Chapter 24
Cool Materials for Passive Cooling in Buildings

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24.1 Introduction

At the current urbanization stage, over 60% of the world population will live in cities by 2030, and more than 68% by 2050 (European Commission 2018). This remarkable trend deserves proper attention, especially since urban sprawl is one of the major causes of harmful environmental issues with serious repercussions on human health (Vardoulakis et al. 2015). Urban overheating, among them, is regarded as one of the most important (Chapman et al. 2017; Susan 2007). Its detrimental escalation has led to the definition of a unique phenomenon: the urban heat island (UHI), which consists of a local temperature increment affecting metropolitan areas with respect to their rural surroundings (Kolokotroni and Giridharan 2008), with the maximum temperatures experienced within the densest city blocks (Xu et al. 2018). Further intensifying the risk is the synergistic interaction between UHIs and regional heat waves (Li and Bou-Zeid 2013), which was shown to produce repercussions that might exceed a simple superposition of the two hazards (Zhao et al. 2018). Beyond the well-known environmental and health-related impacts, UHIs are also involved in the exacerbation of building cooling loads (Santamouris 2014) and in the consequent increase in peak electricity demand (Ihara et al. 2008).

As a result, in recent years, several research contributions have been developing and investigating UHI mitigation techniques with the aim of tackling local and global overheating. In particular, using of cool materials was found to be a highly effective solution for reducing both surface and air temperature peaks in the urban environment during summer (Li et al. 2014). In this chapter, we firstly present and

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classify these materials, together with the methods that are generally used for their characterization, with special focus on their numerical assessment via several computational methods. At a later stage we discuss the impact of cool materials on building energy consumption and we examine their most common shortcomings. Finally, the most promising future trends and the potential advances in this technology are presented.

24.2 Basics of Cool Material Physical Behaviour

24.2.1 Generalities

Cool materials represent a cost-effective passive technique that contributes to achieving lower cooling energy loads by reducing surface and air temperatures in the built environment, particularly in the building fabric. By definition cool materials are characterized by (1) high solar reflectance (SR) and (2) high infrared emittance (ε).

The former property estimates the ability of a surface to reflect the incoming solar radiation. It is measured on a scale from 0 to 1, and its definition is carried out considering the hemispherical radiation and integrating over the complete solar spectrum. Infrared emittance, on the other hand, measures the capability of a surface to release heat upon absorbing it from the surrounding environment. It is also measured on a scale from 0 to 1 and quantifies how well a selected surface radiates energy compared to a black body maintained at the same temperature. Solar reflectance and infrared emittance are combined in a secondary indicator largely used in building engineering: the solar reflectance index (SRI) (ASTM E1980-11 2019). The SRI, which also takes into account convective cooling effects, is defined from 0, i.e. a standard black surface (SR = 5%, ε = 90%), to 1, i.e. standard white surface (SR = 80%, ε = 90%).

Surfaces combining high solar reflectance and high infrared emittance can reflect most of the incoming solar radiation and, at the same time, re-emit a large portion of the absorbed one, albeit small. Therefore, they will remain cooler and maintain a lower surface temperature if compared to similar surfaces with lower SR and ε values. This unique behaviour can be particularly favourable in building applications, where the amount of heat transferred through the building envelop is directly proportional to the indoor/outdoor surface temperature difference. Thereon, the use of cool materials in buildings allows to reduce the amount of heat transferred from the outdoor to the indoor, above all in case of extreme solar heat gains.

24.2.2 Thermal Performance of Cool Materials

As previously said, cool surfaces show lower surface temperatures compared to non-cool solutions. In fact, the high solar reflectance and high thermal emittance allow them to absorb less energy from the sun, and release more ambient heat. The general law representing all the main heat-exchanging phenomena, apart from the latent contributions, taking place on a flat surface is described in the following (see Fig. 24.1):

$$\left(1-\mathrm{SR}\right)I=\varepsilon\sigma\left(T_{\mathrm{s}}^{4}-T_{\mathrm{sky}}^{4}\right)+h_{\mathrm{c}}\left(T_{\mathrm{s}}-T_{\mathrm{air}}\right)-\lambda\frac{dT}{dx} \tag{24.1}$$

where SR is the solar reflectance of the surface (−); I is the insolation (W/m^2); ε is the thermal emittance (−); σ is the Stefan–Boltzmann constant ($\sigma = 56.685 \times 10^{-8}$ W/m^2 K^4); T_s, T_{sky} and T_{air} are the surface, sky and air temperatures (K); h_c is the convection coefficient (W/m^2 K); λ is the thermal conductivity of the surface (W/m K); and dT/dx is the temperature gradient (in the x direction).

As it can be seen, the first term, which represents the net radiation absorbed by the surface, is directly proportional to the solar reflectance, while the term with the highest dependence on the temperature difference on the right-hand side of Eq. (24.1) is directly proportional to the thermal emittance. These two terms play the major role in the final thermal balance of a highly insulated flat surface and so they are the main factors influencing the thermal performance of a roof or more generally of a surface during the day and the night, respectively. Whatever the orientation of a surface, sky view factors (SVFs) should always be considered and used to split the amount of insolation to be considered. In radiative heat transfer, a view factor $F_{A\rightarrow B}$ is generally defined as the proportion of the radiation which leaves surface A that strikes surface B. Similarly, the sky view factor is a measure of the openness of a surface: a SVF equal to 1 means an unobstructed while a SVF of 0 means a completely obstructed view of the sky. For a given built form, the sky view factor at ground level decreases built density and height.

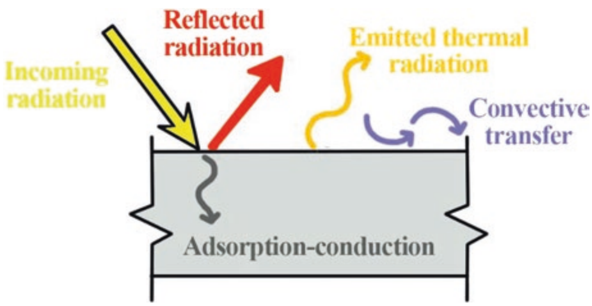

Fig. 24.1 Scheme of the energy balance of a flat surface exposed to solar radiation

24.2.3 Classification of Cool Materials

Cool materials are typically divided based on their application, or their visible reflectance. In the first case, we talk about cool materials for roofs, and cool materials for roads and paving solutions (Santamouris et al. 2011). In the second, we define white or light-coloured cool materials, and coloured cool materials (Synnefa and Santamouris 2016). Material science, however, has opened the way to a huge number of innovative applications that are nowadays difficult to classify following such schematizations. All this considered, in this chapter we present a new classification encompassing all the solutions explored by the present research panorama on cool materials. As shown in Fig. 24.2, six different groups of materials can roughly be defined and presented: high-reflective, cool-coloured, retroreflective, photoluminescent, thermochromic and recycled/reused materials.

The knowledge that light-coloured materials allow to maintain cooler surface temperatures is deeply rooted in the past; however, from a scientific point of view, one of the first contributions to analyse such an effect was the study by Givoni and Hoffiman (1968) comparing white and grey-coloured building facades under unventilated conditions. This work paved the way for developing the first group of cool materials, i.e. the high-reflective materials.

Inspired by vernacular architectures in Mediterranean and other hot climates, said materials traditionally focused the efforts on improving the overall visible reflectance of a surface. Since 1968, several research teams all around the world developed different kinds of high-reflective solutions for the built environment. The

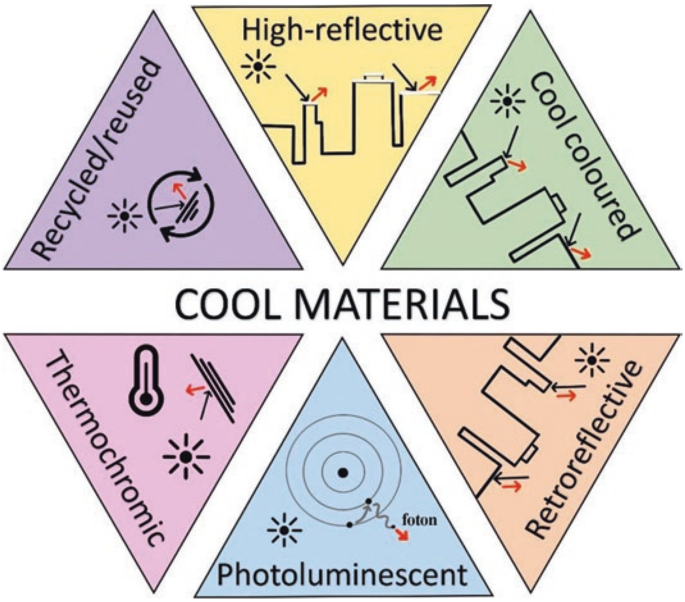

Fig. 24.2 Classification of cool materials, according to the latest research developments

main applications regarded high-reflective roofs (Akbari et al. 1998; Akridge 1998; Pisello and Cotana 2014), paints and coatings for walls (Revel et al. 2014; Zinzi 2016), paving (Doulos et al. 2004; Santamouris et al. 2012), shading devices (Pisello 2015), elastomeric membranes (Fabiani et al. 2020a; Pisello et al. 2016a, b, 2017) and natural cool materials (Castaldo et al. 2015; Pisello et al. 2014). Most of these solutions are based on two white pigments with high reflectance in the whole visible and near-infrared (Vis–NIR) range, i.e. rutile (the most common polymorph of titanium dioxide) and calcite (the most stable polymorph of calcium carbonate) (Pisello et al. 2016c).

The use of white building components is often associated to important limitations in terms of architectural integration, long-term deterioration and glare penalty. All this considered, several scientists struggled for developing cool-coloured alternatives to integrate in more acceptable applications for the built environment. Cool-coloured materials can highly reflect in the near-infrared part of the solar spectrum while maintaining the same visual aspect of their conventional coloured counterparts. A general, initial investigation about these dyes was carried out by Levinson et al. (2005) in their study identifying different pigments capable to absorb less than 10% of the solar energy in the NIR. Several researches followed, producing and investigating the thermal energy performance of coatings for roofs (Levinson et al. 2007; Synnefa et al. 2007), shading devices (Zinzi et al. 2012) and paving systems (Synnefa et al. 2011; Xie et al. 2019). The use of cool-coloured solutions is particularly important for the energy retrofit of historic buildings. In this view, Rosso et al. (2017a, b), among others, focused their attention on the integration of cool-coloured pigments in cement pastes and concretes, in the attempt of identifying the perfect compromise between innovation and heritage for tackling surface overheating.

Both white and coloured cool materials are produced and investigated as surfaces following the Lambertian reflection law. As a consequence, each of these solutions shows an isotropic solar reflectance value, although variable within the solar spectrum. Retroreflective (RR) materials, on the other hand, are a class of cool applications equipped with the skill of reflecting the incident solar radiation directly back to its source, and only on that direction (Fig. 24.3) (Hernández-Pérez et al. 2017; Qin et al. 2016). Opposed to the previously described diffuse solutions, retroreflective materials are particularly effective when applied on vertical walls, in densely built urban areas where sharp incident angles between the solar radiation and the surface allow to maximize their beneficial effect (Rossi et al. 2015a, 2016).

An additional class of cool materials, i.e. the photoluminescent one, makes use of photoluminescence together with simple reflection to improve its resilience to surface overheating (Berdahl et al. 2016; Levinson et al. 2017). Photoluminescence is one of the many forms of luminescence in nature and refers to the physical phenomenon by which an electron emits energy in the form of light as a consequence of a relaxation process. The extra energy radiated in this way was originally transferred to the electron by a photon, causing its migration to a higher energy level in the atom. Therefore, the integration of photoluminescent materials in urban components could produce a surface with excellent effective solar absorption capacity, given its potential to reflect and dissipate heat by means of both common thermal

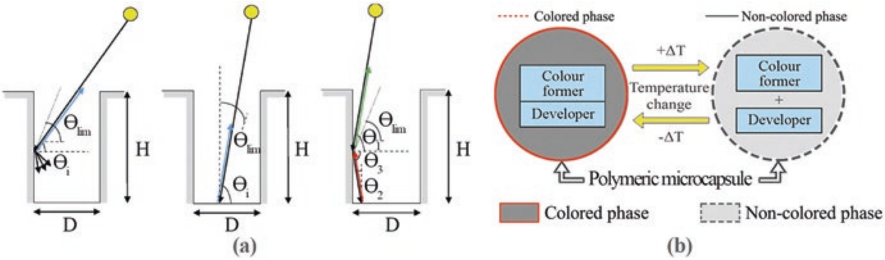

Fig. 24.3 Cooling mechanism of (**a**) retroreflective (RR) and (**b**) thermochromic materials. (Rossi et al. 2015b; Fabiani et al. 2020b, elaboration with permission from Elsevier Ltd.)

emittance and unique photoluminescent phenomenon. In this context, Berdahl et al. (2016) focused their attention on the unique deep red and near-infrared efficient emissivity of ruby (aluminium oxide doped with chromium) and proposed it as a robust fluorescent solution for cooling applications. They also suggested ND-doped YAG, cadmium pigments and their alloys as remarkable fluorescence examples. Over and above, the introduction of phosphorescent materials, with their capability to re-emit light even up to 104 s later, could represent a promising solution, particularly in road applications, given their potential to be integrated in existing artificial lighting systems for electricity consumption reduction.

All types of cool materials presented above share a detrimental and yet inescapable setback, that is, increased heating energy demand during winter. Building on this, a further class of cool materials was introduced and is lately being investigated by the scientific community: thermochromics, i.e. advanced materials capable of reversibly tuning their colour from darker to lighter tones as a function of the local temperature boundary conditions (Fabiani et al. 2019; Garshasbi and Santamouris 2019). Thermochromic solutions have been mostly integrated in advanced coatings (Fabiani et al. 2020b; Yiping et al. 2002), mortars (Perez et al. 2018) and roof (Hu and Yu 2019) applications. They show an improved thermal energy performance that allows to obtain better indoor thermal comfort conditions throughout the year, although they also show non-negligible photodegradation occurrences (Karlessi et al. 2009).

The last kind of cool materials is composed of all those applications aiming to reduce the amount of embodied energy stored in their production process. The group of recycled/reused materials would probably be better defined as a cluster, rather than a class, since it arranges together all those solutions that, although integrating different cooling mechanisms, are born under an eco-friendly approach. As an example, Zinzi and Fasano (2009) used milk and vinegar to produce a cool blend with impressive cooling properties. Ferrari et al. (2013) manufactured a high-albedo engobe by using recycled glass and alumina on a ceramic support, while Libbra et al. (2011) explored the cooling potential of cool-coloured tile coverings as a substitution of conventional roof tiles in historical centres with propitious results.

24.3 Experimental Investigation of Cool Materials

In this section, references, standards and experimental procedures for measuring the main properties of a cool material are firstly dealt with, particularly focusing on recent research developments in this field. As previously discussed, several experimental in-lab and in-field studies have abundantly demonstrated the potential of high-albedo solutions in buildings in terms of energy saving for cooling, indoor comfort conditions and surface thermal characteristics. For this reason, many governmental authorities and technical organizations have supported the elaboration of new standards, i.e. ASHRAE, ASTM and ISO standards, for encouraging the implementation of highly reflective applications in the built environment (Akbari et al. 2001). The progress achieved in these years was partly determined by the work of important clusters such as the Heat Island Group from the Lawrence Berkeley National Laboratory, the Cool Roof Rating Council (CRRC) and the European Cool Roofs Council (EU-CRC), linking public and private institutions in order to control material quality and provide reliable measurement procedures. The following subsections will (1) describe the most important experimental procedures for quantifying solar reflectance and thermal emittance of cool materials (according to specific reference standard) and (2) present the main results of advanced numerical studies assessing the potential of cool solution at large scale.

24.3.1 Solar Reflectance Analysis

Solar reflectance values can be measured by using (1) a spectrophotometer with an integrating sphere, (2) a reflectometer and (3) a pyranometer.

SR measurements carried out using a spectrophotometer with an integrating sphere follow the ASTM E903-12 standard (2012). The use of the integrating sphere allows to obtain the spectral near-normal hemispherical reflectance in the range of 250–2500 nm. The final SR values are then calculated through a weighted average value with respect to the standard solar spectral irradiance (ASTM G173-03 2012). The main components of a spectrophotometer are the light source (covering the range of 250–2500 nm), the diffraction grating and mirrors, and the integrating sphere, which is internally coated with a highly reflective finish. Such an experimental equipment allows to measure solar reflectance and transmittance of a planar sample with respect to a reference (standard white of known reflectance) as a function of the wavelength (λ). Additionally, it can also be used to calculate the solar absorbance of the investigated surface.

The measurement procedure to be followed when using a reflectometer is reported in ASTM C1549-16 (2016). This instrument is used for field measurements and it can measure the reflectance by varying the air mass setup. The calibration procedure of a reflectometer is carried out using a blackbody cavity (reference for null reflectance), and a surface of known reflectance, previously characterized through solar spectrophotometer according to ASTM E903-12. This measurement method is particularly suitable for characterizing reflectance properties of opaque and homogeneous materials through fast and relatively simple field measurements (Fig. 24.4).

The last kind of in-field measurement procedure for measuring the reflectance of a surface makes use of a pyranometer and follows ASTM E1918-16 standard (2016). A pyranometer can be used to measure clear sky global solar reflectance of a horizontal or low-sloped surface when the sun angle to the normal surface is lower than 45° (during the central hours of the day). This measuring technique is potentially compromised by the presence of shadows, and background and instrumental errors. Additionally, it requires accurate instruments, able to detect global solar radiation in the range of 300–2500 nm, and a minimum surface of 4 m^2. In order to reduce differential effects in convective heat exchanges and optimize the precision of the albedo measurements, a double-pyranometer apparatus, i.e. albedometer, is normally used. In this case, the upward-oriented pyranometer measures the radiation arriving to the sample, while the downward orientation captures the reflected radiation. The albedo is then calculated as the ratio between reflected and incoming global solar radiation values.

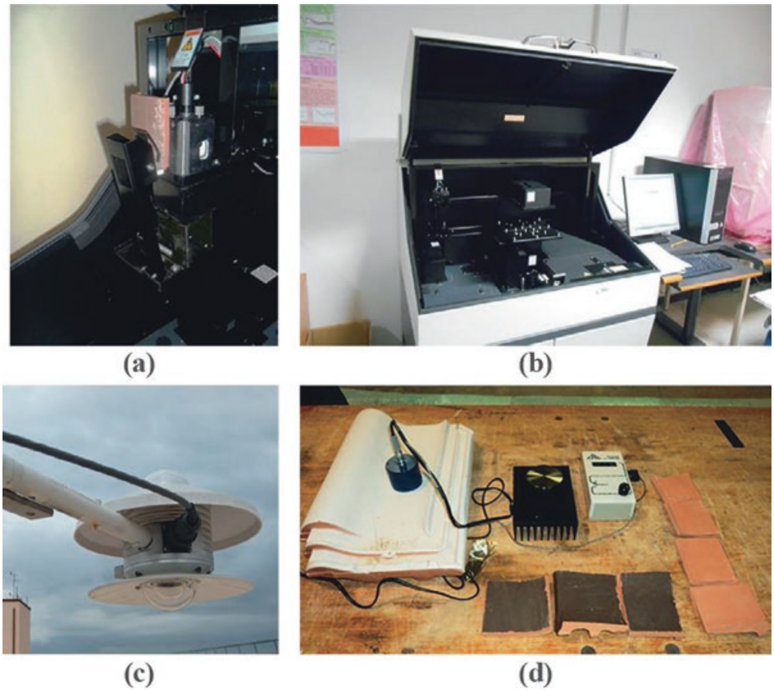

Fig. 24.4 (**a**, **b**) Spectrophotometer with an integrating sphere for in-lab SR measurements, (**c**) albedometer for in-field SR measurements and (**d**) portable emissometer for in-lab thermal emittance measurements

24.3.2 Thermal Emittance Analysis

The main reference standards which can be used to measure the thermal emittance of a surface are the ASTM C1371-15 (2015) and the ASTM E408-13 (2019) standard. The former makes use of portable emissometers, and the latter describes the inspection meter technique.

The first experimental technique makes use of a portable differential thermopile emissometer and it allows to measure hemispherical emittance of a surface or a coating. When using a portable emissometer, it is important to firstly operate a simple yet essential calibration procedure using samples with known high-emittance and known low-emittance values. Additionally, the sample, which has to have a minimum surface of 15 cm^2, needs to be positioned over a heat sink to prevent excessive temperature increase during the course of the measurement.

The second procedure generally used to measure thermal emittance is the inspection meter technique and it consists of two different test methods (A and B), characterized by different limitations and accuracy. Both these methods are based on thermal reflectance measurement and only estimate emittance as a calculated value. All this considered, although their results are not strongly affected by temperature drifts, they often generate erroneous estimations of the thermal emittance and, for this reason, the use of portable emissometers is preferred in the common practice.

24.4 Computational Investigation of Cool Materials

In parallel to the most common experimental investigation techniques, the analysis of the UHI mitigation potential of highly reflecting cool materials was also carried out through numerical simulations, as a reliable tool to explore a variety of configurations and boundary conditions with little experimental effort. This field of investigation was particularly boosted by the remarkable advances in computational resources and the ever-greater need of high spatial modelling accuracy in microclimate studies of the past decades. Among others, surface energy balance or budget (SEB) models, computational fluid dynamics (CFD) and building energy performance simulations (BEPS) are widely acknowledged tools, particularly appreciated by the scientific community. In this section, we present the main characteristics of these models, with special focus on cool materials' applications. We present the main contributions in the current research background and discuss the main findings derived from their application.

24.4.1 Cool Materials in Surface Energy Balance (SEB) Models

Computational methods for urban microclimate analysis originally involved the "simplified approach" of surface energy balance or surface energy budget (SEB) models. Based on the law of energy conservation for a specific control volume, these models follow the principle of surface energy balance proposed by Oke (1982), which allows to write Eq. (24.2) for each facet of the control volume:

$$R_N = H + \mathrm{LE} + G \tag{24.2}$$

where $R_N = S^{\downarrow} + L^{\downarrow} + S^{\uparrow} + L^{\uparrow}$ is the net radiation (S is the short wave and L is the long wave, while the downward and upward arrows denote the downwelling and upwelling components), H is the sensible heat flux, LE is the latent heat flux and G is the conductive heat flux, respectively. This equation cannot realistically be solved for every point on the urban surface and, therefore, a certain level of approximation is required. Four basic approaches have been used to simplify this problem (Fig. 24.5):

– *Slab models*, treating the urban geometry as a flat surface with a large roughness length and small albedo (Best 2005)
– *Volumetric averaging models*, considering the energy balance of a volume incorporating buildings, air and underlying substrate (Grimmond et al. 1991)

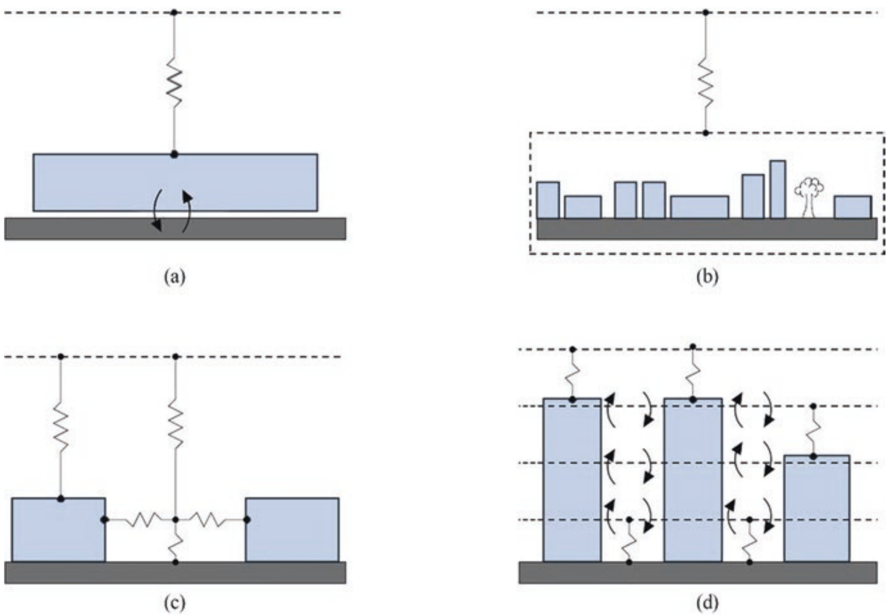

Fig. 24.5 Schematic of the four basic approaches in modelling the urban energy balance. (**a**) Slab models; (**b**) volumetric averaging models; (**c**) single-layer models; (**d**) multilayer models

– *Single-layer urban street canyon or urban canopy models*, considering the different building facets in a two-dimensional, symmetrical street canyon with infinite length (Masson 2000)
– *Multilayer urban street canyon or urban canopy models*, considering the different building facets in a three-dimensional geometry (Martilli et al. 2002)

Volume-averaging models (VAMs) and single-layer urban canopy models (S-UCMs), in particular, have been widely used in the scientific community. They provide the basis for numerical microclimate analyses, yet they give no information about wind velocity fields and they cannot properly model flow patterns that seriously affect sensible heat flux in urban surfaces (Toparlar et al. 2017). The main difference between volume-averaging and urban canopy models lies in the way the urban surface is discretized and its energy balance calculated. VAMs indeed only allow to consider a volume average representative of all the surfaces and the air enclosed within it, while UCMs distinguish among different types of urban facets (e.g. building roofs, walls and ground); therefore, they allow to have a more detailed representation of local energy exchanges in urban areas (Masson 2000; Kusaka et al. 2001; Grimmond and Oke 2002), and they are particularly useful for quantifying the local effect of advanced materials for urban surfaces. By using this unique feature, for example, Fabiani et al. (2019) were able to quantify the urban heat island mitigation potential of a high-reflective roof and of an equivalent thermochromic-based application, and compare it to that of a traditional dark solution. Results showed that the thermochromic produces enhanced short-wave solar reflection in summer conditions while also reducing the reflected solar fraction in winter. This is due to the adaptive nature of the thermochromics, which allows to obtain a 5.6% reduction in the cooling energy needs in the face of almost negligible increases in the heating demand. In the same way, Manni et al. (2019) developed an innovative algorithm using a Monte Carlo-based routine for conducting full ray-tracing solar analyses aimed at evaluating the influence of retroreflective materials on the energy balance of the urban canopy.

Despite their exceptional capability to quantify local changes in the urban energy balance, UCMs are most largely used in combination with mesoscale atmospheric models for correctly parameterizing the interactions between urban surfaces and bordering atmosphere (Ramamurthy et al. 2014). In his work about the effectiveness of different UHI mitigation strategies, for example, Zhang et al. (2017) used the weather research and forecasting (WRF) model coupled with a physically based single-layer UCM to predict both local and regional effect of cool roofs. He found that the integration of cool materials seriously affects surface energy partition, and the sensible flux of the urban skin, in particular, was found to be strictly correlated to local variations in solar reflectance. The regional effect could be found in both surface and near-surface air temperatures when the roofs were covered with high-reflectance materials (SR = 0.7) or, alternatively, when the fraction of green roofs reached 50% (Fig. 24.6). In a similar way, Li et al. (2014) quantified cool and green roof mitigation effect at the city scale by coupling WRF with the Princeton urban canopy model (PUCM). Based on their results, covering 30% of the roof areas with

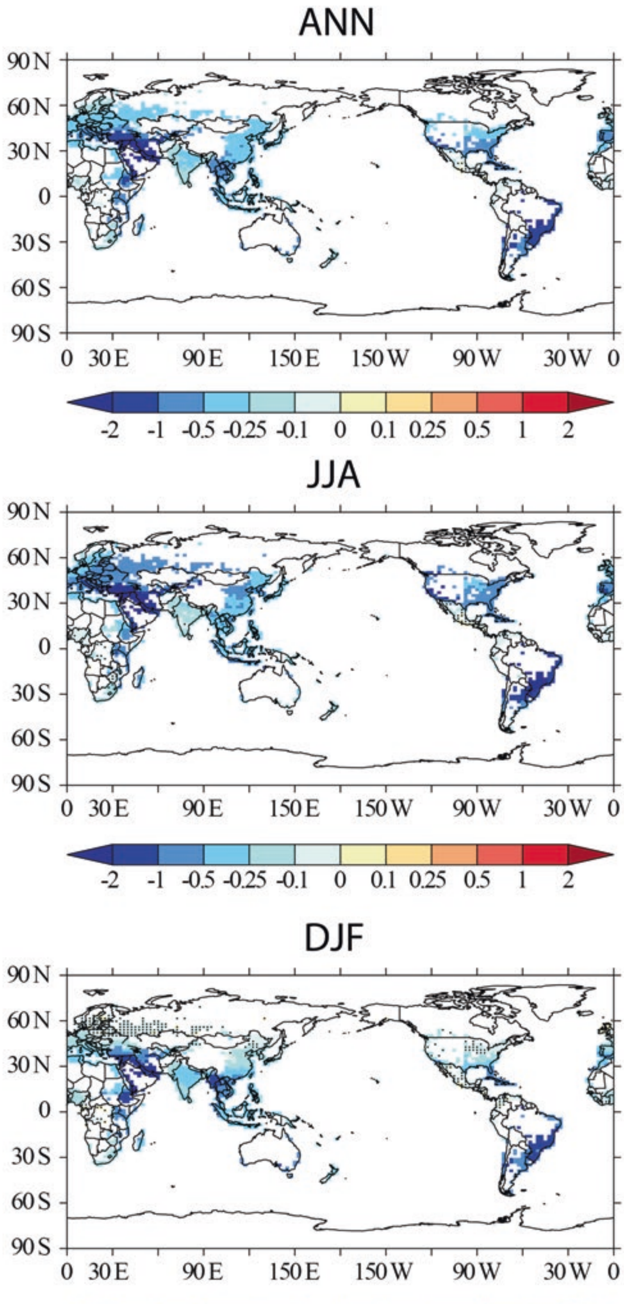

Fig. 24.6 Changes in urban heat islands (urban minus rural surface air temperature) from increasing roof albedo, averaged annually (ANN), in summer (JJA) and in winter (DJF). Dotted areas are where differences are not statistically significant at 95% confidence interval. Each panel shows differences between COOL and DARK cases (Zhang et al. 2016)

cool roofs with an albedo of 0.7 could produce a 1 °C near-surface air temperature reduction in the Baltimore-Washington metropolitan area. An additional reduction of 0.14 °C could be obtained if the cool roof fraction were to be raised to 50%, and the albedo value changed from 0.7 to 0.9. Zhang et al. (2018) combined urban canopy and mesoscale atmospheric models to quantify and compare the effectiveness of cool roofs and walls with SR of 0.5 and 0.9 as UHI mitigation strategies. They found that the average air temperature reductions induced by both these applications is proportional to the increase in albedo.

24.4.2 Cool Materials in Computational Fluid Dynamic (CFD) Models

Computational fluid dynamic (CFD) models analyse and solve problems that involve fluid flows. CFD is based on the Navier-Stokes equations, describing the correlation among velocity, pressure, temperature and density of a moving fluid. In contrast with simple energy balance models, CFD couples explicitly velocity and temperature fields, possibly considering humidity and pollution fields as well, and it can resolve the flow field at much finer scales (Toparlar et al. 2017). CFD simulations, however, require a much more detailed representation of the urban geometry, together with a detailed definition of specific boundary conditions for all relevant flow variables, and adequate computational resources (Blocken 2015). CFD models allow the study of the urban microclimate at different scales of investigation, ranging from the meteorological mesoscale to the building scale and the indoor environment (Fig. 24.7).

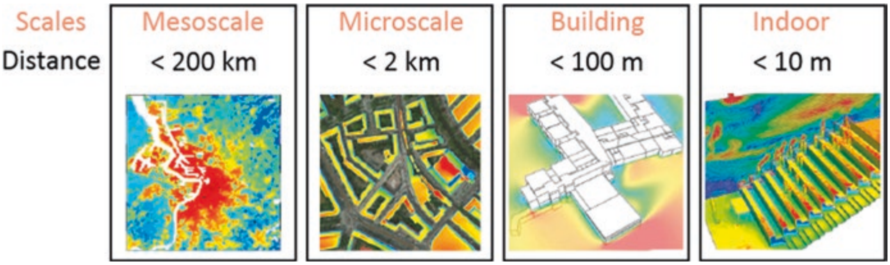

Fig. 24.7 Schematic representation of the spatial scales in climate modelling, with typical horizontal dimensions (Toparlar et al. 2017)

24.4.2.1 Mesoscale Computational Fluid Dynamic

Meteorological mesoscale simulations refer to climatic studies investigating atmospheric developing over horizontal distances of several hundred kilometres, numerical weather prediction (NWP) models (Lynch 2008). These models date back to the 1970s and were originally applied for 2D computational domains, where urban areas were defined as localized heat sources (Bornstein 1975). Yet, the necessity to further increase the representativeness of these models led to including specific 3D representations of the built environment, initially in the form of basic forcing functions for topography, building heights, roughness variations and temperature perturbations (Vukovich Dunn and Crissman 1976; Saitoh et al. 1996), and finally, as fully developed surface energy balance models (Li et al. 2014; Ramamurthy et al. 2014). Effectively coupling SEBs and NWPs allowed to quantify the mesoscale effect of different kinds of cool materials as previously described in Sect. 24.4.1 for the specific case of UCMs. Zhou and Shepherd (2010), for example, modelled the area of Atlanta, USA, with the Weather Research and Forecasting (WRF)-NOAH Land Surface Model (LSM) and concluded that tripling city's albedo could effectively attenuate UHI intensity. Similarly, Zhang et al. (2016) used the Community System Model (version 1.2.0) at the urban, continental and global scales. They reported a statistically significant annual and global mean temperature decrease due to large-scale implementation of cool materials, which registered everywhere, with the exception of some regions in Africa and Mexico.

24.4.2.2 Microscale Computational Fluid Dynamic

CFD simulations at the meteorological microscale consider horizontal distances up to a few kilometres. They are useful for accurately modelling specific buildings or limited urban areas and, particularly, evaluating local modifications in relatively smaller air domains compared to the applications at the mesoscale. In recent years, because of the significant advances in computational resources and given the development of evermore user-friendly interfaces and tools, CFD studies at the meteorological microscale have gained popularity. They are often used to investigate wind flow around buildings, pedestrian comfort, wind-driven rain, pollutant dispersion, snow drift and similar topics. Concerning cool materials' applications, CFD studies at the microscale are particularly suitable for evaluating the effect of these materials on the local microclimate and identifying the consequences of their implementation in a selected urban context. Most of these studies solve RANS equations using the acknowledged k-ε model.

Georgakis et al. (2014), for example, used Ansys CFX to evaluate the effect of different coatings with albedo of 0.3, 0.6 and 0.9 on a deep street urban canyon. They found that the integration of these coatings on the surfaces of the canyon could reduce local surface temperatures by 7–8 °C at the ground level, and by 2–3 °C on the walls of the overlooking buildings. Finally, they also concluded that the ambient air temperature inside the canyon may decrease up to 1 °C. A different package of the Ansys suite, i.e. Ansys Fluent, was used by Herbert et al. (1998) to evaluate the effect of cool materials' implementation in Los Angeles. The authors designed an imaginary canyon with an above-canyon wind speed of 3 ms^{-1} and ran two simulations: the former taking into account common building materials, and the latter assuming that all the surfaces of the canyon were painted white. Results showed lower overall air temperatures and within-canyon air temperatures during the overall extent of the simulation for the "white" city configuration. In particular, both these temperatures were reduced by approximately 1 °C during the peak hours of the day.

Another acknowledged CFD tool, i.e. Star CCM+, was used by Botham-Myint et al. (2015) for measuring the thermal perturbation or "thermal footprint" caused by a white roof in different urban geometries. They found that introducing the cool material on the roof of a short building surrounded by taller constructions could improve the effectiveness of this solution. The same tool was used by Yang et al. (2017) for quantifying the UHI mitigation effect of a PCM cool roof system applied on a residential and on a commercial city block. Results showed a greater effect in the commercial zone (characterized by a larger roof area), where the urban canopy layer registered a 7.8 °C temperature reduction in summer, and a reduction of 11.3 °C in winter (Fig. 24.8). Concerning the residential zone, in this case the temperatures were decreased by 6.4 °C in summer and 10.5 °C in winter, respectively (Fig. 24.9).

Several open-source CFD codes also exist and were used for evaluating the effect of cool applications at the microclimate scale. Qu et al. (2012), for example, used the Code_Saturne (Archambeau et al. 2004) for simulating the effect of materials with increasing albedo values in a specific building block. They found that increasing the solar reflectance of all the urban surface case study from 0.1 to 0.6 drastically reduces the net radiation term in surface energy balance of the urban skin. Consequently, the potential temperature close to the cool walls and roofs may decrease by 2 °C. ENVI-met is another free tool which has frequently been used for simulating the thermal performance of cool materials in the built environment. Pigliautile et al. (2020), for instance, used ENVI-met for assessing the UHI mitigation potential of evapotranspiration and high-reflectance surfaces in a full-scale experimental set-up composed of more than 20 continuously monitored cubicles in a Mediterranean continental climate. Based on their results, they state that the high-albedo solution has the highest potential in mitigating summer overheating, while the introduction of greenery could be more effective in packed configurations with low-albedo envelopes. The same tool coupled with an energy performance model was used by Cardinali et al. (2020) for assessing the impact of outdoor microclimate improvements, including cool solutions, on building energy performance (Fig. 24.10).

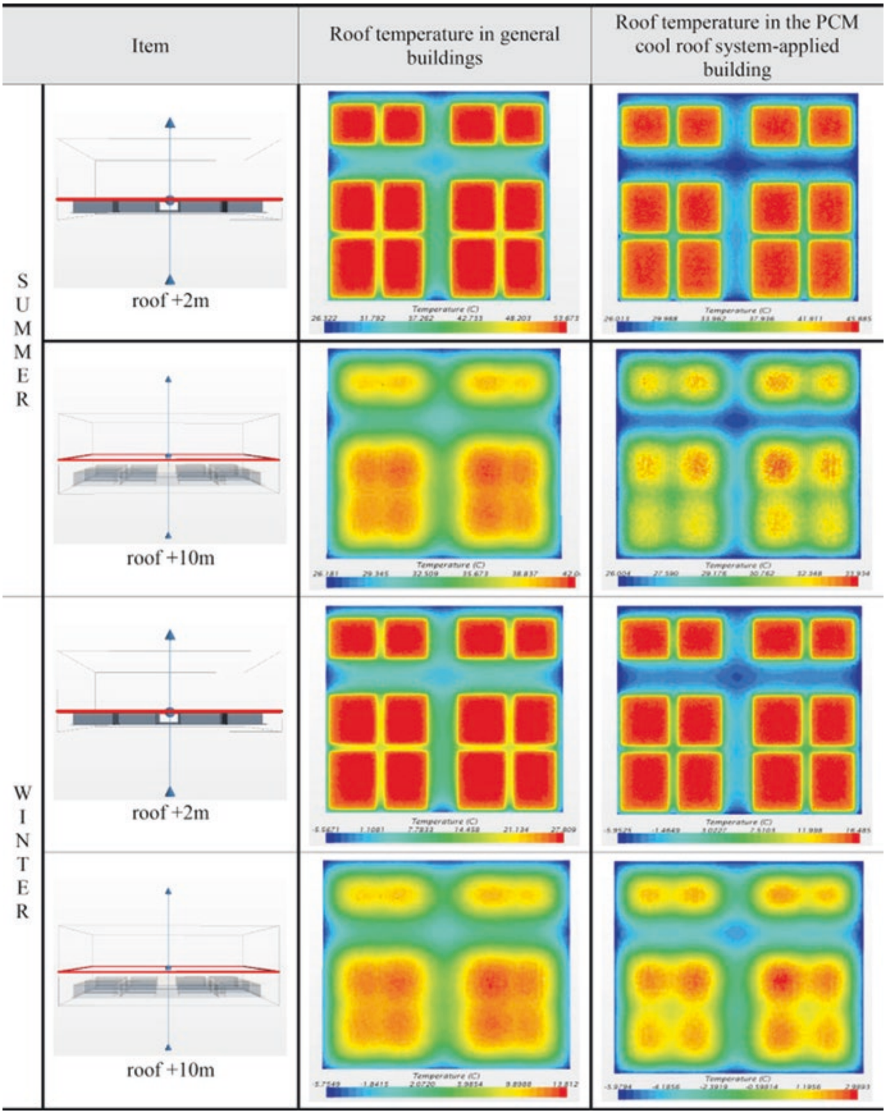

Fig. 24.8 Temperature distribution of commercial area (horizontal section). (Yang et al. 2017, with permission from Elsevier Ltd.)

24.4.2.3 Building-Scale Computational Fluid Dynamic

Computational fluid dynamic can also be used for producing a detailed analysis of the local microclimate around one or a few buildings. In this case we talk about building-scale CFD and we generally consider distances below 100 m on the horizontal surface. This application makes use of the same tools and platforms used in

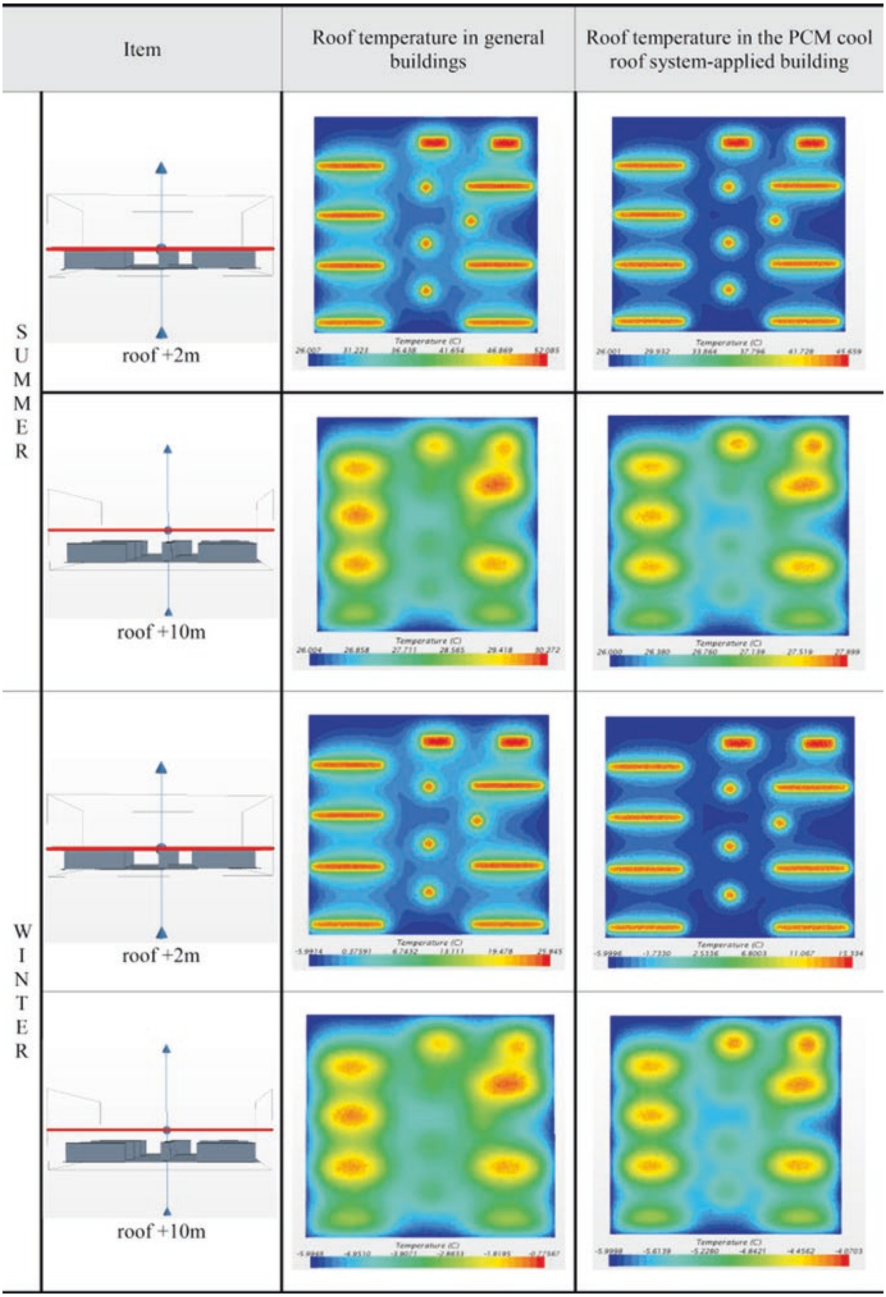

Fig. 24.9 Temperature distribution of residential area (horizontal section). (Yang et al. 2017, with permission from Elsevier Ltd.)

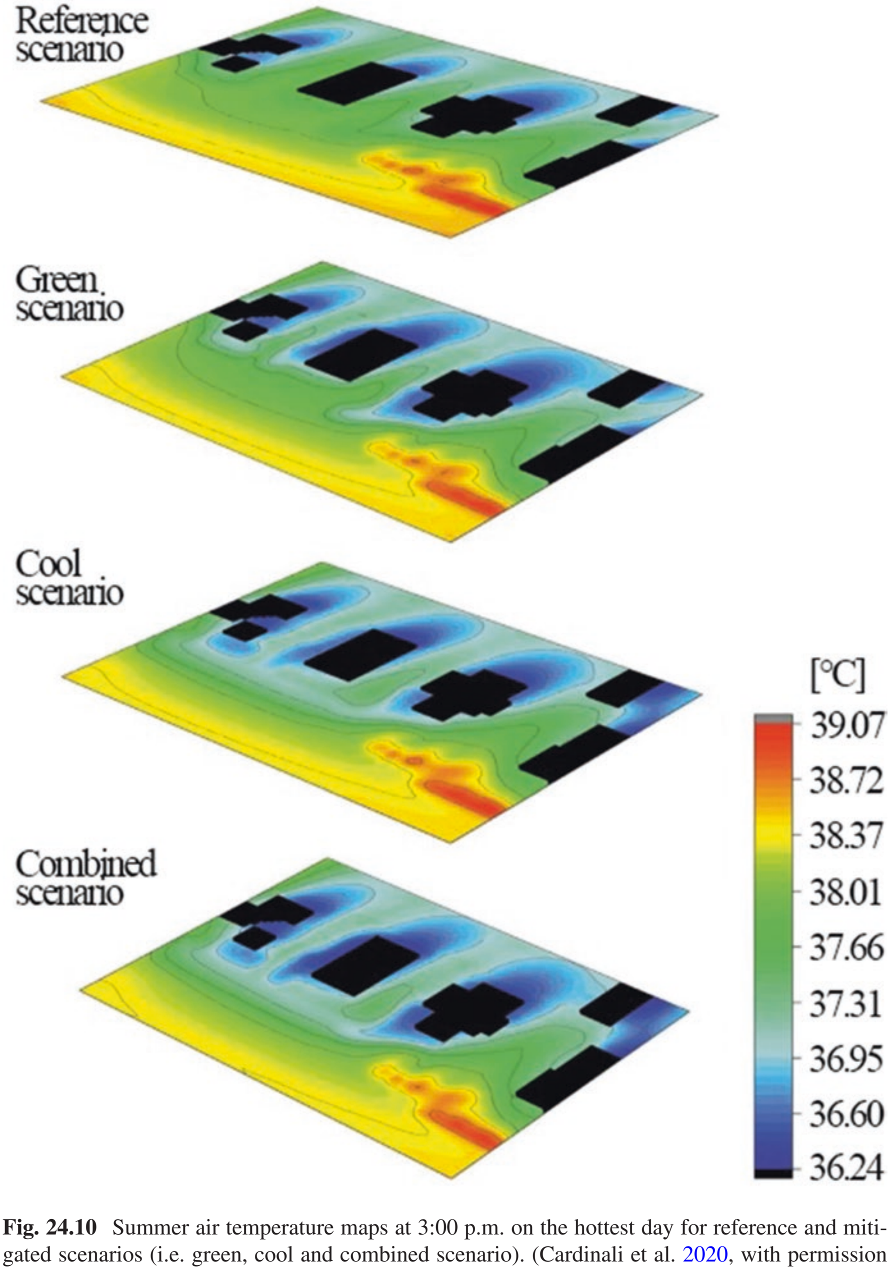

Fig. 24.10 Summer air temperature maps at 3:00 p.m. on the hottest day for reference and mitigated scenarios (i.e. green, cool and combined scenario). (Cardinali et al. 2020, with permission from Elsevier Ltd.)

the microclimate scale, yet more detailed input data are needed in terms of both geometry and microclimate parameters. The improved precision in the input and local boundary conditions allows to obtain detailed outputs from the model and, consequently, to more carefully describe the evolution of local flow field. This kind of models is often used for investigating pollutant dispersion and local temperature gradients. Haghighat and Mirzaei (2011), for example, used Fluent software for studying the effect of non-uniform wall surface temperature distribution on the pollution dispersion and flow pattern within a short street canyon. In particular, they investigated the capability of active and passive techniques (e.g. cool materials) to reduce the pollutant concentration level in the canyon. Ghaffarianhoseini et al. (2015), for instance, used ENVI-met for simulating the thermal performance of courtyards in the hot and humid climate of Kuala Lumpur, Malaysia. Based on the obtained results, they specify guidelines for optimizing the design of courtyards and enhancing their thermal performance. In particular, they found that although the introduction of cool materials generally reduces local air temperatures in the simulated environment, they also generally produce considerably higher mean radiant temperatures, and consequently produce higher discomfort conditions. As a matter of fact, results from their simulations show that the predicted mean vote (PMV) value of the courtyard rises from 4 to 5, and finally 6, with increasing albedo from 0.3 to 0.55, and 0.93, respectively (Fig. 24.11).

24.4.2.4 Computational Fluid Dynamic in the Indoor Environment

Given their complex nature, and the generally high computation time of most CFD analyses, these models were originally mostly used to perform heat transfer analysis in closed cavities, generally representing portions of buildings with varying external coating reflectance. The use of such an advanced technique allowed to further corroborate the positive results obtained in dynamic simulations with a more careful investigation of the indoor thermal comfort in 3D models focused on airflows and local discomfort conditions. Revel et al. (2014), for example, used Star CCM+ code for conducting a transient (24-h long) conjugate heat transfer study for investigating the effect of cool facade tiles and roof membrane on the external and internal surface temperature of the simulated building, as well as on the indoor air temperature. They found a 3.0 and 1.5 °C reduction in terms of external and internal surface temperature, respectively (Fig. 24.12). In terms of indoor temperature, reductions of peak values of 0.9 and 0.7 °C at the centre of the air volume have been found when using the cool facade and roof. In a similar way, Pisello et al. (2016d) developed and validated a two-dimensional CFD analysis of an attic room in a residential building, with the aim of quantifying the effect of a cool roof solution within the indoor environment of the thermal zone adjacent to the roof, and analysing the attic local thermal comfort conditions. They found up to 2.8 and 1.5 °C air temperature reduction in the cool configuration, in summer and winter conditions, respectively. Additionally, they also reported the capability of the cool application to

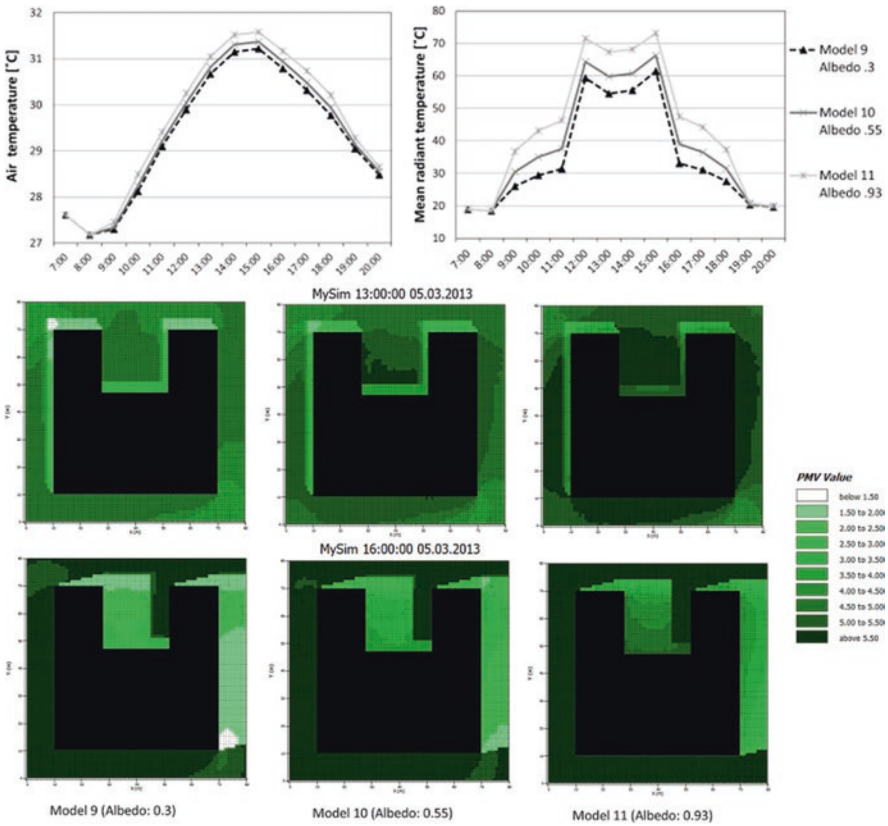

Fig. 24.11 Hourly ambient air temperature (top left), mean radiant temperature (top right) and simulated distributions of PMV in courtyard models with albedo values of 0.3, 0.55 and 0.93 at 13:00 and 16:00, at 2 m height (bottom). (Ghaffarianhoseini et al. 2015, elaborated with permission from Elsevier Ltd.)

significantly reduce the intense thermal stratification caused by summer overheating, which seriously affects local comfort conditions in the attic (Fig. 24.13).

24.4.3 Cool Materials in Building Energy Performance Simulations (BEPS)

An initial approach with numerical simulations of cool components for the built environment mainly aimed at quantifying their possible impact on the final energy requirements for cooling and heating in residential buildings. All this considered, different researchers used dynamic thermal energy simulation tools to investigate the introduction of cool materials in different cities around the world and estimate possible winter penalties with varying climate boundary conditions.

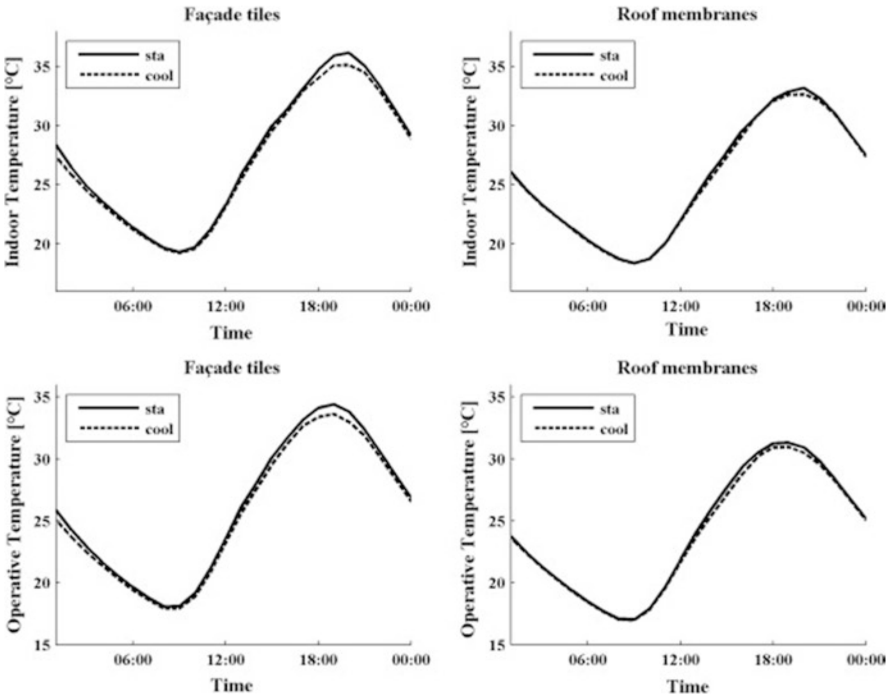

Fig. 24.12 Daily profiles of indoor and operative temperature at the centre of the indoor air volume for the standard and cool models. (Revel et al. 2014, with permission from Elsevier Ltd.)

Piselli et al. (2017), for instance, minimized building annual energy requirements for air conditioning by optimizing the roof coating solar reflectance capability under different boundary conditions and climate contexts. Based on their study, they concluded that the optimum roof solar reflectance to reduce the annual building HVAC energy consumption is mainly affected by the climate context. The same authors used a similar optimization approach for defining the most promising roof configuration in terms of solar reflectance of the external coating and thermal insulation layer thickness in the case of a standard small office building under varying climate conditions. They concluded that the cool roof was able to optimize the annual HVAC energy consumption of the case study building in almost all considered climate conditions, except the coldest zones (Fig. 24.14) (Piselli et al. 2019).

The optimum combination of cool coatings and insulation thickness was also the main topic of the work by Saafi and Daouas (2018). In this case however, the authors took into account two typical Tunisian roof structures for residential buildings, and three types of thermal insulation materials. They carried out a life cycle cost analysis considering the energy consumption derived from a dynamic simulation tool, and concluded that in the selected climate conditions, the cooling energy loads are more sensitive to the variations of solar reflectivity compared to the heating loads and the effect of reflectivity is always more pronounced for low-roof insulation

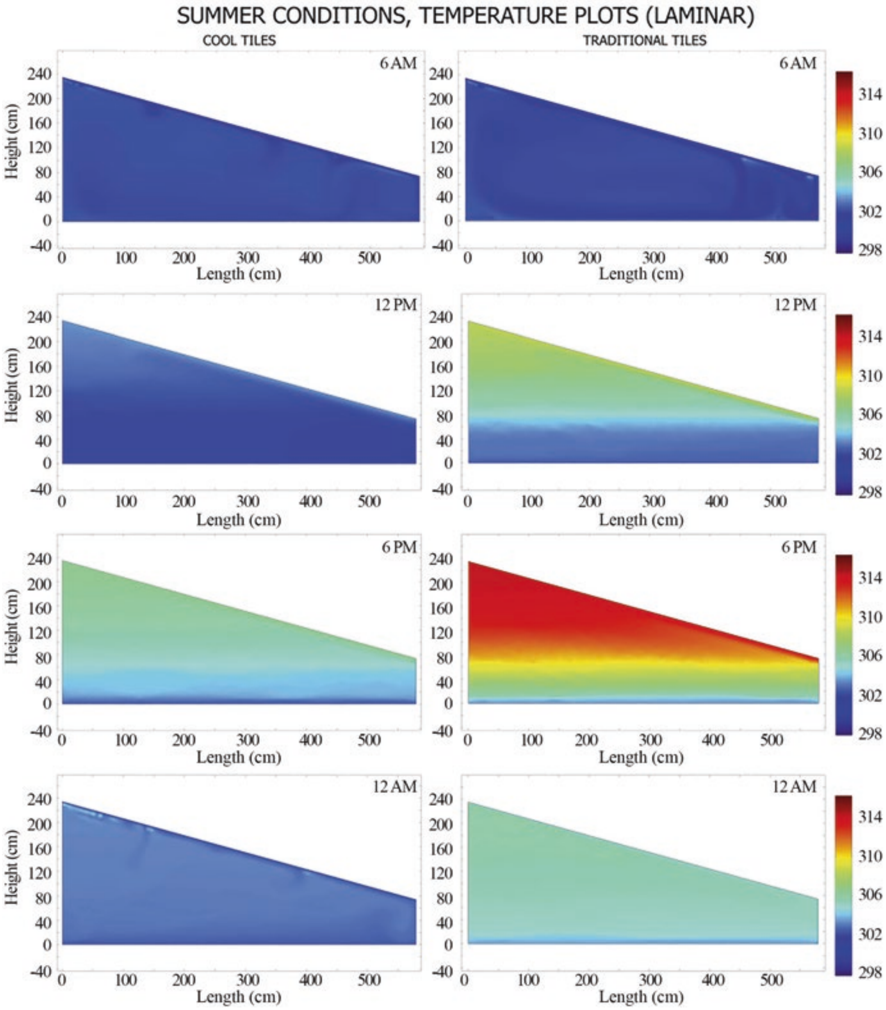

Fig. 24.13 Temperature distribution for cool and traditional tiles at different time steps in summer conditions. (Pisello et al. 2016d, with permission from Elsevier Ltd.)

levels. The effect of cool materials on the annual energy consumption of a case study building and the related costs was also investigated by Jo et al. (2010). In this case, however, the thermal energy investigation concerned the implementation of cool roof coatings (with an albedo value equal to 0.72, against the original value of 0.3) on a single-storey office building equipped with a data processing centre in Phoenix, Arizona. Given the necessity of maintaining a constant and relatively lower temperature profile 24 h, the introduction of the cool solution allowed to obtain 3.16% energy savings per year, corresponding to about 22,000$/year.

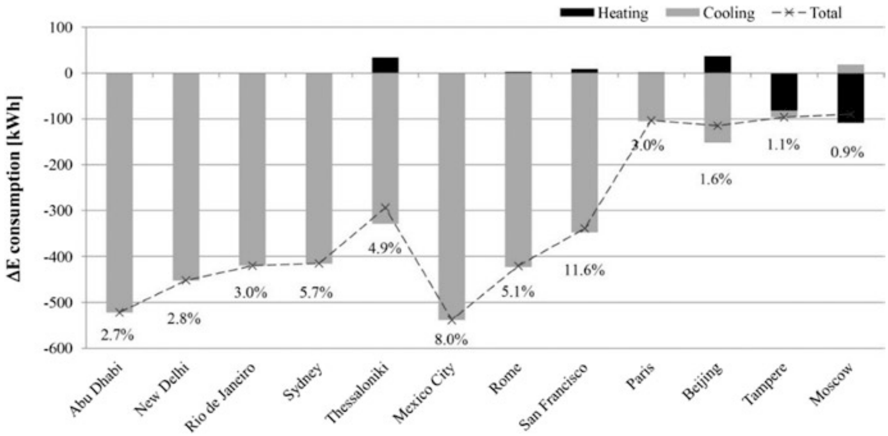

Fig. 24.14 Difference of building HVAC energy consumption between the optimum and the "standard roof" configuration in each climate zone, reporting the annual and the separate contributions for heating and cooling (Piselli et al. 2019)

Building energy simulations are particularly useful for identifying the possible energy savings associated to the implementation of innovative building components equipped with cool coatings based on advanced material technologies. Nie et al. (2020), for example, used this kind of analysis for quantifying the potential energy saving derived from the implementation of an optical coating integrating glass bubbles within a polymer film which allows a selective solar reflectivity increase from 0.06 to 0.92 while maintaining the mid-infrared emissivity above 0.85. They estimated that the applications of the polymer coating on common buildings could guarantee a potential annual energy savings of 2–12 MJ/m^2 and CO_2 emission savings of about 0.3–1.5 kg/m^2. In a similar study, Park and Krarti (2016) estimated that by introducing a variable reflectivity roof coating, characterized by a solar reflectance of 0.55 in summer and 0.3 in winter, it could be possible to reduce building cooling loads without increasing the heating loads in the winter period.

All the above simulations were carried out using a widely acknowledged software called EnergyPlus, which, given its dynamic nature, ease of use and free availability, probably represents the most important software for building energy performance simulations in scientific applications. Yet other tools exist and are widely used by scientists all over the world. Revel et al. (2014), for example, used ESP-r for carrying out dynamic energy-saving calculations and defining the amount of energy that could be saved by replacing standard facade tiles with their equivalent cool alternatives on a standard multistorey building. They found that a maximum of 1.1 kWh/m^2 could be saved in Rome, while this value could increase up to 1.7 kWh/m^2 in Palermo. Wang et al. (2008), on the other hand, used EDSL TAS for investigating the thermal energy performance of a retail shed with a pitched roof equipped with air conditioning for cooling and heating purpose in different locations around the world. The case study building was equipped with 12 different coatings characterized by an albedo value ranging from 0.05 to 0.65. As expected, their results confirmed that the high-reflective coatings are associated to higher energy savings (25–38%) in hotter climates.

Although the obtained results are usually particularly sensitive to the specific climate conditions and on the building characteristics, a general reference pattern can be extrapolated. The introduction of cool materials always produces a reduction on the cooling load, while the heating load increase is limited and is generally compensated by the cooling load decrease (Santamouris et al. 2008).

24.5 Shortcomings of Cool Materials

As previously mentioned, high-reflectance components for buildings and pavements are becoming increasingly important as a passive strategy to save energy for cooling and improve indoor and outdoor thermal comfort conditions. The benefits derived from their use arise from their capability to reduce surface overheating, and it can be accounted for at building, city and even global scales. In this context, however, all cool materials share two inescapable shortcomings: winter penalty and reduction of their performance over time due to ageing processes. The former problem is gradually being solved by resorting to adaptive materials that can tailor their behaviour in response to local boundary conditions. The latter represents an unsolved issue that needs to be tackled seriously, since ageing phenomena such as soiling and weathering can progressively modify the surface properties of the investigated solutions. Therefore, solar reflectance properties of such materials should be specified before and after environmental exposure, in a way to exhaustively describe their thermal optic performance during the course of their life cycle. In this section we give a brief analysis of the main environmental agents affecting cool materials' durability and we describe the main techniques used for studying this phenomenon.

24.5.1 The Role of Weathering

Weathering is a detrimental phenomenon due to the effect of all those environmental agents that can influence the physical behaviour and durability of a coating or a surface exposed to light, heat and moisture (Santamouris et al. 2011). The science of weathering is a complex topic that should be studied as a part of the materials' production, measurement, test design, exposure and evaluation as a whole.

The first possible source of degradation is the interaction with light. Shorter and consequently higher energy wavelengths are easily absorbed by most polymeric materials. The interaction with solar radiation, in particular, characterized by huge variations in intensity and spectral distribution, due to different local boundary conditions (as time of the year, location and atmospheric effects) can easily induce destructive reactions and colour changes on a surface.

A second harmful interaction concerns intense temperature fluctuations that can directly lead to a disruptive degradation process. The effect depends on the mechanical stresses produced on a matric by the differential thermal expansion. The effect depends, of course, on the heat source and the specific properties of the sample such as reflectance, absorbance, emissivity and conductivity.

Moisture can touch and penetrate within a surface inducing both chemical and physical stresses in different ways (rain, snow and ice are the most important ones). When ice is formed the associated volume expansion is responsible for increased internal physical stress. The de-icing process, in particular, can cause abrupt contractions and these cyclic dimensional changes can seriously deteriorate the mechanical strength of the material. At a later stage, acid water from the rain often carries atmospheric pollutants that might create corrosive or chemically adverse phenomena. Wind pressure, finally, can cause structural/mechanical modifications in both horizontal and vertical building components, inducing cracks and other damaging effects.

24.5.2 The Role of Soiling

Soiling mechanisms consist of the deposition of atmospheric particulate over a surface and can be coupled or not with the presence or growth of microorganisms (Sleiman et al. 2014).

Deposition of atmospheric particulate matter is the dominant source of soiling agents accumulating on exposed surfaces in the built environment. The combination of these pollutants, particularly black carbon and organic matter emitted during combustion processes and traffic, with oxygen and water vapour is responsible for the formation of oxides and hydroxides. These last molecules can easily corrode materials and damage external surfaces, affecting their solar reflectance capability.

Biological contaminants consist of fungi and other organic agents that proliferate in environments filled with moisture. These microorganisms or microplants deposit over a surface and radically affect its optical properties. All this considered, nowadays periodic removal and restoration tasks are scheduled for most advanced high-performance building applications making use of cool materials.

24.5.3 Quantifying Progressive Degradation of Cool Materials

The estimation of the long-term performance of cool surfaces can be tested in three different ways: natural weathering exposition, accelerated weathering tests and artificial soiling experiments.

In natural weathering exposition, cool components for the building envelope or cool paving solutions are exposed to real weathering agents such as the sun, the rain and the wind. This kind of degradation analysis makes use of natural forcing and is carried out by means of specific test racks, with appropriate distance above ground and to the surrounding area. Other important parameters in this kind of analyses are the sunlight angle, period of exposure and length of the test, generally determined by the purpose of the experiment and the parameters to be measured. In any case, natural weathering procedures are usually long-term experimental campaigns focused on material durability. Of course, during these campaigns a huge set of environmental and geometric characteristics are controlled and monitored, and the solar reflectance and emittance properties are quantified at least before and after the exposure period.

Accelerated weathering tests are in-lab tests carried out using weathering test chambers equipped with a xenon lamp, in order to simulate severe outdoor exposure conditions. This kind of tests is used to anticipate and predict the damaging of coatings and membranes, under the effect of accelerated degradation conditions. No unique correlation exists between outdoor natural and accelerated weathering procedures, so this degradation analysis should always be designed for comparison purposes and analysed with care.

Advanced test chambers and apparatus are also used in artificial soiling experiments. In this case, however, not only the most severe outdoor climatic conditions but also atmospheric pollutants are reproduced and integrated in specifically designed experimental campaigns. In this kind of tests, microbial growth reproduction is particularly important being a major agent of roof soiling in humid climates.

24.6 Future Trends

This chapter provided an in-depth investigation of one of the most interesting kind of materials for building applications, i.e. cool materials. As described above, cool materials are an environmentally friendly and relatively cost-effective solution aimed at reducing building energy needs and improving local and eventually global environmental conditions. Recent research findings showed the importance of developing new technologies capable of reducing the major shortcomings of these relatively simple components: winter penalty and ageing.

Winter penalty can be drastically reduced by using adaptive cool solutions, that is, an innovative kind of materials capable of tailoring their thermo-optic properties in response to local boundary conditions. Future trends in this field will focus on the development and use of nanoscale thermochromics based on quantum dots and plasmonic and photonic structures, among others. These advanced solutions could successfully be used to obtain innovative structures that could highly reflect solar radiation in the UV, visible and near-infrared range while behaving as a black body within the atmospheric window, i.e. between 8 and 13 μm, allowing the so-called radiative cooling phenomenon.

Concerning the issue of ageing, as already discussed, long-term durability is nowadays the real weakness of cool applications that cannot guarantee adequate performance throughout the lifespan of a building, but are susceptible to non-negligible changes over time due to the action of external agents and to the exposure to ambient and adverse weather conditions. For this reason, future trends in research should also focus on the improvement of the thermal energy performance of such solutions in terms of extreme deterioration over time.

References

Akbari, H., Gartland, L., & Konopacki, S. (1998). Measured energy savings of light colored roofs: Results from three California demonstration sites.

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy, 70*(3), 295–310. https://doi.org/10.1016/S0038-092X(00)00089-X.

Akridge, J. M. (1998). High-albedo roof coatings-impact on energy consumption. In *ASHRAE Transactions.*

Archambeau, F., Méchitoua, N., & Sakiz, M. (2004). Code Saturne: A finite volume code for the computation of turbulent incompressible flows—Industrial applications. *International Journal on Finite Volumes, 1*(1). Retrieved from http://www.latp.univ-mrs.fr/IJFV/spip.php?article3, https://hal.archives-ouvertes.fr/hal-01115371

ASTM C1371-15. (2015). *Standard test method for determination of emittance of materials near room temperature using portable emissometers*. West Conshohocken, PA: American Society for Testing Materials. https://doi.org/10.1520/C1371-15.

ASTM C1549-16. (2016). *Standard test method for determination of solar reflectance near ambient temperature using a portable solar reflectometer*. West Conshohocken, PA: American Society for Testing Materials. https://doi.org/10.1520/C1549-16.

ASTM E1918-16. (2016). *Standard test method for measuring solar reflectance of horizontal and low-sloped surfaces in the field*. West Conshohocken, PA: American Society for Testing Materials. https://doi.org/10.1520/E1918-16.

ASTM E1980-11. (2019). *Standard practice for calculating solar reflectance index of horizontal and low-sloped opaque surfaces*. West Conshohocken, PA: American Society for Testing Materials. https://doi.org/10.1520/E1980-11.2.

ASTM E408-13. (2019). *Standard test methods for total normal emittance of surfaces using inspection-meter techniques*. West Conshohocken, PA: American Society for Testing Materials. https://doi.org/10.1520/E0408-13R19.

ASTM E903-12. (2012). *Standard test method for solar absorptance, reflectance, and transmittance of materials using integrating spheres*. West Conshohocken, PA: American Society for Testing Materials.

ASTM G173-03. (2012). *Standard tables for reference solar spectral irradiances: Direct normal and hemispherical on 37° tilted surface*. West Conshohocken, PA: American Society for Testing Materials. https://doi.org/10.1520/G0173-03R12.

Berdahl, P., Chen, S. S., Destaillats, H., Kirchstetter, T. W., Levinson, R. M., & Zalich, M. A. (2016). Fluorescent cooling of objects exposed to sunlight—The ruby example. *Solar Energy Materials and Solar Cells, 157*, 312–317. https://doi.org/10.1016/j.solmat.2016.05.058.

Best, M. J. (2005). Representing urban areas within operational numerical weather prediction models. *Boundary-Layer Meteorology, 114*(1), 91–109. https://doi.org/10.1007/s10546-004-4834-5.

Blocken, B. (2015). Computational fluid dynamics for urban physics: Importance, scales, possibilities, limitations and ten tips and tricks towards accurate and reliable simulations. *Building and Environment, 91*, 219–245. https://doi.org/10.1016/j.buildenv.2015.02.015.

Bornstein, R. D. (1975). The two-dimensional URBMET urban boundary layer model. *Journal of Applied Meteorology, 14*(8), 1459–1477. https://doi.org/10.1175/1520-0450(1975)014<1459:TTDUUB>2.0.CO;2.

Botham-Myint, D., Recktenwald, G. W., & Sailor, D. J. (2015). Thermal footprint effect of rooftop urban cooling strategies. *Urban Climate, 14*(2015), 268–277. https://doi.org/10.1016/j.uclim.2015.07.005.

Cardinali, M., Pisello, A. L., Piselli, C., Pigliautile, I., & Cotana, F. (2020). Microclimate mitigation for enhancing energy and environmental performance of Near Zero Energy Settlements in Italy. *Sustainable Cities and Society, 53*, 101964. https://doi.org/10.1016/j.scs.2019.101964.

Castaldo, V. L., Coccia, V., Cotana, F., Pignatta, G., Pisello, A. L., & Rossi, F. (2015). Thermal-energy analysis of natural "cool" stone aggregates as passive cooling and global warming mitigation technique. *Urban Climate, 14*, 301–314. https://doi.org/10.1016/j.uclim.2015.05.006.

Chapman, S., Watson, J. E. M., Salazar, A., Thatcher, M., & McAlpine, C. A. (2017). The impact of urbanization and climate change on urban temperatures: A systematic review. *Landscape Ecology, 32*(10), 1921–1935. https://doi.org/10.1007/s10980-017-0561-4.

Doulos, L., Santamouris, M., & Livada, I. (2004). Passive cooling of outdoor urban spaces. The role of materials. *Solar Energy, 77*(2), 231–249. https://doi.org/10.1016/j.solener.2004.04.005.

European Commission. (2018). *Continuing urbanisation—Knowledge for policy*. Retrieved from https://ec.europa.eu/knowledge4policy/foresight/topic/continuing-urbanisation_en

Fabiani, C., Pisello, A. L., Bou-Zeid, E., Yang, J., & Cotana, F. (2019). Adaptive measures for mitigating urban heat islands: The potential of thermochromic materials to control roofing energy balance. *Applied Energy, 247*, 155–170. https://doi.org/10.1016/j.apenergy.2019.04.020.

Fabiani, C., Piselli, C., & Pisello, A. L. (2020a). Thermo-optic durability of cool roof membranes: Effect of shape stabilized phase change material inclusion on building energy efficiency. *Energy and Buildings, 207*, 109592. https://doi.org/10.1016/j.enbuild.2019.109592.

Fabiani, C., Castaldo, V. L., & Pisello, A. L. (2020b). Thermochromic materials for indoor thermal comfort improvement: Finite difference modeling and validation in a real case-study building. *Applied Energy, 262*, 114147.

Ferrari, C., Libbra, A., Muscio, A., & Siligardi, C. (2013). Design of ceramic tiles with high solar reflectance through the development of a functional engobe. *Ceramics International, 39*(8), 9583–9590. https://doi.org/10.1016/j.ceramint.2013.05.077.

Garshasbi, S., & Santamouris, M. (2019). Using advanced thermochromic technologies in the built environment: Recent development and potential to decrease the energy consumption and fight urban overheating. *Solar Energy Materials and Solar Cells, 191*, 21–32. https://doi.org/10.1016/j.solmat.2018.10.023.

Georgakis, C., Zoras, S., & Santamouris, M. (2014). Studying the effect of "cool" coatings in street urban canyons and its potential as a heat island mitigation technique. *Sustainable Cities and Society, 13*, 20–31. https://doi.org/10.1016/j.scs.2014.04.002.

Ghaffarianhoseini, A., Berardi, U., & Ghaffarianhoseini, A. (2015). Thermal performance characteristics of unshaded courtyards in hot and humid climates. *Building and Environment, 87*, 154–168. https://doi.org/10.1016/j.buildenv.2015.02.001.

Givoni, B., & Hoffiman, M. E. (1968). *Effect of building materials on internal temperatures*. Research report. Haifa: Building Research Station, Technion.

Grimmond, C. S. B., & Oke, T. R. (2002). Turbulent heat fluxes in urban areas: Observations and a local-scale urban meteorological parameterization scheme (LUMPS). *Journal of Applied Meteorology, 41*(7), 792–810. https://doi.org/10.1175/1520-0450(2002)041<0792:THFIUA>2.0.CO;2.

Grimmond, C. S. B., Cleugh, H. A., & Oke, T. R. (1991). An objective urban heat storage model and its comparison with other schemes. *Atmospheric Environment. Part B. Urban Atmosphere, 25*(3), 311–326. https://doi.org/10.1016/0957-1272(91)90003-W.

Haghighat, F., & Mirzaei, P. A. (2011). Impact of non-uniform urban surface temperature on pollution dispersion in urban areas. *Building Simulation, 4*(3), 227–244. https://doi.org/10.1007/s12273-011-0035-6.

Herbert, J. M., Johnson, G. T., & Arnfield, A. J. (1998). Modelling the thermal climate in city canyons. *Environmental Modelling and Software, 13*(3–4), 267–277. https://doi.org/10.1016/S1364-8152(98)00027-9.

Hernández-Pérez, I., Xamán, J., Macías-Melo, E. V., & Aguilar-Castro, K. M. (2017). Reflective materials for cost-effective energy-efficient retrofitting of roofs. In *Cost-effective energy efficient building retrofitting* (pp. 119–139). Duxford: Woodhead Publishing. https://doi.org/10.1016/B978-0-08-101128-7.00004-6.

Hu, J., & Yu, X. B. (2019). Adaptive thermochromic roof system: Assessment of performance under different climates. *Energy and Buildings, 192*, 1–14. https://doi.org/10.1016/j.enbuild.2019.02.040.

Ihara, T., Kikegawa, Y., Asahi, K., Genchi, Y., & Kondo, H. (2008). Changes in year-round air temperature and annual energy consumption in office building areas by urban heat-island countermeasures and energy-saving measures. *Applied Energy, 85*(1), 12–25. https://doi.org/10.1016/j.apenergy.2007.06.012.

Jo, J. H., Carlson, J. D., Golden, J. S., & Bryan, H. (2010). An integrated empirical and modeling methodology for analyzing solar reflective roof technologies on commercial buildings. *Building and Environment, 45*(2), 453–460. https://doi.org/10.1016/j.buildenv.2009.07.001.

Karlessi, T., Santamouris, M., Apostolakis, K., Synnefa, A., & Livada, I. (2009). Development and testing of thermochromic coatings for buildings and urban structures. *Solar Energy, 83*(4), 538–551. https://doi.org/10.1016/j.solener.2008.10.005.

Kolokotroni, M., & Giridharan, R. (2008). Urban heat island intensity in London: An investigation of the impact of physical characteristics on changes in outdoor air temperature during summer. *Solar Energy, 82*(11), 986–998. https://doi.org/10.1016/j.solener.2008.05.004.

Kusaka, H., Kondo, H., Kikegawa, Y., & Kimura, F. (2001). A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. *Boundary-Layer Meteorology, 101*(3), 329–358. https://doi.org/10.1023/A:1019207923078.

Levinson, R., Berdahl, P., & Akbari, H. (2005). Solar spectral optical properties of pigments—Part II: Survey of common colorants. *Solar Energy Materials and Solar Cells, 89*(4), 351–389. https://doi.org/10.1016/j.solmat.2004.11.013.

Levinson, R., Akbari, H., & Reilly, J. C. (2007). Cooler tile-roofed buildings with near-infrared-reflective non-white coatings. *Building and Environment, 42*(7), 2591–2605. https://doi.org/10.1016/j.buildenv.2006.06.005.

Levinson, R., Chen, S., Ferrari, C., Berdahl, P., & Slack, J. (2017). Methods and instrumentation to measure the effective solar reflectance of fluorescent cool surfaces. *Energy and Buildings, 152*, 752–765. https://doi.org/10.1016/j.enbuild.2016.11.007.

Li, D., & Bou-Zeid, E. (2013). Synergistic interactions between urban heat islands and heat waves: The impact in cities is larger than the sum of its parts. *Journal of Applied Meteorology and Climatology, 52*(9), 2051–2064. https://doi.org/10.1175/JAMC-D-13-02.1.

Li, D., Bou-Zeid, E., & Oppenheimer, M. (2014). The effectiveness of cool and green roofs as urban heat island mitigation strategies. *Environmental Research Letters, 9*(5). https://doi.org/10.1088/1748-9326/9/5/055002.

Libbra, A., Tarozzi, L., Muscio, A., & Corticelli, M. A. (2011). Spectral response data for development of cool coloured tile coverings. *Optics and Laser Technology, 43*(2), 394–400. https://doi.org/10.1016/j.optlastec.2009.07.001.

Lynch, P. (2008). The origins of computer weather prediction and climate modeling. *Journal of Computational Physics, 227*(7), 3431–3444. https://doi.org/10.1016/j.jcp.2007.02.034.

Manni, M., Lobaccaro, G., Goia, F., Nicolini, A., & Rossi, F. (2019). Exploiting selective angular properties of retro-reflective coatings to mitigate solar irradiation within the urban canyon. *Solar Energy, 189*, 74–85. https://doi.org/10.1016/j.solener.2019.07.045.

Martilli, A., Clappier, A., & Rotach, M. W. (2002). An urban surface exchange parameterisation for mesoscale models. *Boundary-Layer Meteorology, 104*(2), 261–304. https://doi.org/10.1023/A:1016099921195.

Masson, V. (2000). A physically-based scheme for the urban energy budget in atmospheric models. *Boundary-Layer Meteorology, 94*(3), 357–397. https://doi.org/10.1023/A:1002463829265.

Nie, X., Yoo, Y., Hewakuruppu, H., Sullivan, J., Krishna, A., & Lee, J. (2020). Cool white polymer coatings based on glass bubbles for buildings. *Scientific Reports, 10*(1). https://doi.org/10.1038/s41598-020-63027-2.

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society, 108*(455), 1–24. https://doi.org/10.1002/qj.49710845502.

Park, B., & Krarti, M. (2016). Energy performance analysis of variable reflectivity envelope systems for commercial buildings. *Energy and Buildings, 124*, 88–98. https://doi.org/10.1016/j.enbuild.2016.04.070.

Perez, G., Allegro, V. R., Corroto, M., Pons, A., & Guerrero, A. (2018). Smart reversible thermochromic mortar for improvement of energy efficiency in buildings. *Construction and Building Materials, 186*, 884–891. https://doi.org/10.1016/j.conbuildmat.2018.07.246.

Pigliautile, I., Chàfer, M., Pisello, A. L., Pérez, G., & Cabeza, L. F. (2020). Inter-building assessment of urban heat island mitigation strategies: Field tests and numerical modelling in a simplified-geometry experimental set-up. *Renewable Energy, 147*, 1663–1675. https://doi.org/10.1016/j.renene.2019.09.082.

Piselli, C., Saffari, M., de Gracia, A., Pisello, A. L., Cotana, F., & Cabeza, L. F. (2017). Optimization of roof solar reflectance under different climate conditions, occupancy, building configuration and energy systems. *Energy and Buildings, 151*, 81–97. https://doi.org/10.1016/j.enbuild.2017.06.045.

Piselli, C., Pisello, A. L., Saffari, M., de Gracia, A., Cotana, F., & Cabeza, L. F. (2019). Cool roof impact on building energy need: The role of thermal insulation with varying climate conditions. *Energies, 12*(17). https://doi.org/10.3390/en12173354.

Pisello, A. L. (2015). Experimental analysis of cool traditional solar shading systems for residential buildings. *Energies, 8*(3), 2197–2210. https://doi.org/10.3390/en8032197.

Pisello, A. L., & Cotana, F. (2014). The thermal effect of an innovative cool roof on residential buildings in Italy: Results from two years of continuous monitoring. *Energy and Buildings, 69*, 154–164. https://doi.org/10.1016/j.enbuild.2013.10.031.

Pisello, A. L., Pignatta, G., Castaldo, V. L., & Cotana, F. (2014). Experimental analysis of natural gravel covering as cool roofing and cool pavement. *Sustainability (Switzerland), 6*(8), 4706–4722. https://doi.org/10.3390/su6084706.

Pisello, A. L., Castaldo, V. L., Pignatta, G., Cotana, F., & Santamouris, M. (2016a). Experimental in-lab and in-field analysis of waterproof membranes for cool roof application and urban heat island mitigation. *Energy and Buildings, 114*, 180–190. https://doi.org/10.1016/j.enbuild.2015.05.026.

Pisello, A. L., Fortunati, E., Mattioli, S., Cabeza, L. F., Barreneche, C., Kenny, J. M., & Cotana, F. (2016b). Innovative cool roofing membrane with integrated phase change materials: Experimental characterization of morphological, thermal and optic-energy behavior. *Energy and Buildings, 112*, 40–48. https://doi.org/10.1016/j.enbuild.2015.11.061.

Pisello, A. L., Castaldo, V. L., Fabiani, C., & Cotana, F. (2016c). Investigation on the effect of innovative cool tiles on local indoor thermal conditions: Finite element modeling and continuous monitoring. *Building and Environment, 97*, 55–68. https://doi.org/10.1016/j.buildenv.2015.11.038.

Pisello, A.L., Paolini, R., Diamanti, M. V., Fortunati, E., Castaldo, V., & Torre, L. (2016d). Nanotech-based cool materials for building energy efficiency. In F. Pacheco Torgal, C. Buratti, S. Kalaiselvam, C.-G. Granqvist, & V. Ivanov (Eds.), *Nano and biotech based materials for energy building efficiency*. (pp. 245–278), Springer International Publishing. https://doi.org/10.1007/978-3-319-27505-5_9.

Pisello, A. L., Castaldo, V. L., Piselli, C., Fabiani, C., & Cotana, F. (2017). Thermal performance of coupled cool roof and cool façade: Experimental monitoring and analytical optimization procedure. *Energy and Buildings, 157*, 35–52. https://doi.org/10.1016/j.enbuild.2017.04.054.

Qin, Y., Liang, J., Tan, K., & Li, F. (2016). A side by side comparison of the cooling effect of building blocks with retro-reflective and diffuse-reflective walls. *Solar Energy, 133*, 172–179. https://doi.org/10.1016/j.solener.2016.03.067.

Qu, Y., Milliez, M., Musson-Genon, L., & Carissimo, B. (2012). Numerical study of the thermal effects of buildings on low-speed airflow taking into account 3D atmospheric radiation in urban canopy. *Journal of Wind Engineering and Industrial Aerodynamics, 104–106*, 474–483. https://doi.org/10.1016/j.jweia.2012.03.008.

Ramamurthy, P., Bou-Zeid, E., Smith, J. A., Wang, Z., Baeck, M. L., Saliendra, N. Z., et al. (2014). Influence of subfacet heterogeneity and material properties on the urban surface energy budget. *Journal of Applied Meteorology and Climatology, 53*(9), 2114–2129. https://doi.org/10.1175/JAMC-D-13-0286.1.

Revel, G. M., Martarelli, M., Emiliani, M., Celotti, L., Nadalini, R., De Ferrari, A., Hermanns, S., & Beckers, E. (2014). Cool products for building envelope–Part II: Experimental and numerical evaluation of thermal performances. *Solar Energy, 105*, 780–791. https://doi.org/10.1016/j.solener.2014.02.035.

Rossi, F., Morini, E., Castellani, B., Nicolini, A., Bonamente, E., Anderini, E., & Cotana, F. (2015a). Beneficial effects of retroreflective materials in urban canyons: Results from seasonal monitoring campaign. *Journal of Physics: Conference Series, 655*(1). https://doi.org/10.1088/1742-6596/655/1/012012.

Rossi, F., Castellani, B., Presciutti, A., Morini, E., Filipponi, M., Nicolini, A., & Santamouris, M. (2015b). Retroreflective façades for urban heat island mitigation: Experimental investigation and energy evaluations. *Applied Energy, 145*, 8–20. https://doi.org/10.1016/j.apenergy.2015.01.129.

Rossi, F., Castellani, B., Presciutti, A., Morini, E., Anderini, E., Filipponi, M., & Nicolini, A. (2016). Experimental evaluation of urban heat island mitigation potential of retro-reflective pavement in urban canyons. *Energy and Buildings, 126*, 340–352. https://doi.org/10.1016/j.enbuild.2016.05.036.

Rosso, F., Pisello, A. L., Castaldo, V. L., Fabiani, C., Cotana, F., Ferrero, M., & Jin, W. (2017a). New cool concrete for building envelopes and urban paving: Optics-energy and thermal assessment in dynamic conditions. *Energy and Buildings, 151*, 381–392. https://doi.org/10.1016/j.enbuild.2017.06.051.

Rosso, F., Pisello, A. L., Castaldo, V. L., Ferrero, M., & Cotana, F. (2017b). On innovative cool-colored materials for building envelopes: Balancing the architectural appearance and the thermal-energy performance in historical districts. *Sustainability (Switzerland), 9*(12). https://doi.org/10.3390/su9122319.

Saafi, K., & Daouas, N. (2018). A life-cycle cost analysis for an optimum combination of cool coating and thermal insulation of residential building roofs in Tunisia. *Energy, 152*, 925–938. https://doi.org/10.1016/j.energy.2018.04.010.

Saitoh, T. S., Shimada, T., & Hoshi, H. (1996). Modeling and simulation of the Tokyo urban heat island. *Atmospheric Environment, 30*(20), 3431–3442. https://doi.org/10.1016/1352-2310(95)00489-0.

Santamouris, M. (2014). Cooling the cities—A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy, 103*, 682–703. https://doi.org/10.1016/j.solener.2012.07.003.

Santamouris, M., Synnefa, A., Kolokotsa, D., Dimitriou, V., & Apostolakis, K. (2008). Passive cooling of the built environment – use of innovative reflective materials to fight heat islands and decrease cooling needs. *International Journal of Low-Carbon Technologies, 3*(2), 71–82. https://doi.org/10.1093/ijlct/3.2.71

Santamouris, M., Synnefa, A., & Karlessi, T. (2011). Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Solar Energy, 85*(12), 3085–3102. https://doi.org/10.1016/j.solener.2010.12.023.

Santamouris, M., Gaitani, N., Spanou, A., Saliari, M., Giannopoulou, K., Vasilakopoulou, K., & Kardomateas, T. (2012). Using cool paving materials to improve microclimate of urban

areas—Design realization and results of the flisvos project. *Building and Environment, 53*, 128–136. https://doi.org/10.1016/j.buildenv.2012.01.022.
Sleiman, M., Kirchstetter, T. W., Berdahl, P., Gilbert, H. E., Quelen, S., Marlot, L., et al. (2014). Soiling of building envelope surfaces and its effect on solar reflectance—Part II: Development of an accelerated aging method for roofing materials. *Solar Energy Materials and Solar Cells, 122*, 271–281. https://doi.org/10.1016/j.solmat.2013.11.028.
Susan, C. (2007). Urbanization and global environmental change: Local effects of urban warming. *Geographical Journal, 60*, 83–87. https://doi.org/10.1111/j.1475-4959.2007.232.
Synnefa, A., & Santamouris, M. (2016). Mitigating the urban heat with cool materials for the buildings' fabric. *Urban Climate Mitigation Techniques*, 67–92. https://doi.org/10.4324/9781315765839.
Synnefa, A., Santamouris, M., & Akbari, H. (2007). Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. *Energy and Buildings, 39*(11), 1167–1174. https://doi.org/10.1016/j.enbuild.2007.01.004.
Synnefa, A., Karlessi, T., Gaitani, N., Santamouris, M., Assimakopoulos, D. N., & Papakatsikas, C. (2011). Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate. *Building and Environment, 46*(1), 38–44. https://doi.org/10.1016/j.buildenv.2010.06.014.
Toparlar, Y., Blocken, B., Maiheu, B., & van Heijst, G. J. F. (2017). A review on the CFD analysis of urban microclimate. *Renewable and Sustainable Energy Reviews, 80*, 1613–1640. https://doi.org/10.1016/j.rser.2017.05.248.
Vardoulakis, S., Dimitroulopoulou, C., Thornes, J., Lai, K. M., Taylor, J., Myers, I., et al. (2015). Impact of climate change on the domestic indoor environment and associated health risks in the UK. *Environment International, 85*, 299–313. https://doi.org/10.1016/j.envint.2015.09.010.
Vukovich Dunn, F. M. J. W., & Crissman, B. W. (1976). A theoretical study of the St. Louis Heat Island: The wind and temperature distribution. *Journal of Applied Meteorology, 15*(5), 417–440. https://doi.org/10.1175/1520-0450(1976)0152.0.CO;2.
Wang, X., Kendrick, C., Ogden, R., & Maxted, J. (2008). Dynamic thermal simulation of a retail shed with solar reflective coatings. *Applied Thermal Engineering, 28*(8–9), 1066–1073. https://doi.org/10.1016/j.applthermaleng.2007.06.011.
Xie, N., Li, H., Abdelhady, A., & Harvey, J. (2019). Laboratorial investigation on optical and thermal properties of cool pavement nano-coatings for urban heat island mitigation. *Building and Environment, 147*, 231–240. https://doi.org/10.1016/j.buildenv.2018.10.017.
Xu, X., González, J. E., Shen, S., Miao, S., & Dou, J. (2018). Impacts of urbanization and air pollution on building energy demands—Beijing case study. *Applied Energy, 225*, 98–109. https://doi.org/10.1016/j.apenergy.2018.04.120.
Yang, Y. K., Kang, I. S., Chung, M. H., Kim, S. M., & Park, J. C. (2017). Effect of PCM cool roof system on the reduction in urban heat island phenomenon. *Building and Environment, 122*, 411–421. https://doi.org/10.1016/j.buildenv.2017.06.015.
Yiping, M., Xiong, Z., Beirong, Z., & Keru, W. (2002). Research on reversible effects and mechanism between the energy-absorbing and energy-reflecting states of chameleon-type building coatings. *Solar Energy, 72*(6), 511–520. Retrieved from http://cat.inist.fr/?aModele=afficheN&cpsidt=13841821.
Zhang, J., Zhang, K., Liu, J., & Ban-Weiss, G. (2016). Revisiting the climate impacts of cool roofs around the globe using an Earth system model. *Environmental Research Letters, 11*(8). https://doi.org/10.1088/1748-9326/11/8/084014.
Zhang, N., Chen, Y., Luo, L., & Wang, Y. (2017). Effectiveness of different urban heat island mitigation methods and their regional impacts. *Journal of Hydrometeorology, 18*(11), 2991–3012. https://doi.org/10.1175/JHM-D-17-0049.1.
Zhang, J., Mohegh, A., Li, Y., Levinson, R., & Ban-Weiss, G. (2018). Systematic comparison of the influence of cool wall versus cool roof adoption on urban climate in the Los Angeles basin. *Environmental Science and Technology, 52*(19), 11188–11197. https://doi.org/10.1021/acs.est.8b00732.

Zhao, L., Oppenheimer, M., Zhu, Q., Baldwin, J. W., Ebi, K. L., Bou-Zeid, E., et al. (2018). Interactions between urban heat islands and heat waves. *Environmental Research Letters, 13*(3). https://doi.org/10.1088/1748-9326/aa9f73.

Zhou, Y., & Marshall Shepherd, J. (2010) Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies. *Natural Hazards, 52*(3), 639–668. https://doi.org/10.1007/s11069-009-9406-z

Zinzi, M. (2016). Exploring the potentialities of cool facades to improve the thermal response of Mediterranean residential buildings. *Solar Energy, 135*, 386–397. https://doi.org/10.1016/j.solener.2016.06.021.

Zinzi, M., & Fasano, G. (2009). Properties and performance of advanced reflective paints to reduce the cooling loads in buildings and mitigate the heat island effect in urban areas. *International Journal of Sustainable Energy, 28*(1–3), 123–139. https://doi.org/10.1080/14786450802453314.

Zinzi, M., Carnielo, E., & Agnoli, S. (2012). Characterization and assessment of cool coloured solar protection devices for Mediterranean residential buildings application. *Energy and Buildings, 50*, 111–119. https://doi.org/10.1016/j.enbuild.2012.03.031.