On the Use of Cool Materials as a Heat Island Mitigation Strategy

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ABSTRACT

The mitigation of the heat island effect can be achieved by the use of cool materials that are characterized by high solar reflectance and infrared emittance values. Several types of cool materials have been tested and their optical and thermal properties reveal that these materials can be classified as “cool” with the ability to maintain lower surface temperatures. Cool materials can be used on buildings and other surfaces of the urban environment. Based on these results, a modeling study was undertaken to assess the urban heat island effect over Athens, Greece, a densely populated city, by trying to analyze the impacts of large-scale increases in surface albedo on ambient temperature. Numerical simulations were performed by the “urbanized” version of the nonhydrostatic fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5, version 3-6-1). Two scenarios of modified albedo were studied: a moderate and an extreme increase in albedo scenario. It was found that large-scale increases in albedo could lower ambient air temperatures by 2°C. Furthermore, the impact of high albedo measures on heat island magnitude was estimated by creating a spatial representation of the urban heat island effect over the modeled area. The results of this study can help to promote the adoption of high albedo measures in building energy codes and urban planning regulations.

1. Introduction

The ambient temperature in urban areas is usually several degrees higher than that of their surrounding suburban and rural areas. This phenomenon is called “the heat island effect” and represents a significant change in the urban microclimate. Summer urban heat islands (UHIs) with daytime air temperatures of 1°–6°C higher than the surrounding rural areas are present in many cities around the world (Taha 1997a; Santamouris 2006). In Athens, Greece, according to climatic measurements performed at 30 urban and suburban stations during the summer of 1997, the daily heat island intensity was found to be close to 10°C (Santamouris et al. 1999; Santamouris 2001; Mihalakakou et al. 2002; Livada et al. 2002). Among the causative factors of the heat island effect are the lower albedo of urban surfaces and the replacement of vegetation by building structures. Urban structures absorb solar energy, causing their surface temperature to become several degrees higher than the ambient air temperatures, and as surfaces become warmer, overall ambient temperature increases. Increased ambient temperatures are responsible for thermal discomfort and also for rising cooling energy consumption, energy demand, and energy prices (Akbari et al. 1992; Hassid et al. 2000; Santamouris et al. 2001). Furthermore, heat islands can lead to worsened air quality because the rate of photochemical ozone production is accelerated at higher temperatures and the emissions of ozone precursors are increased (Taha et al. 1994).

The causes of the urban heat island can lead to the approaches that could reduce the intensity of the urban heat island effect. Specifically, if the albedo and/or vegetative cover can be increased in urban areas there is the prospect for reducing urban air temperatures with the associated benefits in terms of air quality and energy consumption. Field measurements and modeling studies support these conclusions.

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Direct field observations verify the impact of high albedo surfaces on near-surface air temperatures. Experimental measurements were carried out at White Sands Monument in New Mexico, an area that has a high albedo (≈0.6) because its surface is composed of white gypsum and little vegetation, and also in the surrounding desert area, which has an albedo of 0.26. Experimental results have shown that in the morning hours, the air over White Sands Monument was 3°C cooler than the air over the surrounding dark surface. It was also found that the air remained cooler throughout daytime hours, but the amount of cooling was reduced later in the day because of increased upwelling (Fishman et al. 1994).

Although the micrometeorological and energy impacts of various surface modification strategies have been evaluated in the field, assessing the potential effects from large-scale increases in albedo can only be done via numerical simulation and a lot of research is still required in this field. To study the impacts of large-scale increases in albedo on urban climate, mesoscale meteorological models are used, for example, the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) and the Colorado State University Mesoscale Model (CSUMM) (Pielke 1974). These models are based on the solution of a set of coupled governing equations representing the conservation of mass (continuity), potential temperature (heat), momentum, and water vapor to obtain data for the prognostic of meteorological fields. Several modeling studies have suggested that urban environmental control strategies such as the increase of surface albedo can reduce surface and air temperatures and this effect is most evident in areas where such surface modifications are most concentrated. More specifically, Sailor (1993, 1995) showed by means of 3D meteorological simulations that increasing the albedo over downtown Los Angeles, California, by an average 0.08 decreased summertime temperature by as much as 1.5°C. Numerical simulations undertaken by Gabersek and Taha (1996) show that implementing heat island reduction strategies may be an effective way of reducing urban air temperatures by up to 5°C in summer. Furthermore, Taha (1997b) found that increasing the albedo of California’s South Coast Air Basin by 0.13 simulated reductions averaging 2°C. In another study on the meteorological impacts of large-scale increases in urban albedo and vegetative fraction that was carried out by Taha et al. (1999) for 10 U.S. regions, it was found that these changes can offset the 1°C–2°C heat islands present in most of the areas analyzed. Taha et al. (2000, 2002) showed that “cool city” strategies can reduce urban air temperatures by a typical 1°C–2°C for the cases of three U.S. cities and by 0.5°C–1°C for the case of the greater Toronto area, Canada. Finally, Taha (2005) reports that large-scale increases in albedo and combined large-scale increases in albedo and vegetation cover resulted in decreases in air temperature of as much as 3°C and up to 3.5°C, respectively, during some hours of the day, for the case of Los Angeles, and 1°C–1.5°C and 1.5°C–2°C, respectively, for the case of Sacramento, California. About 80% of the modifiable area is affected by increases in albedo smaller than 0.04 and increases in soil moisture (due to the addition of trees) smaller than 0.016 at model grid resolution.

This decrease in air temperature resulting from the large-scale use of cool materials [i.e., materials with high solar reflectance (SR) and infrared emittance values] can lead to a reduction of cooling energy use and peak cooling loads (Rosenfeld et al. 1998; Taha et al. 1999). It has been demonstrated that increasing the urban albedo by about 20% results in cooling energy savings that vary between 2.9% and 21% for Toronto and 62% for Sacramento (Akbari and Taha 1992; Taha et al. 1988). Akbari and Konopacki (2005) have calculated the cooling energy savings due to the application of heat island mitigation strategies (application of cool materials and increase in vegetation cover) for 240 regions in the United States. It was found that for residential buildings the cooling energy savings vary between 12% and 25%, for office buildings between 5% and 18%, and for commercial (retail stores) buildings between 7% and 17%.

Furthermore, the city-scale application of cool materials can reduce air pollution both directly and indirectly (Rosenfeld et al. 1995, 1998; Akbari et al. 2001). Direct reduction of air pollution is due to the fact that less cooling energy is used; therefore fewer power plant emissions are produced (CO₂, NOₓ, and PM10 particles). Indirect air pollution reductions reflect the fact that the reaction of ozone formation (that produces smog) accelerates at higher temperatures, therefore at lower urban air temperatures the probability of smog formation is decreased (Taha 1997b). More specifically, a number of measurements and simulation studies have demonstrated that decreasing the air temperature of Los Angeles by 1.5°C–2°C using heat island mitigation strategies results in a reduction of 10%–20% in population-weighted smog (ozone) (Taha 1994; Taha et al. 1994, 1997, 1999, 2000). It should be pointed out, however, that the occurrence of elevated ozone concentrations is a regional issue and although there is a threshold temperature above which the likelihood of smog events increases, other factors such as atmospheric and
surface transport mechanisms greatly influence the ozone distribution (Gray and Finster 1999).

This study aims to investigate the impacts of using cool materials that have the ability to increase the albedo of surfaces at city scale on ambient temperature through examination of the urban heat island effect over Athens. The city of Athens is a densely built and densely populated city, characterized by warm weather conditions and significant solar availability. The urban heat island effect is very strong in this region compared to other cities (Santamouris et al. 1999; Santamouris 2001, 2006). Such conditions allow the demonstration of the significant impact (potential) that existing cool and newly developed cool colored materials can have on the mitigation of the UHI. Numerical simulations were performed by the “urbanized” version of the nonhydrostatic MM5, version 3-6-1. Two scenarios of moderate and high increased albedo were studied and their effect on air temperature was estimated.

2. Cool materials for lower surface temperatures

Among heat island mitigation strategies, the use of cool materials has gained a lot of interest during the past few years because it is an efficient, low-cost, and easy to apply solution (Rosenfeld et al. 1995, 1998). Cool materials are characterized by high solar reflectance and infrared emittance values. The term solar reflectance designates the total reflectance of a surface (considering the hemispherical reflectance of radiation) integrated over the solar spectrum, including specular and diffuse reflection. The infrared emittance specifies how well a surface radiates energy away from itself compared with a blackbody operating at the same temperature (Siegel and Howell 2002). These two properties mainly affect the temperature of a surface (Bretz et al. 1997). Increasing either reflectance and/or emittance lowers a surface’s temperature and contributes to the decrease in temperature of the ambient air as the heat convection intensity from a cooler surface is lower. For peak solar conditions (about 1000 W m\(^{-2}\)) for an insulated surface and under a low wind condition, the temperature of a black surface with solar reflectance of 0.05 is about 50°C higher than ambient air temperature. For a white surface with solar reflectance of 0.8, the temperature rise is about 10°C.

For this study the estimates of the potential for altering the urban albedo of Athens are based on a two-dimensional analysis and do not consider vertical surfaces like walls. Furthermore, only the albedo of building structures (rooftops) was changed. For this reason, only materials that can be used on building rooftops have been considered. A number of white or light colored materials (e.g., cool surface coatings, reflective tiles, light colored marble and mosaic, concrete and conventional asphalt with white aggregate) are currently commercially available for rooftops, having high solar reflectance values ranging from 0.4 to 0.85 (Lawrence Berkeley National Laboratory 2008; Energy Star 2008). The thermal emissivity of these materials was measured to be about 0.9 (Berdahl and Bretz 1997; Synnefa et al. 2006). Surface temperature measurements have demonstrated that a cool coating can reduce a concrete tile’s surface temperature by 7.5°C and it can be 15°C cooler than a silver gray coating (Berdahl and Bretz 1997; Synnefa et al. 2006). Furthermore, new cool colored materials that are highly reflective in the near-infrared are being developed using specialized infrared reflective pigments for the situations where the aesthetics of darker colors are preferred or where the use of white-colored products produces glare problems (Akbari et al. 2004; Synnefa et al. 2007). These materials absorb in the visible range to appear to have a specific color, but they are highly reflective in the near-infrared part of the electromagnetic spectrum to maintain a high solar reflectance overall. This is very important considering the fact that about one-half of all solar power arrives as invisible near-infrared radiation. Experimental measurements have demonstrated that the maximum difference between the solar reflectance of a cool and conventional color-matched coating was 0.22 with a corresponding surface temperature difference of 10.2°C (Synnefa et al. 2007). Another study reports that the solar reflectance of commercially available products has increased to 0.30–0.45 (Akbari et al. 2005).

3. Description of the modeling method

The meteorological model used in this study is the nonhydrostatic MM5, version 3-6-1, (Grell et al. 1994), with the modified Medium-Range Forecast (MRF) urban atmospheric boundary layer scheme (Dandou et al. 2005). The MM5 numerical simulations were performed by applying the 25-category U.S. Geological Survey (USGS) land use classification scheme to provide the land-cover data for the model domains.

The land use for the numerical simulation was then updated by the information derived from satellite image analysis. In particular, one Landsat-5/Thematic Mapper image, acquired on 13 May 2003 and covering the greater Athens area, was digitally processed and analyzed to extract all urban elements greater than the size of a 30-m pixel spatial resolution. By supervised classification, an updated and more realistic representation of the urban extent was obtained. The nine land use subcategories in the urban area that were derived
from the satellite image analysis and the albedo values considered for the base-case scenario are shown in Table 1. This detailed information was used in the MRF urban scheme to construct new fields for various parameters such as albedo, roughness length, and the semiempirical coefficients for the heat storage flux within the urban limits of the city, by applying an aggregation procedure. This was achieved by providing to each 30-m pixel (from the higher-resolution domain) literature values (e.g., Grimmond et al. 1991; Grimmond and Oke 1999) for the various parameters, according to the above urban categories. Thereafter, these values were aggregated to each 4- and 0.45-km² grid cell in the MM5 modeling domains using an area-weighting scheme. Thus, the new values of the parameters, in the modified version, reflect the presence of all of the areas with different specifications within each 4- and 0.45-km² grid cell and are not related to a fixed land use type. The net all-wave radiation at the surface during the daylight hours was assumed to be reduced by the amount of heat absorbed by the buildings, so as to take into account the building effects (e.g., shadowing).

The simulated domains covered the extended areas of Europe, Greece, Attica Peninsula, and the city of Athens, respectively. The spatial resolution for the innermost nested domain (the city of Athens) was 0.67 × 0.67 km² (Fig. 1).

The initial and lateral boundary conditions for the outermost domain were provided by a coarser numerical weather prediction model—the European Centre for Medium-Range Weather Forecasts (ECMWF)—as well as sea surface temperature (SST) data every 6 h. The anthropogenic heat flux was considered to reflect mainly the transportation emissions. In particular, the anthropogenic heat flux is calculated as a temporal and spatial function of the NO emission inventory, which mainly depicts the anthropogenic activities, with a maximum value taken at 130 W m⁻² in the city center, based on the literature (Dandou et al. 2005). During the month of August (simulated day), the main source of anthropogenic heat is traffic. The maximum values of anthropogenic heat from electricity consumption and the buildings account for 6.7 and 10 W m⁻², respectively, for this month and for the city of Athens (Katsara 2007). No central heating was considered because of the summer simulated day. The simulation date is 15 August 2005, a representative clear and warm summer day. The prevailing meteorological conditions, provided by the National Observatory of Athens (NOA), are described in Table 2. Figure 2 gives the measured (by NOA) and the calculated (by the model) solar irradiance.

The above-mentioned modifications that have been proved necessary for a better representation of urban areas bring the simulated air temperature results closer to measured temperatures (Dandou et al. 2005). Grossman-Clarke et al. (2005) have also demonstrated that refined land use–land-cover classification for the Phoenix (Arizona) metropolitan area together with bulk approaches for characteristics of the urban surface energy budget significantly improve the simulated diurnal temperature cycles. Such procedures address issues regarding the appropriate use of thermal remote sensing data (Roth et al. 1989; Voogt and Oke 2003) to better describe urban surface characteristics. The surface is critical to climatological understandings, as the surface is

<table>
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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Max air temperature (°C)</td>
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<tr>
<td>Avg air temperature (°C)</td>
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</tr>
<tr>
<td>RH %</td>
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<tr>
<td>Prevailing wind direction</td>
<td>SSW</td>
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<tr>
<td>Avg wind speed (m s⁻¹)</td>
<td>3</td>
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FIG. 1. Topography contours at 50-m intervals (beginning at sea level) of the fourth nested domain.
the principal location of sinks of heat, mass, and momentum (Voogt and Oke 1997).

The base-case albedo for building structures (rooftops) was defined by the satellite image analysis and was set to 0.18. It was found by spectral reflectance measurements on small roofing materials samples that this value corresponds to a gray concrete roof, which is the typical case for the Athens metropolitan area (Stathopoulou et al. 2007). Figure 3a shows the base-case albedo scenario. Two modified albedo scenarios were chosen for the simulations based on the experimental results reported in section 2: a moderate and feasible increase in the buildings’ rooftop albedo of 0.45 ($\alpha_{bs} = 0.63$), and an extreme case where the albedo of building rooftops is considered to be 0.85. The albedo values that were chosen for the simulation were based on spectral reflectance measurements on a number of available cool and cool colored coatings and were conducted using an ultraviolet–visible–near-infrared (UV–VIS–NIR) spectrophotometer (Varian Carry 5000) fitted with a 150-mm-diameter integrating sphere (Labsphere DRA 2500) that collects both specular and diffuse radiation. The reference standard reflectance material used for the measurement was a polytetrafluoroethylene (PTFE) plate (Labsphere). Spectral reflectance data were used to calculate the solar reflectance of each sample. The calculation was done by the
weighted averaging method, using a standard solar spectrum as the weighting function. The spectrum employed is that suggested by ASTM (ASTM Standard E903–96 1996; ASTM Standard G159–91 1996). The first albedo increase scenario also accounts for the effects of albedo reduction due to weathering, aging, dust accumulation, and soiling of a roof with an initial albedo value close to 0.85.

Among the 1502 grid cells that correspond to land, 1284 grids are available for albedo modifications (i.e., including rooftop percentage). It is important to point out that the values of albedo given correspond to individual surfaces and not to the scale of a grid cell. Figures 3b and 3c depict the moderate and extreme increase in albedo scenarios of the modeling domain. As it is shown in these figures, the potential to modify the albedo is higher in the urban center and the high-density residential areas where it is easy to apply highly reflective coatings to change the rooftop albedo.

4. Simulation results

In this section the modeled impacts of increased urban albedo on air temperature are discussed. Although it is understood that all meteorological parameters (wind speed, mixing height, etc.) are affected by the surface modifications, this analysis focuses on air temperature because it is the parameter that is most relevant to the issue of heat island mitigation. Two types of analysis are presented: first, two-dimensional changes of air temperatures are shown for both scenarios, and second, time series of air temperature are given for the two scenarios simulated.

From the simulations it was found that the impact of albedo changes on temperature is quite significant. The impact of higher albedo primarily influences the regions that underwent the simulated increase in albedo. In general, the spatial distribution of temperature change correlates to the level of surface modifications in the modifiable areas. The simulations suggest that the urban areas (as well as other suburban and rural areas) are generally cooler than in the base case. The impact of albedo increase is higher from 1200 to 1500 LST. More specifically, for the moderate increase in albedo case, the temperature depression at 2-m height at 1200 LST varies between 0.5°C and 1.5°C (Fig. 4a). If the albedo is further increased (extreme albedo case), then the temperature difference from the base case varies between 1°C and 2°C, with individual depressions as high as 2.2°C (Fig. 4b). Most of the temperature depression occurs in the central and central east basin. The changes in air temperature that are observed in the majority of the areas of the modeling domain are due to the increase of the surface albedo, which results in less solar gains for the surface. There are, however, some areas that exhibit a small increase in temperature that are probably due to vertical and horizontal mixing changes. During the night, the temperature remains in general unchanged between the base case and the modified albedo scenarios (Fig. 5).

Figure 6 illustrates the mean daily temperature change for a 24-h period (15 August 2005) for the grid cells corresponding to the urban core of Athens. In this figure, the simulation results for the base case were subtracted from the simulation results for the two increased albedo scenarios. The largest impact occurs between 1200 and 1300 (LST) and corresponds to a temperature depression of 1.3°C for the moderate increase in albedo scenario and 1.6°C for the high increase in albedo scenario. In general, the typical temperature
The change pattern is a decrease during daytime and little or no decrease during the night. More specifically, the air temperature depression starts at 0900 LST and stops at around 2000 LST, but its magnitude during the day varies. The sudden drop of the temperature difference observed at 0800 and 1700 LST could probably be related to the model’s abrupt transition between stable and unstable regimes during the transition periods.

The impact of high albedo measures on heat island intensity was also estimated. A mean urban core temperature was calculated using the grid cells corresponding to the urban core for the base case and the two modified albedo scenarios. The air temperature corresponding to the surrounding cells (suburban, rural, etc.) was subtracted from the urban core’s temperature. This factor enables the analysis of the heat island generated by the urban system (heat island intensity). A spatial representation of the heat island intensity \( T_{\text{urban core}} - T_{\text{surrounding cells}} \) for the base case and the two modified albedo scenarios at 1400 LST is shown in Figs. 7. As can be observed from the figures, for the base case the heat island intensity between the urban center and the suburban and rural areas varies between 1° and 5°C, and for the urban and suburban coastal areas it varies between 2° and 6°C. This greater temperature difference between the urban core and the suburban coastal areas is probably due to the presence of sea breeze. This heat island intensity appears reduced in Figs. 7b and 7c. To investigate if the impact of the albedo increase is different for suburban rural and suburban coastal areas, the temperature difference between the urban core and these two types of suburban areas has been calculated. More specifically, the heat island intensity between the urban center and the suburban and rural areas varies between 1° and 4°C and 1° and 3°C, and for the urban and suburban coastal areas between 1° and 4°C and 1° and 3°C for the moderate and high increase in albedo scenarios, respectively.

Figures 8 and 9 depict the temporal variation of the urban heat island magnitude between the urban core and an urban coastal area (Fig. 8) as well as a suburban–rural area at the northern part of Athens (Fig. 9). As is shown in Fig. 8 the UHI between the urban center and the urban coastal area begins at around 0700 LST and reaches its maximum of about 5°–6°C between 1200 and 1400 LST. From 0300 to 0600 LST the temperature at the urban coastal area is lower than the urban center. This is probably due to the land breeze that was developed, lowering the air temperature of the urban core. For the second case (Fig. 9), there is a heat island effect (about 3°C) during the night and between 1000 and 1400 LST. For both cases the effect of increased albedo becomes apparent from 0900 to 1600 LST and it is maximized during peak solar conditions, decreasing the urban heat island effect by 1.2°–1.6°C. From the above analysis it can be concluded that although the temporal variation of the heat island magnitude is different between the urban core and the suburban rural and coastal areas, the maximum decrease of the urban heat island effect due to the application of cool materials is on average the same for both cases.

It should be pointed out that in this study, only the albedo of building rooftops has been increased. The impact of high albedo on air temperature would have been even greater if the albedo of roads and pavements had also been increased, as they represent a large portion of the urban surface area (Golden 2004). Increasing the albedo of a pavement results in reducing its surface temperature and in lowering air temperatures.

![Fig. 6. Changes in 2-m air temperature between the base case and the moderate and high increased albedo scenarios for the urban core of Athens.](http://journals.ametsoc.org/jamc/article-pdf/47/11/2846/3539701/2008jamc1830_1.pdf)
For the case of roads and pavements, the increase in albedo should be small to avoid glare problems. However, it is difficult to estimate the percentage of these kinds of surfaces available for albedo modifications, taking into account that the roads are usually covered by heavy traffic during daytime or parked cars, and pavements are shadowed by trees, other buildings, etc. Nevertheless, a decrease in air temperature of 2°C...
is quite significant. Akbari et al. (1990) report that for every degree that the temperature rises above 18°C, the peak cooling demand in Los Angeles increases by 3%, and the probability of a smog incident increases by 5% for every degree that the daily maximum temperature rises above 21°C. Large-scale increases in albedo can decrease air temperatures, cooling energy consumption, and improve air quality; however, they can also have adverse effects. For example, increasing urban albedo could result in increasing energy consumption during wintertime. Although the various relevant studies that have been carried out demonstrate that the positive effects in general outweigh the negative impacts, detailed evaluation of the costs and benefits of the various heat island mitigation strategies should be carried out before their implementation.

5. Conclusions

In this study an analysis was conducted to assess the potential impact on ambient temperatures of increasing the albedo of building rooftops at city scale. The study was carried out for the city of Athens, Greece, which is characterized by a very strong urban heat island effect compared to other cities for which similar studies have been carried out, allowing the demonstration of the significant impact (the potential) that existing cool and newly developed cool colored materials can have on the mitigation of the UHI. Numerical simulations were performed by the “urbanized” version of the nonhydrostatic MM5 (version 3-6-1) and were supplemented by information derived from satellite image analysis for the greater Athens area. Two modified albedo scenarios were studied: a moderate ($\alpha_{bs} = 0.63$) and an extreme ($\alpha = 0.85$) increase in albedo scenario. It was found that for the first case, the temperature depression at 2-m height was as high as 1.5°C and for the second case as high as 2.2°C. The typical temperature change pattern is a decrease during daytime and little or no decrease during the night. A spatial representation of the UHI and the temporal variations of its magnitude show that the implementation of high albedo strategies decreases the heat island intensity by 1°–2°C on average. The impact would have been even greater if the albedo of roads and pavements was also increased. This analysis shows that adopting large-scale high albedo measures by using building materials with high solar reflectance can significantly reduce ambient temperatures. City-scale application of cool materials will result in a reduction in energy consumption by reducing both direct radiative heating of buildings and ambient temperatures, and will improve thermal comfort levels in outdoor spaces. The use of high albedo measures together with increasing urban vegetation greatly increases the effectiveness of heat island mitigation. These measures do not require behavior modification and they can be implemented for new development as well as introduced during retrofitting and maintenance. They offer a cost-effective approach to increasing thermal comfort, reducing energy consumption and preventing air pollution, providing an important benefit for minimal cost.

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