Using advanced Urban Canopy Models to investigate the potential of thermochromic materials as urban heat island mitigation strategies

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ABSTRACT

Recent trends in urbanization processes are causing serious threats at both local and global environmental scale. Greenhouse gas emissions, heat waves, and the heat island effect are constantly growing in intensity and produce increasing discomfort and health impacts in urban populations. In this context, the building sector is currently developing advanced and adaptive materials for building envelope and paving surface applications characterized by high energy performance and low embodied energy. Most of these innovative materials are firstly analysed at the component scale by means of laboratory investigations, while their effect on the built environment is generally assessed at a later stage, by means of advanced computer simulations in buildings and urban microclimate monitoring or modelling. In this context, this work focuses on the evaluation of the UHI modulation potential of materials with advanced dynamic optical properties, i.e. variable surface albedo, for surface urban canyon applications. Specifically, the Princeton Urban Canopy Model (PUCM) is applied with the aim of investigating the potential of advanced urban roofing material to modulate the urban heat island. The aim is to minimize the heat island in the summer but to let it develop in the winter, using roofing applications characterized by a dynamic temperature-dependent optical behavior. In particular, the effect of thermochromic materials on local energy transport phenomena is assessed and benchmarked against more common cool roof solutions. Results show that the modified UCM can effectively be implemented to represent temperature-dependent albedo variations. Additionally, this study demonstrates that using thermochromic materials produces a smart optical response to local environmental stimuli and allows enhanced short wave solar reflection in summer conditions, reduced reflected solar fraction in winter, and adaptive properties during transition periods.

KEYWORDS

Urban Canopy Model, Urban Heat Island, Building Envelope, Roof Albedo, Urban Canyon, Thermochromic materials.

INTRODUCTION

An urban heat island (UHI) is a metropolitan area that is much warmer than its rural surroundings, where the maximum temperatures occur within its densest parts (Kolokotroni and Giridharan, 2008; Giannopoulou et al., 2011). Recent research contributions suggest that even relatively small cities, i.e. of just over 200,000 people, could be affected by this detrimental phenomenon, which consequently could be more common than expected (Borbora and Das, 2014; O'Malley et al. 2015). All this considered, a deeper understanding of the main causes and effects of the UHI is nowadays of paramount importance, together with the development of ever more effective mitigation strategies and solutions. The existing literature acknowledges several mitigation strategies such as air ventilation, shading of buildings,

expansion of green surfaces, use of water and use of high albedo materials on buildings' surfaces (O'Malley et al. 2015). In particular, using cool roofing materials has been found to be highly effective in reducing both surface and air temperature peaks in the urban environment in summer (Takebayashi and Moriyama, 2012). However, they were also found to negatively affect the same parameters in winter conditions, were a roof with a law albedo value allows to increase the solar gains through the building walls, and consequently, reduce the building energy use (Hosseini and Akbari 2014; Pisello et al., 2016). All this considered, some researchers have investigated the possibility of using thermochromic pigments, i.e. parcels that respond to the surrounding environment by reversibly changing their colour from darker to lighter tones as the temperature rises (Ma et al., 2001), to produce innovative building coatings (Karlessi et al., 2008).
In this work, the Princeton Urban Canopy Model (PUCM) (Li et al. 2014; Yang and Wang 2015) is used to investigate the potential of such dynamic albedo materials as UHI mitigation strategies in the summer, while also investigating their possible countereffect in winter.

METHODS

The Princeton UCM adopts the single-layer "big-canyon" representation for urban areas, and uses an advanced surface exchange scheme, coupling the transport of energy and water inside urban canopies. It considers the one-dimensional energy balance for an infinitesimally-thin surface layer of each considered *i-th* surface (i = ground, wall and roof), at the surface-air interface, which can be expressed as:

$$R_n = H + LE + G \tag{1}$$

where R_n is the net radiation, H is the sensible heat flux, LE is the latent heat flux (from soil evapotranspiration and/or plant transpiration) and G is the heat storage term (flux into the surface). The net radiation R_n is defined as the sum of the net shortwave and longwave radiation from each considered surface i (i = ground, wall and roof), S_i^{net} and L_i^{net}, respectively. The shortwave component is defined based on the multiple reflection scheme (up to 2 reflections) according to equation 2:

$$S_i^{net} = (1-\alpha_i)S_i^{total} + \sum_j^3 \alpha_j S_j^{total} \frac{A_j}{A_i} \psi_{j\to i}(1-\alpha_i) + \sum_j^3 \alpha_j S_j^{total} \sum_k^3 \frac{A_j}{A_k} \psi_{j\to k} \alpha_k \frac{A_k}{A_i} \psi_{k\to i} \tag{2}$$

where α_i is the albedo, $\psi_{j\to i}$ is the view factor from surface j to surface i, S_i^{total} is the total shortwave radiation per unit area incident on surface i, and A_i is the area of surface i relative to the canyon width or sky area in two dimensions (W).
While the longwave component is defined as:

$$L_i^{net} = \sum_j^4 \varepsilon_i L_j \frac{A_j}{A_i} \psi_{j\to i} + \sum_j^4 L_j \sum_k^3 \frac{A_j}{A_k} \psi_{j\to k} (1-\varepsilon_k) \frac{A_k}{A_i} \psi_{k\to i} - \varepsilon_i \sigma T_i^4 \tag{3}$$

where ε is the emissivity, σ is the Stephan–Boltzmann constant, T_i is the surface temperature of the i^{th} surface, and L is the flux of longwave radiation emitted from each surface or the downward longwave radiation from the sky. Here, the j index denotes ground, walls, trees, or sky, and the k index denotes ground, walls, or trees only.

The Princeton UCM implements an explicit resolution for sub-facet heterogeneity in building walls, rooftops and ground facet, each of which is independently modeled by using unique physical and thermal attributes. Consequently, the thermo-optical properties of every single surface introduced in the model may be separately controlled. In this work, the albedo of the roof is dynamically defined as a function of the roof temperature at the outermost layer that responds in a finite time (not instantly) to temperature changes according to:

$$\alpha(T) = \alpha_{dark} + \frac{\alpha_{cool} - \alpha_{dark}}{2}(1 + erf(t_{norm}(T))) \tag{4}$$

where $\alpha(T)$ is the albedo at temperature T, α_{dark} is the albedo for temperatures below the thermochromic transition temperature (T_{tc} = 30°C), α_{cool} is the albedo for temperatures above the thermochromic transition temperature, $erf(t_{norm})$ is the error function, and t_{norm} is the normalized time, defined as a function of the thermochromic transition interval t_{TC} and, consequently, of the roof surface temperature. The thermochromic transition interval was selected to be 20 minutes based of previous researches (Karlessi et al., 2008).

Three different roof configurations where considered and compared in this work: dark roof ($\alpha=0.15$), thermochromic roof ($\alpha=0.15 \rightarrow 0.75$), and cool roof ($\alpha=0.75$). Each configuration was simulated for 4 different months: May, July, October 2011, and January 2012, and finally average day profiles where defined for each of them.

The simulations were carried out considering an urban canyon located in Princeton (NJ), characterized by an aspect ratio (building height over street width) of 0.80 and a built-up area fraction equal to 0.84. Local environmental boundary conditions obtained from a dedicated weather station, with a sampling rate of 30 minutes also placed in Princeton were used as forcing constraints in each of the three-considered scenario. More in detail, the model was driven by air temperature, specific humidity, atmospheric pressure, wind speed, shortwave radiation, longwave radiation and precipitation values, which were interpolated from the original weather data to fit the simulation time interval (10 seconds), throughout the simulation.

RESULTS AND DISCUSSIONS

Results for the four months simulations are shown in Figure 1; depicted are the roof surface temperature (*TR*), sensible heat flux (*HR*) and latent heat flux (*LER*) of the three considered roof configurations. As can be seen, the dark roof always presents the highest values for all the considered months, while the cool roof is always associated with the lowest surface temperature and heat fluxes. This behavior is good in terms of UHI mitigation potential during the hottest months, but inevitably reduces the heat gains during winter, causing a more intense energy consumption for heating purposes in this period of the year and negating some of the winter-time benefits of the UHI at the city scale. The thermochromic roof, on the other hand, shows the interesting ability to dampen the heat gains during summer, producing a more stable temperature profile during the average day of the month in May and July, while preserving the beneficial behavior of the dark roof in October and January, when the thermochromic transition temperature is almost never reached, and consequently the roof keeps a lower albedo and is able to absorb heat from the incident incoming radiation.

Table 1 summarizes the maximum and minimum temperature and heat flux values observed in the three considered configurations for the four simulated months. As expected, the thermochromic roof is characterized by an intermediate behavior that allows it to closely approach the cool roof profile during the hottest months (34.0 vs 33.5°C of maximum temperature for the thermochromic and the cool configuration, respectively), and reproduce the dark roof behavior in the cooler months (TRmin = –1.8°C in both cases).

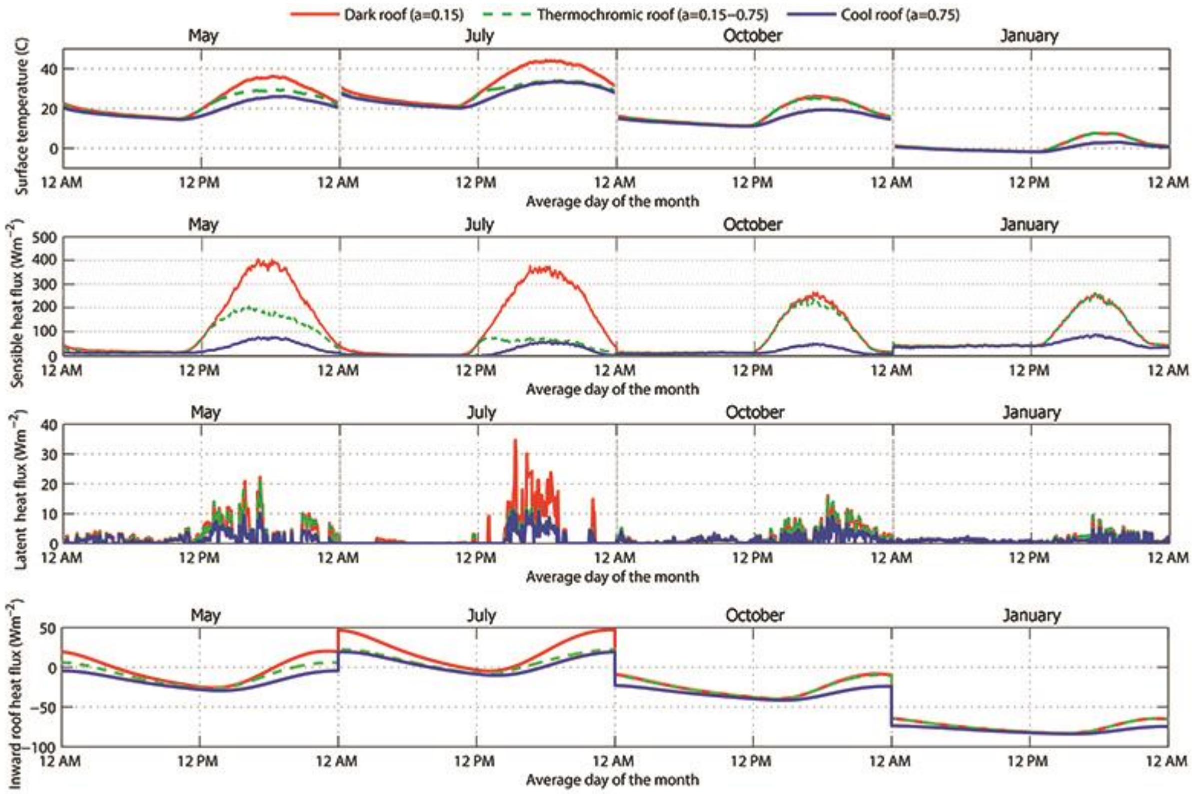

Figure 1. Roof surface temperature, sensible and latent heat flux, and inward heat flux for the three considered roof configurations, i.e. dark, thermochromic and cool roof.

Large differences can also be observed when the roof sensible (*HR*) and the latent (*LER*) heat fluxes are considered. More in detail, the thermochromic roof reduces the maximum sensible heat flux released in the atmosphere from 430.4 to 288.1 Wm^{-2} when compared to the dark roof configuration, which is a significant reduction in terms of UHI mitigation potential, although lower than the one obtained in the cool roof configuration, i.e. 86.7 Wm^{-2}. As for the latent heat flux, of course the minimum value is not different from one configuration to the other, but the maximum one was found to be equal to 38.3, 20.7 and 11.8 Wm^{-2} for the dark, the thermochromic and the cool roof configuration, respectively.

Finally, the heat flux at the interface between the indoor air domain and the internal roof surface is reduced from 47.2 Wm^{-2} in the dark roof configuration to 22.5 Wm^{-2} in the thermochromic roof, and to 19.6 Wm^{-2} in the cool roof one. In winter conditions, on the other hand, the introduction of the dynamic albedo reduces the outward heat losses obtained using the cool roof configuration only from –83.8 to –83.1 Wm^{-2} (in this case the minus sign denotes that the heat flux is transferred from the inside towards the outer environment). This ability to absorb heat in the winter is a beneficial advantage of the thermochromic roof.

The atypical temperature and heat fluxes profiles obtained for the thermochromic roof is a consequence of its dynamic nature that allows it to adjust its ability to reflect the incoming radiation as a function of the local surface temperature. Figure 2 shows the albedo variation profile obtained for the thermochromic roof during a representative week in May. As can be seen, each time the roof temperature overcomes the thermochromic transition temperature T_{TC}, the albedo starts to increase, and finally reaches the cool roof limit value of 0.75.

Table 1. Considered scenarios with the respective albedo values and the obtained maximum and minimum roof temperature (TR), sensible heat flux (HR), latent heat flux (LER) at the outer surface, and the heat flux at the inner surface (Qin) values.

	Dark roof (DR)	Thermochromic roof (TCR)	Cool roof (CR)
Albedo (-)	0.15	0.15→0.75	0.75
TRmax (°C)	44.2	34.0	33.5
TRmin (°C)	–1.8	–1.8	–1.8
HRmax (Wm^{-2})	430.4	288.1	86.7
HRmin (Wm^{-2})	–0.03	–0.46	–1.06
LERmax (Wm^{-2})	38.3	20.7	11.8
LERmin (Wm^{-2})	0	0	0
QinRmax (Wm^{-2})	–83.1	–83.1	–83.8
QinRmin (Wm^{-2})	47.2	22.5	19.6

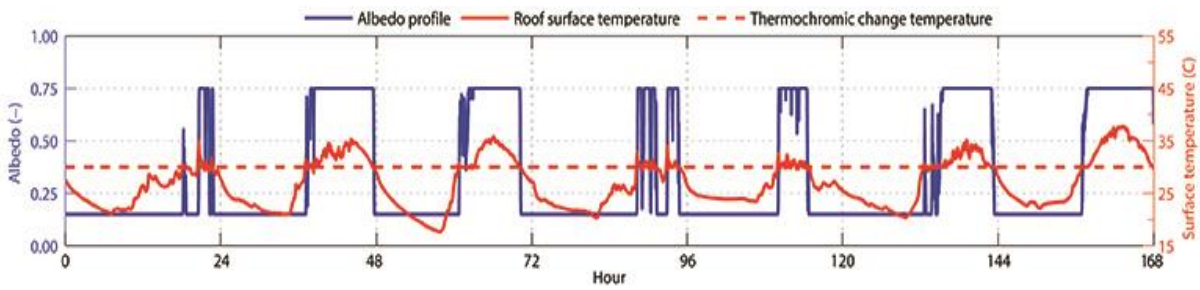

Figure 2. Albedo profile and roof surface temperature during a typical week in May for the thermochromic roof.

CONCLUSIONS

In this work, the UHI mitigation potential of an innovative thermochromic roof, capable of dynamically changing its albedo between 0.15 and 0.75 was investigated and compared to more common solutions such as a classic dark roof (α=0.15) and a high performance cool roof (α=0.75). The three roof configurations where investigated considering four different months-long simulations in order to evaluate the performance of the roofs in summer and winter conditions (July 2011 and January 2012), as well as during transition periods (May and October 2011). Results confirm that the thermochromic roof’s ability to dynamically change its albedo to reflect the incoming solar radiation in response to the surface roof temperature has beneficial impacts. More in detail, when the roof surface is characterized by temperatures below the transition threshold, the thermochromic configuration behaves as a classic dark roof, allowing the overall urban surface to absorb heat in the form of solar heat gains. This reduces the winter penalty of the high performance cool roof and reproduces the temperature and heat flux profiles of the more convenient dark roof configuration during cooler periods.

Every time the roof surface overcomes the transition threshold temperature, on the other hand, the thermochromic roof starts to change its albedo, and within a maximum time of 20 minutes (coloring or decoloring time interval) behaves as a high albedo roof with high solar reflectance capability. Consequently, the thermochromic coating allows to reduce the heat gains during warmer months and reduces both the roof surface temperature and heat fluxes, which will positively affect the UHI effect in its surroundings.

In conclusion, the use of thermochromic coatings in building roofs can indeed be considered as an interesting solution to mitigate the increase of air temperatures in the urban environment during summer, while maintaining the positive absorption of solar radiation in winter. Future research should, however, be conducted in order to investigate the effect of thermochromic materials with different transition temperatures and albedo variation profiles. Additionally, it would be interesting to quantify the benefits associated with this innovative roof configuration in terms of resulting building energy loads and consumption, and also to quantify its consequences on the overall urban microclimate.

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