ε: Mean Land Surface Emissivity of the TIR Bands.
W: Atmospheric water vapour content (g/cm^2)
$\Delta\varepsilon$: Difference in Land Surface Emissivity.

TB is a parameter that indicates both the rate of energy that radiates at a certain wavelength and the surface brightness (or the intensity) of the source. The calibration process to convert the DN values (Q_{cal}) from each TIR band to TOA spectral radiance (L_λ) was conducted as follows:

$$L_\lambda = M_L\,Q_{cal} + A_L \quad (2)$$

where:

L_λ: TOA spectral radiance.
M_L: Band-specific multiplicative rescaling factor.
Q_{cal}: Quantized and calibrated standard product pixel values.
A_L: Band-specific additive rescaling factor.

Once calculated, L_λ was then converted to the At-Satellite Brightness Temperature according to Rajeshwari & Mani [23]. The surface emissivity (LSE) was calculated according to Rajeshwari & Mani by making use of the Fractional Vegetation Cover (FVC) [23–25]. The FVC describes the nature and the amount of the vegetation cover as well as the proportions of the vegetation on the ground surface and the visibility of ground to a sensor [26].

The LSE for Band 10 and Band 11 from the TIR were generated and the mean difference land surface emissivity was found [23]. Finally, using Equation (1) above, the LST (K) was obtained in raster format for the entire LANDSAT 8 scene.

2.2. Identification of UHI Zones

The results of the satellite data processing (Section 2.1) above show a spatially explicit detection of the urban heat distribution at chosen areas at the time of analysis. During the satellite overpass, a heat distribution pattern was observed with evident temperature gradients, especially pronounced away from the coastline and towards the inner parts of the island. Figure 1 shows how both the majority of the Northern and Southern Harbour Districts of the Maltese Islands show temperature hotspot areas that reached a surface temperature of around 39 °C within urban centres compared to cooler areas (around 30 °C) that were found especially close to the coastline. Cooler temperatures can be seen wherever green spaces are present such as the Marsa Golf course (Figure 1). What is also important to note is the subtle pattern of warmer temperatures that is evident over urban areas that emanate from the high-temperature foci. Most of these areas include historical urban areas.

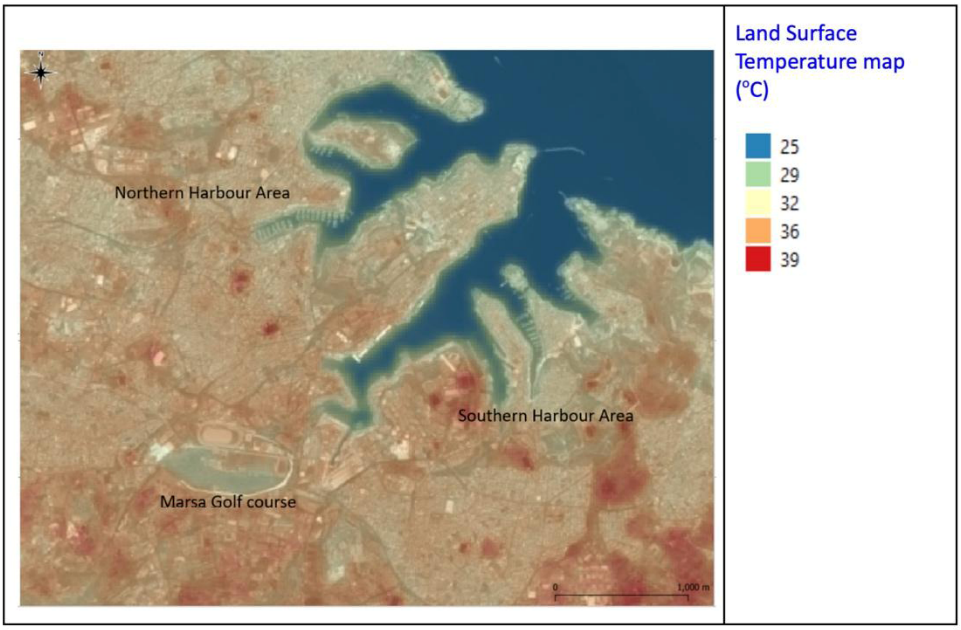

Figure 1. Spatial distribution of LST (°C) within the Northern and Southern Harbour Districts of the Maltese Islands estimated from LANDSAT 8 TIR that was acquired on 25 July 2020.

3. Historical Buildings under a Changing, Warmer Climate

A warming climate can cause significant impacts on buildings, especially historical buildings. The increasing temperatures can cause damage to already weakened buildings, as well as accelerate the deterioration of susceptible building materials [27]. Historical buildings which are particularly vulnerable include ones which have not been repaired, or where inappropriate materials/methods were used to repair/replace better suited original materials. Additionally, extreme weather events such as torrential flooding, which are becoming more frequent and intense in the Mediterranean [28] due to climate change, can cause catastrophic damage to traditional and historical buildings, as seen recently in the Umbria and Puglia regions of Italy. On the other hand, well-built and well-maintained stone structures usually fare much better. As such, it is crucial to implement appropriate measures to protect historical and traditional buildings which rapidly become vulnerable when neglected and ensure their preservation for future generations. At the same time, research is showing that certain traditional practices and materials, including those used in the construction of roofs that make up some vernacular and historic buildings, especially in the Mediterranean, can not only be sustainable in a changing climate, but can also potentially be adapted to dovetail with modern-day construction practices since they have the ability to reduce the energy needed to keep their interiors cooler [29]—research on this aspect continues.

The impact of a warming climate on residents in buildings can be significant. As temperatures rise, buildings may become uncomfortable or even unhealthy for occupants to spend any length of time in. In extreme cases, the increased heat can lead to heat stroke or other heat-related illnesses [30,31]—these effects have already been mentioned above in relation to the UHI. Those who dwell in buildings that are not designed with energy efficiency in mind, or in those not adapted to their environment (traditional buildings, on the other hand, are thus adapted), may be less equipped to handle extreme temperatures, thus leading to higher energy bills and greater carbon emissions. It is particularly important therefore to implement strategies that can mitigate the impact of a warming climate on occupants of historical and traditional buildings; this will include fully exploiting the potential of well-built traditional roofs and introducing carbon neutral measures.

To assess the local future exposure of traditional and historical buildings and their dwellers, we used the WorldClim CMIP6 bioclimatic variables derived by a total of eight different global climate models (BCC-CSM2-MR, CanESM5, CNRM-CM6-1, CNRM-ESM2-1, IPSL-CM6A-LR, MIROC6, MIROC-ES2L, and MRI-ESM2-0 [32]) to assess the future projections of temperature under climate change. For this study, the bioclimatic variables were derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6) data, which is a global climate model dataset that provides climate projections for the 21st century [33]. Only temperature-related measurements, such as mean temperature of the warmest and coldest quarters, were used for this study to create climate maps for the Maltese Islands.

Figures 2–4 show some of the projected CMIP6 temperature-related measures for the Maltese Islands under the chosen climate scenarios SSP1-*2.6* (best-case scenario), SSP2-*4.5*, SSP3-*7.0* and SSP5-*8.5* (worst-case scenario). In the SSP notation, the first number refers to the assumed shared socio-economic pathway (SSP), and the second one shown in italics refers to the approximate global effective radiative forcing (ERF) [34] in 2100. The optimistic scenario (SSP1-*2.6*) assumes a peak and decline of greenhouse gas (GHG) emissions by 2050 and shows a projected stabilisation of the mean and maximum ambient air temperature. On the other hand, SSP5-*8.5* assumes high economic growth, low population growth, and high fossil-fuel use. The difference between the two results based on SSP1-*2.6* and SSP5-*8.5* in terms of temperature (°C) is circa 4 °C (Figures 2 and 3). The higher rates of temperature increase are evident for all time periods under the remaining climate scenarios. Particularly evident are the temperature gradients of the profiles shown under SSP5-*8.5*. These values are to be treated as approximate projections, and one should not exclude that these will be accompanied with extreme values as part of the natural climatic variability of the Maltese Islands. The projected temperature profiles representing the mean ambient temperature of the coldest month continue to point to a warmer climate during the peak of the winter season, bordering a 2 °C difference between 2021 and 2100 for SSP5-*8.5*. These results therefore point to a potentially marked increase in the UHI that is only partly attributed due to a warming climate. The degree of UHI will of course be further augmented through continuous urban growth and further extension of the artificial land cover in Malta [35].

Using these variables, we are able to project how Malta will be impacted by climate change in the coming decades. This information can be very critical for policymakers engaged in urban planning, and building design, adaptation and conservation, as it can inform decisions about how to prepare for, and mitigate, the impacts of climate change. In conjunction with identifying the presence and number of traditional roofs in particular areas, something which our project also attained, and which will be explained below, the effects of traditional vs. modern roofs on the UHI in historic urban centres can be delineated—something which is planned for future work.

With regard to the current adaptation measures available for residents, domestic internal air conditioning is considered to be the primary mode. This implies a measure that is currently energy intensive. Now it is important to note that in Malta, the energy mix consists of natural gas (86%), oil and petroleum products (2%), and renewables, biofuels and biomass (12%) [36]. The electricity supply during 2021 consisted of net generation from power plants (71%), supply from net imports (19.1%) and renewable sources (9.9%) [37]. In 2021, the month of August (308.8 GWh) had the highest electricity demand with a share of 11.6%, followed by the month of July (287.6 GWh) having a share of 10.8% from the amount of electricity supplied during that year. A quick estimate based on the study made by

Damm et al. [13] would point to an additional increase of 573.9 MW and 548.6 MW for July and August, respectively, by mid-century, under the 'business as usual' climate scenario (RCP5-*8.5*) at the current rates of electricity consumption. It is important to note that between 2017–2021, the months of June till August always showed the highest electricity demand. Moreover, this increased electricity demand will be particularly felt within the thermal hotspots that have been identified under Section 2.2.

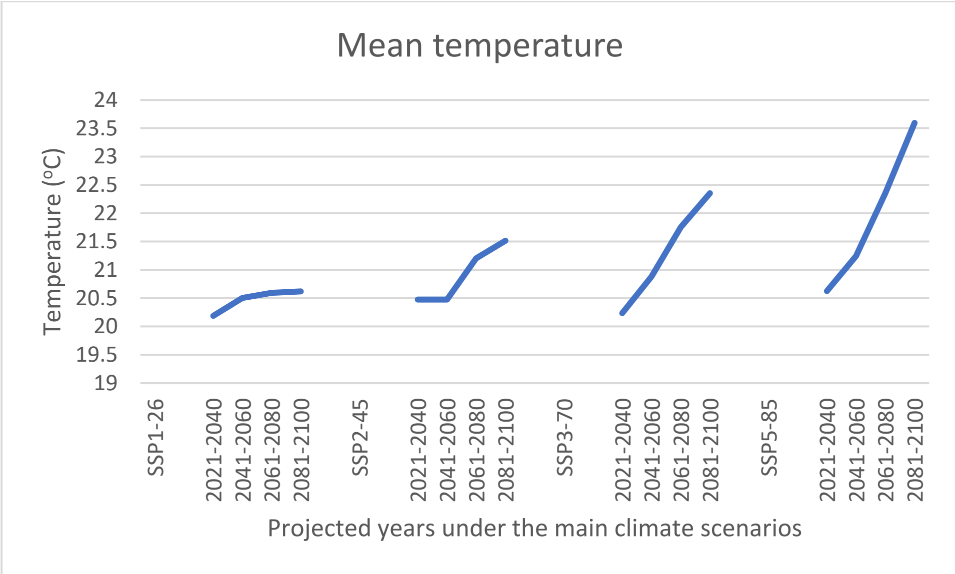

Figure 2. Local variation of the projected mean ambient air temperature under the four main scenarios SSP1-*2.6*, SSP2-*4.5*, SSP3-*7.0*, and SSP5-*8.5*, representing the mean values of a number of global climate models.

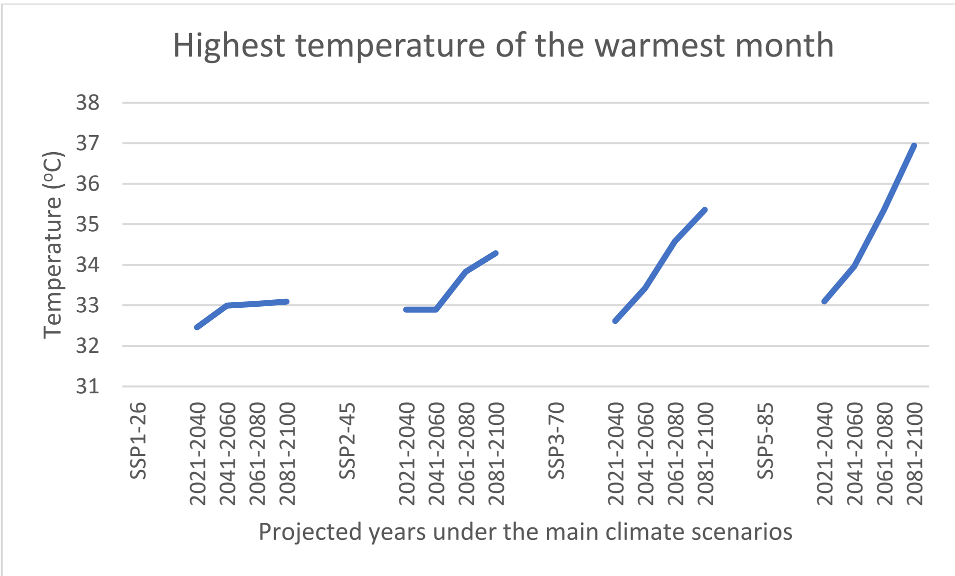

Figure 3. Local variation of the projected highest ambient air temperature of the warmest month under the four main scenarios SSP1-*2.6*, SSP2-*4.5*, SSP3-*7.0*, and SSP5-*8.5*, representing the mean values of a number of global climate models.

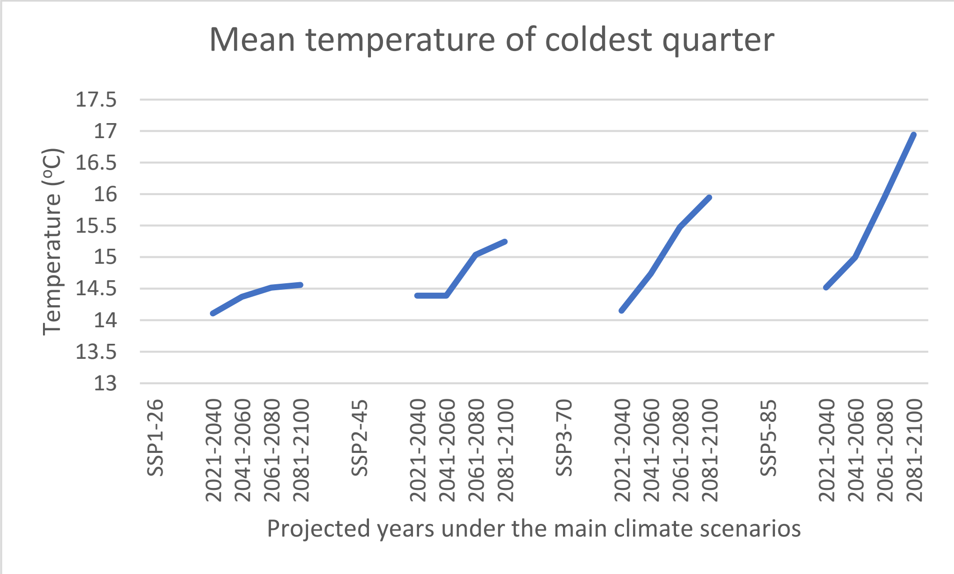

Figure 4. Local variation of the projected mean temperature of the coldest month under the four main scenarios SSP1-*2.6*, SSP2-*4.5*, SSP3-*7.0*, and SSP5-*8.5*, representing the mean values of a number of global climate models.

4. Traditional Buildings in the Mediterranean—Roofs with Layered Breathable Materials

Roofs are the building elements most exposed to the sun, representing up to 32% of the horizontal surfaces of built-up areas [38]. Preventing this greatly exposed part of the building from heating up, especially in the hotter months in warmer climates, is therefore desirable. In the Mediterranean, one way this has traditionally been addressed has been through the evaporative properties of the porous materials usually used for such roofs, a function which was discovered and exploited through indigenous knowledge when making use of locally available materials over the centuries; the advantages of having "cool roofs" is now being revived through modern day research [39–42]. Cool roof, green roof, and evaporative roof technologies are being researched [41,43–46] and developed worldwide in hot climates to limit the negative impact of unsuitable roofs on the Urban Heat Island, reduce energy consumption, and promote internal comfort levels in a sustainable manner.

It is important to note that the traditional building in the Mediterranean behaves as a "system", where, in summer, a relatively cool, ventilated internal environment is maintained, as already has been mentioned, by the presence of thick walls, high ceilings, shuttered/louvred windows together with courtyards and shaded terraces, typical all around the region [47], working hand-in-hand with the already mentioned layered roofs consisting for the most part of natural, porous and thus breathable materials [48]. In the Maltese Islands, the traditional *deffun* mortar roofs impart evaporative, passive cooling, transmitted to the upper floor of the building in the hot and humid Mediterranean climate. This is also a feature in many other Mediterranean countries. In the case of Malta, the *deffun* mortar is a traditional water-resistant layer placed over limestone slabs; it consists of hydrated lime, mixed with crushed pottery (*deffun*), over which water is sprinkled. This is then well compacted (manually in the past) and then covered with straw to prevent fast water evaporation and promote curing. It needs yearly maintenance after the hot summer months, before the first September rains.

The traditional construction of the roofing "system" [16] is in fact a "sandwich" layer as follows (Figure 5) from bottom to top: limestone slabs resting on stone arches or, later, beams made of timber or iron; limestone chippings mixed with stone dust and lime; and finally the surface layer of *deffun* mixed with lime. A similar type of construction is also present in traditional buildings in many of the neighbouring Mediterranean countries [49]. It is important to note here that the Mediterranean—and Malta is no exception—is characterised by flat roofs which not only have an important function of collecting the (often scarce) rainwater, channelling it to underground cisterns to be stored for use during the dry summer months, but also have a social function, where families and friends often gather together during the cooler summer evenings to entertain each other, and often eat together. This is very different from the usual function of roofs in colder climates. It must be pointed out here that *deffun* mortar roofs, being hand laid, are notoriously inhomogeneous—a feature of these roofs which will be taken up later, when discussing our results.

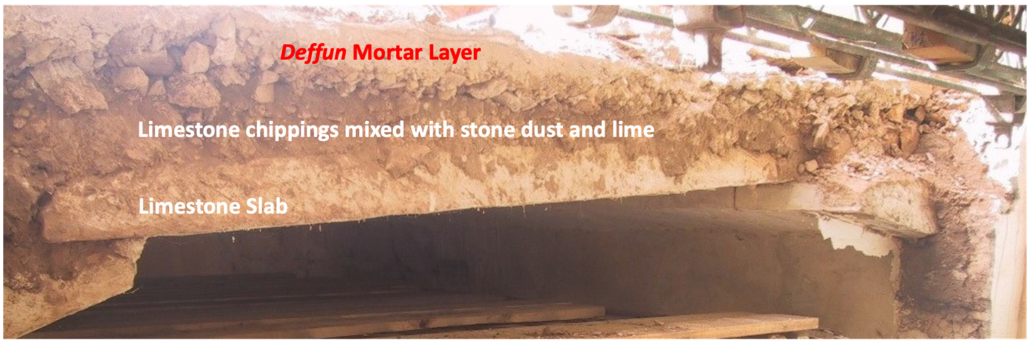

Figure 5. Cross-section of a traditional roof system in Malta, showing the three main layers, from bottom to top: limestone slab; limestone chippings mixed with stone dust and lime; and the surface layer of traditional lime-based *deffun* mortar.

Evaporative roofs work by utilising the intrinsic properties of porous materials to achieve cooling, a mechanism that effectively reduces the temperature of the roof surfaces and provides a cooler ambient temperature in the underlying rooms. Water from rainfall or high night-time humidity (dew) is stored within the pores of these materials; the absorbed water then evaporates during the day (especially on sunny days, which are not lacking in a Mediterranean climate) and therefore maintains a lower surface temperature through the latent heat of water evaporation [50]. In hot and dry climates where green roofs may sometimes pose problems [51,52], where there can be issues of planting a roof as in the case of historic buildings, and where roofs were traditionally of the evaporative type, this latter type of cooling can present an efficient, cost-effective and acceptable solution. Where natural wetting is lacking, this method of cooling can also be implemented through techniques such as promoting evaporation through spraying a fine mist of water, or even by utilising specialised materials like phase-change materials (PCM). "These materials absorb solar and infrared radiation and release a portion of the accrued thermal energy through convective and radiative processes into the atmosphere" [53,54]. Research on these roof types seeks to combine traditional building concepts with modern technologies for energy-efficient solutions, an area of research which should also be developed more widely for Mediterranean roofs.

The quantification of thermal and moisture-related parameters of Malta's traditional evaporative roofs, as well as those of other roof types (for comparison), has been explored very little and has never been studied using both direct and indirect data in combination. A notable exception is the MSc dissertation "An evaluation of the effects of contemporary interventions on the environmental behaviour of traditional local buildings: a study of unmodified and modified traditional lime-mortar-roofs (Malta)" carried out under the supervision of the lead author of the current paper [55].

This type of research is also mostly lacking in other Mediterranean countries, except for green roofs [56–59]. Evaporative roofs are the subject of this study by the authors of this paper, who are seeking to quantify the thermal (and eventually the moisture) behaviour of the roof "sandwich" layers, to link these factors to the often reported "cooling effect" felt in the upper floors of such buildings in the hottest of months, integrate them with the UHI effect, and establish how these effects can be modified in a changing climate. This paper reports the results of the first phase of this study, a pilot study concentrating on six roofs on historic buildings (a mix of traditional, modified and modern roofs) in Malta.

5. The Innovative Methodology to Study Traditional Roofs

Our novel methodology [29] to study the thermal behaviour of Mediterranean traditional evaporative roof types has, over the past three years, provided for the first time quantitative information on their thermal behaviour. The work being reported here spanned from February 2020 to September 2022; the results presented here focus on the data collected in the summer months of 2021, where the most comprehensive dataset exists, mostly due to the several interruptions brought about by the pandemic, and operational issues. Using a targeted blend of very fine resolution UAV (drone) thermal data, and in situ monitoring of heat (and moisture) fluxes above, underneath and through the roofing materials, the behaviour of these roofs is starting to be understood. Another important milestone in this research was when it was verified that the remote methods being proposed and used, i.e., satellite and UAV technology, can independently, or jointly, identify traditional, and modified traditional, roofs remotely—a discovery with far-reaching implications, as will be explained further on.

The Development of the Methodology

To develop this new methodology, a number of key steps [16] were followed. The steps included the selection of historical buildings in different traditional urban centres in Malta, buildings where the roofs represent traditional materials and technologies. It was decided to include in the pilot study both unmodified and modified traditional roofs; modified traditional roof types come in various forms, as this is often carried out on an ad hoc basis by the owner of the building—what was used in this project was a *deffun* mortar roof covered with a modern membrane, quite common in Malta. Baseline data were collected from these roofs, including information on each roof build-up, to identify and classify each roof type. Data from a modern roof were also collected for comparison; this consisted of a concrete roof, also covered with a modern membrane. For operational and logistic reasons, it was decided that the number of roofs to be studied would be 6 these being: one roof part traditional/part hybrid shown in Figure 6 (“hybrid” meaning a system of modern concrete resting on stone arches); two other traditional roofs; two traditional modified roofs; and one modern (concrete planks covered in carpet membrane) roof. The roofs were studied in two phases: phase 1 in 2021 and phase 2 in 2022. What was consistently kept constant was that all of these buildings were built in a “massive” way, i.e., with very thick stone walls, small apertures, and high ceilings, and where we were kept informed of movements/changes which happened within the underlying rooms during the study period. All of this enabled us to safely say that most of the differences registered were most probably due to the different roof types.

At this stage of the research, multispectral data started being collected using a combination of instruments including in situ air and surface temperature measurements (in close proximity to the roof and from the external surrounding environment); in situ (as well as air) temperature measurements were obtained from permanently placed sensors mounted directly above and below the roofs under study. In addition, high-resolution thermal and multispectral sensors (DJI Zenmuse XT2 and the Multispectral (RGB/NDVI) AGX710 Gimbal by Sentera) were mounted on a UAV; this allowed for monitoring of entire roofs at a sub-centimetre resolution. Climatic data from locally installed weather stations and national weather stations were incorporated and consolidated. Data from all three sources were then cross-referenced to assess the potential of the methodology.

The satellite being used was not useful for the study of roof behaviour but proved to be essential for the remote identification of roof types, as has already been mentioned. Knowing both individual roof behaviour and the identification and quantification of different roof types will be fundamental for understanding the UHI of historic cores, as will be expanded below. The satellite data consisted of Blue (B), Green (G), Red (R), Near

InfraRed (NIR) and Panchromatic images in GeoTIF format; no thermal data were available. On the other hand, the Sentinel-1 SAR (Synthetic Aperture Radar) data could not be used for the moisture characterization of the roofs since the lower resolution of the sensor (5 m $\times$ 20 m) does not allow isolating the target buildings from the surrounding ones; this made it impossible to compare satellite-based and ground-based moisture assessment.

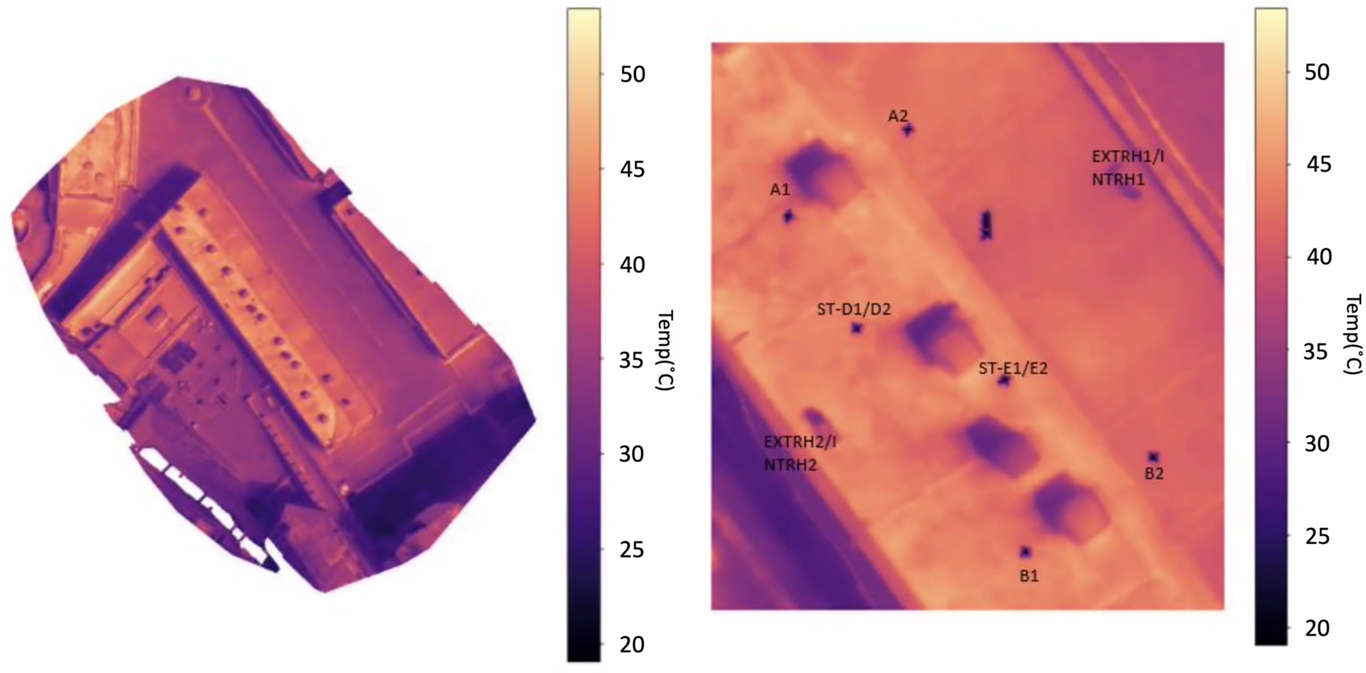

Figure 6. Drone-assisted infrared thermography images showing temperature scaling from hottest (light colour at 50 °C) to coldest (dark colour at 20 °C) of historical barracks (roof part traditional/part hybrid) located at Fort St. Angelo, August 2021 (internal technical report by subcontractors to the EO4HBCS project, SISTEMA [60]).

For the individual roof behaviour, the data from the six selected individual roofs were cross-referenced through multi-source pixel data fusion and correlation between the seasonal remotely sensed data and in situ measurements. Next, the detection and interpretation of trends were developed into quantifiable material properties such as potential dispersion and thermal insulation. Classification through radiometric comparisons was also carried out, giving a picture of the thermal behaviour of the different roof types.

Calculating the potential dispersion and thermal insulation allowed for the roofs' thermal behaviour to be defined (internal technical report by subcontractors to the EO4HBCS project, SISTEMA [60]). The potential dispersion (Equation (3) below) measures the heat flux between the external and internal environment through the roofs, and thus quantifies the degree of protection afforded by the roof materials and roof system to the internal environment from the external one.

$$\frac{|T_W - T_{out}|}{|T_{in} - T_{out}|} \tag{3}$$

where:

T_W is the air temperature from the weather station.
T_{out} is the air temperature from the external sensor at 25 cm above the roof.
T_{in} is the air temperature from the internal sensor at 25 cm below the roof.

On the other hand, heat transfer through the roofing materials is dominated by two main factors: absorption of solar radiation and infrared emission to the atmosphere. The relationship between the surface insulation assessment and the surface radiative assessment measures the thermal insulation of the material (Equation (4)):

$$\frac{|T_s - T_{ss}|}{|T_d - T_s|} \quad (4)$$

where:

T_s is the roof surface temperature from the in situ sensor.
T_{ss} is the roof sub-surface temperature from the in situ sensor at a 6cm depth.
T_d is the roof surface temperature as measured by the high-resolution thermal sensor mounted on the UAV.

For our purposes, only the surface radiative assessment was found to be useful as shall be explained in the next section; here information on the heat transmission and hence the materials' capacity to achieve insulation was successfully deduced as per Figure 6 below.

It is important to note that, at this stage, studies of moisture behaviour have so far been less successful. A trial to correlate co-temporal temperature and humidity data against the in situ measurements by using freely available Copernicus satellite data through Sentinel-1 (SAR) was made; however, its 10 m spatial resolution was found to be inadequate for monitoring roofs in dense urban areas in the Maltese Islands, in particular for the characteristic small roofs under study. Roof areas in Malta range from 12 m^2 for typical traditional roofs to a maximum of ca. 300 m^2. As there are already some data from laboratory testing for moisture-related properties of the roofing material types [55], it is planned that this area of research will continue to be developed, as well as seeking out better resolution satellite data to complement these data.

6. Results

This innovative study has given two broad outcomes: that the methodology to combine UAV and in situ data to understand the thermal behaviour of traditional (and other) roofs was successful; and the use of satellite data to identify (and quantify) traditional and modified traditional roofs was also successful. First, the behaviour of traditional roofs will be explained, showing how linking both identification and behaviour can provide valuable information which can be integrated with UHI data to help adaptation in a changing climate will be discussed later.

Traditional roof behaviour: Overall, traditional roofs gave the best compromise between potential dispersion and insulation (the results of the hottest summer months of June to August 2021 are being shown here, where the highest temperature registered for 2021 was 41.5 °C in June and the highest mean temperature was of 33.8 °C in August [61]—Figure 7), i.e., these roof types provided the most protection of the underlying floors from the hot external environment. For potential dispersion (i.e., heat flux through the roofs), traditional roofs performed better compared to the other roof types studied. It must be pointed out that modern roof data, on the other hand, indicated a good performance for potential dispersion, but the results were considered anomalous due to the noticeable leaking of air-conditioned air from an adjacent area—all other roofs considered were well away from any air-conditioned areas.

When analysing data for thermal insulation, the surface assessment ($|T_s - T_{ss}|$) was found to be dependent on the location of the in situ sensors and uncorrelated with seasonal conditions, making it not useful for the purpose of this study. On the other hand, the surface radiative assessment ($|T_d - T_s|$) proved to be more useful because it is able to characterise the emissivity capabilities of the roofs (wherein transmission is low if the overall emission is high—see Figure 6). Here, traditional roofs showed an overall lower heat transmission translating into higher insulation. Only entries with $T_s > 30$ °C were considered to take into account the hottest conditions (Figure 8).

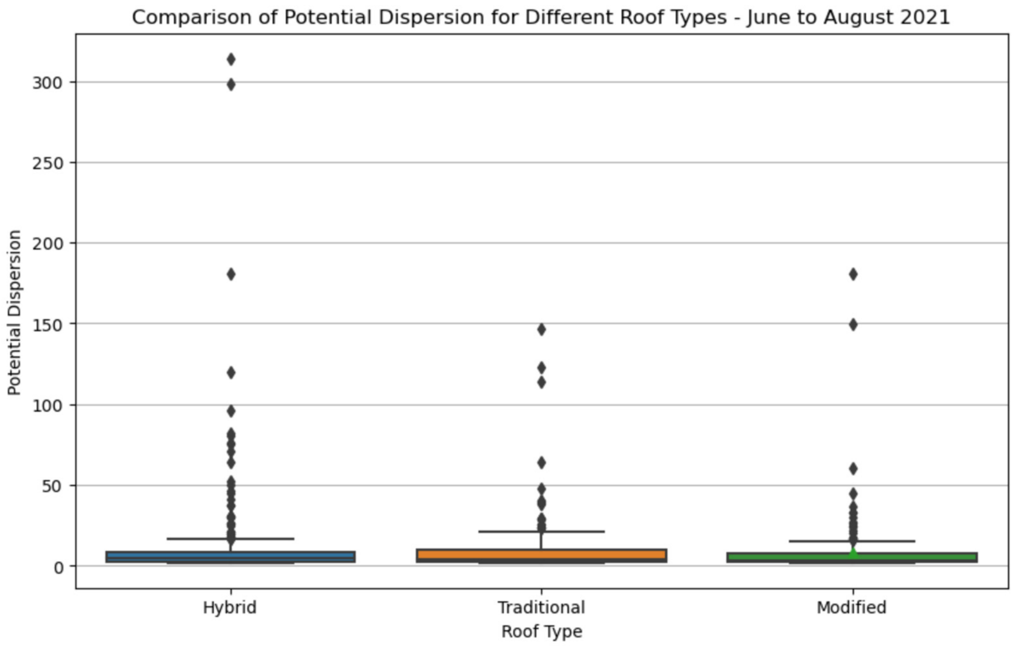

Figure 7. Potential dispersion results show a better overall performance for traditional roofs in the hottest summer months of June, July and August 2021.

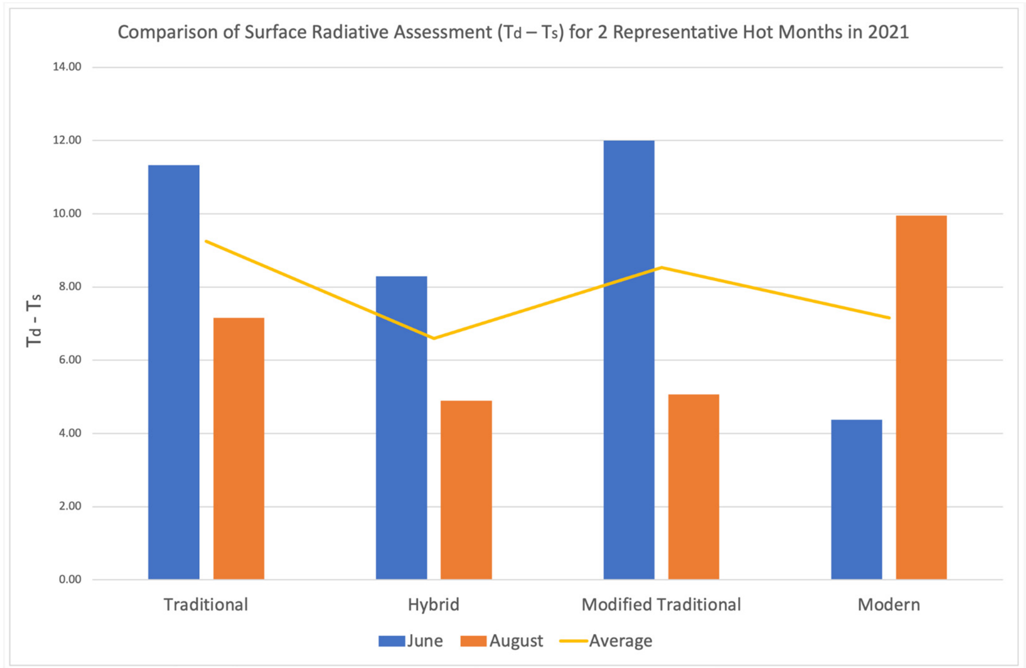

Figure 8. Comparison of surface radiative assessment for two representative hot months in the summer of 2021 showing a higher average for traditional roofs. NB High emission = low transmission.

Although the satellite images were not found to be useful to characterise roof behaviour, they proved useful to identify roof types in view of their reflectance properties at several wavebands that were detectable by the satellite sensors used for this study. Thus, remote methods (satellite and UAV) can easily, and in a cost-effective manner, quantify the number of traditional, and traditional modified, roofs (as shown by the case study of Malta) with implications towards addressing the UHI in a changing climate, as will also be explained below. Costs will need to be considered when commercial satellites are used.

7. Discussion and Challenges

Our research has thus confirmed the hypothesis, at least for our initial pilot project, that traditional *deffun* mortar roofs in Malta provide insulation against the external environment, as regards thermal properties, and in this respect, perform better than modified traditional or hybrid roofs. Higher insulating properties and a lower heat flux through a roof mean that the internal environment is more "sheltered" from the external heat, thus potentially reducing the need for active cooling mechanisms (e.g., air conditioning), which themselves can have an adverse impact on the surrounding UHI. This must, however, be considered, as already mentioned, as particularly effective when jointly working with the rest of the traditional building features (at least in the Mediterranean). It must, however, be emphasised (as will be mentioned in the section on Future Work (below) that these studies must be expanded to include more of these roof types, over a larger time span, in order to be able to have larger datasets to consider.

It must also be remembered that, whereas there is a contribution to heating (and cooling) by the roof itself, this is only one part of a system of how these buildings were planned and built in the past. It needs to be also emphasised once again that there is also an even bigger system—the historic centre itself—within which these buildings function which can greatly impinge on their ability to provide passive cooling.

As briefly already mentioned, this study has also found that it is possible to identify different roof types using remote technologies, in particular satellite data. This, together with our other overarching result, will prove to be highly beneficial in the understanding of not only how individual traditional and historic buildings can passively help keep the upper floors of such buildings cooler in summer, but can also contribute to lowering the UHI of historic urban centres which contain clusters of such buildings.

This traditional knowledge, known and utilised efficiently for centuries all around the Mediterranean to mitigate the torrid summer heat, has now been quantified, at least in part (for Malta's *deffun* mortar roofs), using the most modern scientific data collection. The information now available needs to continue to be augmented, not only for roofs, and different roof types across the Mediterranean, but also for the whole of the traditional buildings themselves, where walls and ceiling heights, basements and courtyards, apertures and their fixtures, have all worked together to produce as cool an internal environment as possible in a passive manner for centuries—this is going to become even more important in a warming climate where carbon emissions need to be reduced. The effects of such buildings, and their street layout, must be known and harnessed in order to work towards a zero-carbon future in historic urban centres.

A proven methodology, based on a pilot study now exists which can work towards improving the energy efficiency of historical and other traditional buildings, with a particular reference to the role which traditional roofs, and their passive cooling effect have—but clear challenges arise. One is related to the precise knowledge of the build-up (layers and materials) and also the state of preservation of traditional roofs. Here, the collaboration of scientists, engineers, architects, owners of traditional buildings, and heritage organisations is imperative, to start to create databases with such information [62], linked to GIS systems. One very good example of this, and which can be built on, is the MEDA initiative with the CORPUS project [62]—this was a partnership among Mediterranean countries to survey traditional heritage, including roof types (but not only) which led to the production of several atlases freely available on the web (now no longer available, a recent search has shown).

Resulting information should then be made freely available, even with the potential of professionals from various fields adding to the data. This will help not only in the preservation and management of such a resource—for now, these traditional roofs must be considered as a resource in the struggle to attain a carbon neutral future in historic city, town and village cores—but also as a source of information for researchers who wish to continue to study and improve on the behaviour of such roofs. The ultimate goal should in fact be to see whether such roofs can be reinstated where they have been lost, or even if an "improved traditional roof" can be suitable for more modern buildings in the same old city centres.

Another challenge is understanding the seasonal thermal and moisture properties of these traditional roofs, which have been seldom studied for lime-based, flat Mediterranean roofs and, for the most part, also for other types of flat roofs in the Mediterranean. Here, in situ studies, laboratory research on replicas, modelling of behaviour and also UAV and satellite data need to come together, working also with computer programmes such as HBIM (Heritage Building Information Modelling) and WUFI [63], to be able to fully understand, and even visualise, the daily and seasonal behaviour of different Mediterranean flat-roof types and relate this directly to other data from the buildings themselves, to give a complete picture of building behaviour.

Linked to the above, the region can become a test bed where the traditional and the innovative come together to promote passive cooling through the retention/reinstatement/improvement of traditional roofs in a changing climate, when and where a carbon neutral future in old cities can become a reality.

We think that the preservation and good use of traditional roofs found in historical cities can play a pivotal role in minimising the energy required to cool historic buildings, ultimately contributing to the pursuit of carbon neutrality in the future. By reducing the demand for artificial cooling, especially when ambient temperatures are expected to increase markedly in the coming decades, traditional roofs can be expected to alleviate the strain on the electrical grid, thereby reducing carbon emissions associated with energy production. The integration of these sustainable solutions not only provides immediate benefits for historic buildings but also enhances the overall resilience of historical cities.

Strategies such as policy incentives and regulations, case studies and success stories, and public awareness campaigns can help policy makers and politicians gain a comprehensive understanding of the benefits of using traditional building stock for achieving carbon neutrality. Such knowledge can lead to the development of effective policies and initiatives to promote the preservation, maintenance, renovation and sustainable use of existing historical buildings and their original roofing materials and building techniques.

8. Conclusions and Future Research

The proven methodology to evaluate the energy efficiency of historical, traditional roof structures, particularly by capitalizing on the passive cooling benefits of Malta's traditional roofs, offers a promising opportunity to contribute to a carbon-neutral future in historic city centres. However, this endeavour is not without its obstacles, necessitating efforts among scientists, engineers, architects, residents and heritage organisations. The Mediterranean offers an ideal testbed where traditional and innovative approaches converge to promote passive cooling through the retention, restoration and enhancement of traditional roofs. We are hopeful that this transformative process enables historic cities to lead the way towards a carbon-neutral future, embracing sustainability as a core principle.

To successfully transition towards carbon neutrality, various strategies must be adopted. Policy incentives and regulations provide the necessary framework to encourage the utilization of traditional building stock, also for energy-efficient purposes. Demonstrating success stories and case studies helps policymakers and politicians better grasp the advantages of adopting traditional building techniques. Additionally, public awareness campaigns play a vital role in engaging communities, fostering a sense of ownership and responsibility for the preservation and sustainable use of historical buildings and their original roofing materials.

This research, and its results, have thus allowed for the elucidation of a number of important take-home messages:

- Higher insulation and a lower heat flux through a roof mean that the internal environment is more "sheltered" from the external heat, thus potentially reducing the need for active cooling mechanisms (e.g., air conditioning), which themselves can have an adverse impact on the surrounding UHI. These studies need to proceed in the following ways:

- Continue in the Maltese Islands by increasing the number of roofs, and different roof types (e.g., traditional roofs modified in different ways) studied in this way to obtain larger datasets to base wider conclusions on;
- Continue and extend to the wider Mediterranean where variations on the *deffun* mortar type of roof are widely present.

- Studying more traditional and modified traditional roofs in the Maltese Islands (to compare with modern roofs) will expand this pilot project which was carried out to create a proof-of-concept system to verify whether or not the performance of different roof systems can be compared and/or quantified using the presented innovative methodology. The repeatability and expansion of this work on a larger sample of the various roof types would further confirm and corroborate these preliminary results.
- By extending this innovative methodology to other similar traditional roofs in the Mediterranean, to study the behaviour of similar and complementary roof types, their behaviour can also be quantified, their energy efficiency improved, and their passive cooling properties promoted, whilst also preserving their historical and cultural value. The restoration and preservation of such buildings can thus lead to one sustainable solution for future climatic issues particularly on a larger scale when applied to historic centres where traditional buildings occur in high concentrations.
- As studies on traditional roof behaviour and performance intensify, including in situ measurements, laboratory simulations, modelling techniques, and combinations thereof become even more established as study methods for roof behaviour, the exploration and inclusion of remote techniques, including satellite data, also in synergy with UAV data and the more established methods, is needed now that a methodology and pilot project have shown that these can be complementary.
- The quantification and new understanding of the energy performance of traditional roofs in a representative Mediterranean country contributes towards other potential synergies in future research, for example, researching together evaporative-roof technology and cool-roof technology, and where the properties of traditional materials may therefore be combined with the application of, for example, a white or reflective roof coating that limits heat gain by imparting both a higher solar reflectance and a higher thermal emittance. Moreover, new insights into modern evaporative- roof technology such as the application of PCMs may be studied in conjunction with traditional roofs in order to enhance the evaporative mechanism using a low-impact and synergistic solution within the solar energy sector.
- Climate change is becoming more apparent, and here the ability of traditional roofs to passively decrease heat gain, and therefore increase occupant comfort, becomes crucial. The correlation between roof behaviour, building maintenance, and occupant well-being need to be fully explored, with an emphasis on passive, sustainable, energy-efficient, and environmentally friendly approaches.
- Traditional roofs are but one of the many variables contributing to the UHI in old urban centres. Once their identification and quantification, and their effect on the internal environment can be estimated, their combined effect with the rest of the traditional building features listed above may be further explored and modelled for a more comprehensive quantification of the effect (positive or otherwise) on traditional buildings of climate change, and the joint effect of traditional buildings on the UHI, even in a warming climate, can be addressed.
- Radiometric comparisons gave positive results in terms of identification of traditional (and modified) roofs which can be very useful to policy makers and future research where traditional roofs over a large area need to be easily identified. The new methodology also has the potential to be tried on a wider regional (Mediterranean) scale where it comes to remotely identifying different roof types—quantifying this parame-

ter, which is usually difficult to measure, can lead to a rediscovered opportunity for a carbon neutral future in historic urban centres in the Mediterranean.

Other future work for both roof identification and behaviour can include the following:

- Using up-and-coming satellite imagery with better resolution. While KOMPSAT 3 satellite data series continue to rank among the best datasets in the world, upcoming satellite imagery technology is set to revolutionise the way we gather information about land cover in view of their increased spectral and spatial resolution. The improved resolution of new and upcoming satellites (e.g., SDGSAT-1 and SatVu) means that we will be able to see finer details of the various roof types. When this is blended with improved spectral information (such as accurate and subtle surface-temperature variations, moisture levels and other environmental factors), then space technology will offer a much-improved way to identify and characterise the properties of traditional roofs.
- Using AI and deep learning to mine large datasets. AI algorithms can be trained automatically to identify and classify different types of rooftops based on surface patterns and properties as derived by improved satellite and drone sensing technology. By leveraging AI and deep learning techniques, we can analyse massive datasets collected from satellites and in situ sensors and, in doing so, continue to improve the accuracy of the classification techniques obtained by this study.
- Developing methodology better, also to identify different roof types, in Malta and the wider Mediterranean. The harnessing of vast amounts of data collected by multiple, high-resolution overpasses of different satellites can open up new possibilities for improving the classification of different roof types based on their spectral signature. Very high-resolution, locational UAV data can sustain this process further by serving as validation data.
- The ultimate aim will be to work with stakeholders, policy makers and heritage authorities, as well as with environmental authorities, to promote the better care, maintenance and preservation of these traditional roofs in a changing climate. With the potential of developing the positive results of using radiometric comparison on satellite data to identify roof types over large areas as previously mentioned, it will be easier to work with decision makers to facilitate interventions (whether regulatory, preservation or otherwise) on traditional roofs, as well as to promote their retention or even reinstallation. In situ verification of roof types is time consuming, impractical and many times not possible. This identified possibility, however, would require further investigation and research through data science techniques such as machine learning in order to exploit the full potential of the full satellite dataset.
- Laboratory work to see if these traditional roof systems can be "improved". Laboratory work can isolate and quantify the effect of traditional roofs on the underlying environment from the rest of the building features; in controlled environments, this insight would then allow tailor-made testing on what material and/or application and/or build-up modifications could enhance their performance. This knowledge, in turn, could allow for the application of good traditional practices to modern and modified systems.

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Abbreviations

AGX710	Sentera Multispectral Sensor for UAV
$B_i(T_i)$	Brightness Temperature
CMIP6	Coupled Model Intercomparison Project 6
DN Values	Digital Number values
ERF	Effective Radiative Forcing
FVC	Fractional Vegetation Cover
GeoTIF	Geo-Tagged Image Format
GHG	Greenhouse Gas
HBIM	Heritage Building Information Modelling
L1T	Level-1 Data
LANDSAT	NASA/USGS Landsat Program
LSE	Land Surface Emissivity
LST	Land Surface Temperature
NDVI	Normalized Difference Vegetation Index
OLI	Optical Land Imager
PCM	Phase Change Materials
RGB	Red-Green-Blue satellite waveband
SSPX-X.X	Shared Socio-Economic Pathway
TB	Temperature Brightness
TIR/S	Thermal Infrared/Sensor
TOA	Top of the Atmosphere
UAV	Unmanned Aerial Vehicle
UHI	Urban Heat Island
USGS	United States Geological Survey

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