Unintended Consequences

A Research Synthesis Examining the Use of Reflective Pavements to Mitigate the Urban Heat Island Effect

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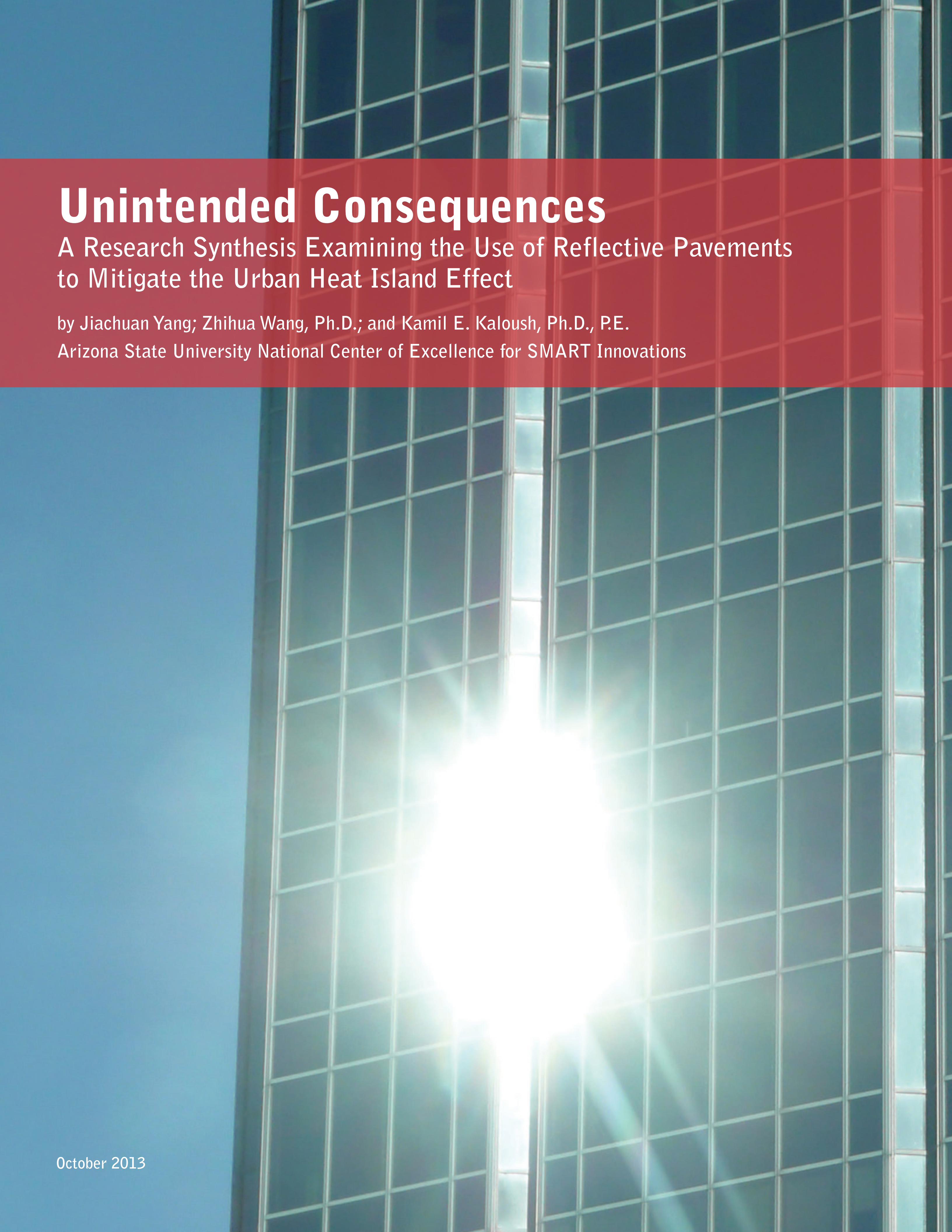

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A White Paper

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EXECUTIVE SUMMARY

The urban heat island effect (UHI), the phenomenon of higher temperatures in urban areas compared to surrounding rural areas, has resulted in scientific, legislative, health, and municipal efforts to mitigate this storage of heat within the built environment. One UHI mitigation strategy that has gained popularity focuses on retrofitting urban surfaces with high-albedo or reflective construction materials, including reflective pavements. Despite perceived benefits, this review demonstrates substantial unintended consequences associated with widespread implementation of reflective pavements, including the potential for increased cooling loads in adjacent buildings; increased heating demands during cold weather; roadway snow and ice buildup during winter months; reduction in precipitation, runoff, and soil water content; and adverse human health impacts.

High-albedo or highly reflective materials can reduce the temperature of urban surfaces like roofs and pavements by reflecting solar radiation away from these surfaces. Although the reduction in surface temperature of high-albedo roofs has been documented to reduce summertime building cooling energy requirements, no similar effect has been documented with regards to high-albedo pavements. Well publicized simulations by Lawrence Berkeley National Laboratory infer that hundreds of billions of dollars in savings due to reduced cooling energy demands can be realized through the deployment of reflective pavements. A review of these simulations, however, identifies the use of unrealistic assumptions, and the findings have not been confirmed by other modeling efforts or field studies.

On the contrary, a number of field studies and modeling efforts have found that while there can be an effect on surface temperature, there is no discernible difference in above-surface air temperature over sizeable pavements with differing albedos. Furthermore, these studies find that reflected radiation from high-albedo pavements can increase the temperature of nearby walls and buildings, increasing the cooling load of the surrounding built environment and increasing the heat discomfort of pedestrians. Harmful reflected UV radiation and glare, unintended consequences of reflective pavements, need special consideration for human health. The results presented in this review cast doubt on the idea that large-scale deployment of reflective pavements will achieve overall energy savings.

Without further detailed investigation, specification and deployment of highly reflective pavements to mitigate UHI are premature due to the unintended and adverse consequences associated with the redirected solar radiation.

1. INTRODUCTION

Urban Heat Island (UHI), the phenomenon of increase in temperature in urban areas as compared to rural surroundings, endemic to the built environment, has resulted in scientific, legislative, health, and municipal stakeholders implementing various strategies in an effort to mitigate this effect (Oke, 1982; USEPA, 2008). One method to reduce UHI is focused on retrofitting urban geometry with high-albedo or reflective construction materials. Albedo, the capacity of reflecting solar radiation of a surface, is defined as the ratio of the reflected radiation from the surface to the incident radiation upon it. The greater the albedo, i.e., the higher the reflectivity, the less the radiative energy absorbed by the surface. Reflected roofing materials have been extensively studied and widely accepted as a means to cool surface temperatures and reduce cooling energy loads for buildings with cool roofs. Moreover, this strategy has been adopted as a requirement in the 2005 version of the California Energy Efficiency Standards for Residential and Nonresidential Buildings (CEC, 2008). Due to its ability to offset greenhouse gases, as identified by Akbari et al. (2009), in 2010 the U.S. Department of Energy launched a cool roof initiative to facilitate reducing carbon emission and potentially slowing some possible precursors to climate change.

Over the past few years, the use of reflective pavement materials has been promoted as a potential mitigation strategy for the UHI effect. This paper documents substantial unintended adverse consequences of adopting reflective pavements as a UHI mitigation strategy. However, the published data regarding either benefits or adverse impacts of using reflective pavements is limited; therefore, data associated with reflective roofs is also reviewed to better understand the potential consequences of adopting reflective pavements as a UHI mitigation strategy.

Although the albedo of both pavement and roofing materials may act similarly in terms of generic physics ... heat transfer mechanisms can be vastly different due to building interactions.

While reflective roofs continue to gain popularity as a strategy to mitigate UHI, concerns about their adverse effect have also been identified. Common reported issues include elevated air temperature over rooftops, building heating penalty, moisture buildup inside roofs, high maintenance costs, and a host of other unintended and adverse consequences (Hutchinson, 2013; Liscum, 2013). Besides impacts on buildings, a recent study from Lawrence Berkeley National Laboratory (LBNL) indicates that large-scale deployment of reflective roofs in urban areas can lead to a measurable increase in temperatures in surrounding rural areas at local and regional scales (Millstein and Menon, 2011).

More recently, additional adverse effects, such as decreased precipitation at regional levels, are also reported (Bala and Nag, 2013; Doughty et al., 2011; Georgescu et al., 2012). Taking these adverse effects into consideration, large-scale planning of reflective roofs needs a more comprehensive study and thorough assessment before its implementation, especially under the condition of future climate change. Unfortunately, to date, no such study on the unintended consequence of reflective roofs exists. Existing summaries of reflective roofs are largely limited to either site-specific field testing or general overviews, which do not compare between historical and recent work, let alone the results from large-scale modeling (ARMA, 2011).

Unlike reflective roofing materials, which have been substantially validated to reduce individual building cooling loads albeit with unintended consequences, reflective pavement materials are less studied. Although the albedo of both pavement and roofing materials may act similarly in terms of generic physics, i.e., as reflectivity increases, the surface temperature of the material decreases, heat transfer mechanisms can be vastly different due to building interactions. For example, roofs reflect solar radiation mostly back toward space, while reflected radiation from roads and walls can be absorbed by urban facets due to "radiative trapping." Therefore, it is essential to study reflective pavements and investigate their impacts on urban environment independently from roofing materials.

In this white paper, our effort is focused on the evaluation, comparison, and summary of the unintended consequences caused by the installation of reflective pavements at a variety of dimensions and scales, by reviewing the documented literature. For this purpose we identify, review, and summarize relevant literature, especially those with perceived scientific influence and credibility from LBNL. The objective of this study is to provide an unbiased, comprehensive overview of potential impacts from implementing reflective pavement strategies to mitigate UHI.

2. POTENTIAL BENEFITS OF REFLECTIVE ROOFS AND PAVEMENTS

Cool roofs are defined by the Cool Roof Rating Council as a product with solar reflectivity (ρ) at least 0.70 and infrared emissivity (ε) of at least 0.75. With these properties, cool roofs are able to reflect more radiation and lower the surface or skin temperature of the roof during daytime. Regardless of the surrounding environment, cool roofs are able to reduce cooling loads of buildings during hot periods, especially early afternoons during the summer.

Cooling energy savings by cool roofs have been observed at several sites. Akbari (2003) found savings of about 0.5 kWh/day for two small non-residential buildings with 14.9 m^2 of roof area after increasing the reflectivity from 0.26 to 0.72. Akbari et al. (2005) also monitored energy use in six California buildings at three different sites and reported an estimated savings in average air conditioning energy use between 42 to 81 Wh/m^2/day. Measured savings in an average peak-period demand varied from 5 to 10 Wh/m^2 of the conditioned area during hot afternoons. Wray and Akbari (2008) observed a 0.3% to 0.6% decrease in rooftop air-conditioner (RTU) condenser energy consumption and a 0.6% to 0.7% increase in the energy efficient ratios when reflectivity increased from 0.58 to 0.85. Further, Akbari et al. (2009) postulated that respectively increasing roof and pavement albedo an additional 0.25 and 0.15 across all urban areas on the Earth, could lead to a change in annual global radiative forcing (RF) of about -4.0×10^7 kW. This change is estimated to be equivalent to saving 44 Gt of CO_2 emissions annually, which is worth approximately $1.1 trillion.

Although these types of findings and observations provide evidence of energy savings from the use of reflective roofs, the studies were all conducted during summer periods, thus heating penalty data was not collected. In addition, these energy savings were collected and computed based on single buildings, where impacts of reflective roofs on the surrounding environment and inter-building thermal interactions are neglected.

3. MAJOR LIMITATIONS OF REFLECTIVE ROOFS AND PAVEMENTS

3.1. ROOF CONDENSATION

Although not necessarily applicable to reflective pavements, when a roof's albedo is increased, it also causes moisture accumulation and condensation problems under the roof. With reduced surface temperature, moisture penetrating into the roof deck during a cold winter cannot dry out rapidly and occasionally results in condensation depending on the weather conditions (Dregger, 2012). In warm regions like Phoenix, accumulated moisture from winter can dry during the summer with reflective roofs. However, in cool-to-cold regions, numerical simulations show that reflective roofing material could increase water content in roofs more than 20% after 5 years (Bludau et al., 2009). A field study by Ennis and Kehrer (2011) also reports that condensation is only found on the back side of highly reflective membranes. Condensation in roofing systems can lead to severe deterioration in metal roof decks, wet spots on the floor, mold growth on the rooftop, and ice build-up in the lap seams, resulting in costly mitigation efforts (Hutchinson, 2008, 2009).

3.2. SNOW AND ICE BUILDUP ON REFLECTIVE ROOFS AND PAVEMENTS

Besides condensation, a lower surface temperature of reflective roofs slows the melting of snow and ice, and makes a roof more susceptible to deeper snow, ice, and icicle formation (Carter and Stangl, 2012). The buildup of snow and ice damages roof components and poses dangers to people working on roofs or walking below them (Ibrahim, 2013). This safety issue becomes even more serious in densely populated urban centers where prominent tall buildings are constructed on small sites with pedestrian and vehicular traffic mere feet from their base. Similar to reflective roofs, the lower surface temperature of reflective pavements in the winter increases maintenance costs and environmental impacts associated with ensuring a safe winter roadway or walkway in colder climates. Because reflective pavements have lower surface temperatures (MnDot, 2013), additional deicing salts are required to ensure clear winter roadways (TranSafety, 1997) and the safety of the traveling public. In fact, at pavement temperatures below 15°F, the use of deicing salts on snow-covered roadways are not as effective and additional chemicals are required (MnDOT, 2013). Use of deicing chemicals is costly and may have negative environmental impacts to nearby soils, vegetation, water, and vehicles (TranSafety, 1997).

3.3. HEATING PENALTY FOR REFLECTIVE ROOFS AND PAVEMENTS

Heating penalty is another unintended and adverse consequence of reflective roofing and pavement materials. While reduced surface temperature of roofing materials can lower building's cooling loads during summer periods, it inevitably increases heating loads in winters. Taha et al. (1999) conducted simulations with a three-dimensional Eulerian mesoscale meteorological model (CSUMM) using DOE-2 to calculate energy loads. The predicted annual gas penalties in residential neighborhoods were 9.67 kWh/m^2 and in office areas were 5.86 kWh/m^2. Bianchi et al. (2007) applied a numerical model (STAR) to address the impact of cool roofs and found an increase of 8.09% in heating penalty during winter. Modeling over 27 cities around the world with TRNSYS thermal simulation software, Synnefa et al. (2007) observed heating penalties in all cities up to 20 kWh/m^2/year after the application of cool roof coatings.

Similar comparisons can be made with reflective paving materials — indicating a potential heating penalty in the winter. According to the Commercial

Buildings Energy Consumption Survey by U.S. Energy Information Administration (2003), heating accounts for 36% of commercial buildings' annual energy consumption, while air conditioning only accounts for 8% in the United States. The U.S. Green Building Council (USGBC) also identifies that across the United States, more energy is consumed heating buildings than used to cool them (Enlink Geoenergy, 2012). In climates with less than 1,000 cooling degree days (CDD), Akbari and Konopacki (2005) found that reflective surfaces, including reflective pavements, can negate any summertime electricity savings due to wintertime heating penalties. Wintertime heating penalty must also be considered as an unintended consequence of reflective pavements, as indicated by Li (2012).

3.4. REFLECTED SOLAR RADIATION

One of the UHI mitigation strategies for relying on reflective roofs and pavements, is its ability to reflect solar radiation, preventing the transfer of thermal energy into and through the material. Reflective pavements lead to greater reflected solar radiation, which can be absorbed by surrounding surfaces and subsequently increases their temperatures. Pearlmutter et al. (2006) showed that light-colored walls would reflect more short-wave radiation and generate a slightly higher heat gain for pedestrians based on a pedestrian-centered conceptual model. Brender and Lindsey (2008) conducted experiments in Las Vegas and observed hotter interior temperatures (5°C at maximum) in the conduit over a white roof as compared to dark-colored roofs. Without proper design, this could result in serious overheating or even failure of electrical cables inside the conduit.

Ibrahim (2012) carried out a field study to explore the impact of roof color on ambient air temperatures and reported a significantly increased air temperature over a white-thermoplastic membrane roof. Pierce (2012) pointed out that the temperature of the membrane below a highly reflective wall surface could be 20°C higher in extreme cases. And results of experiments by Li (2012, as part of the LBNL research effort on reflective pavements) implied that the temperature of the building wall would be heated up by the reflected energy from the pavement surface, which could be at maximum ≈2 to 5°C higher around noon. Subsequently, the increased temperature makes air conditioning units work harder, accelerates the heat aging of the membrane, damages surrounding building components, and causes heat discomfort for pedestrians. This effect causes potential problems for the high-density urban areas where building components are in close proximity to each other (Li, 2012). For example, increasing the albedo from 0.15 to 0.5 would substantially impact the comfort of people standing on the more reflective pavement, increasing the temperature they feel by 3 to 6°C (Lynn et al., 2009).

3.5. HEALTH RISKS

In addition to its impact on the thermal environment to surrounding buildings, reflected solar radiation increases potential health risks on humans. High reflectivity from light-colored surface can increase the intensity of indirect ultraviolet (UV) radiation to people. UV radiation is harmful to living cells and can result in sunburn, increased rate of aging of the skin, and skin cancer, with its damage accumulating over years (CCOHS, online source). Childhood sun exposure may play an important role in the development of skin cancer later in adult life. Therefore the amount of reflected radiation should be taken into consideration when planning for ground and building pavements, especially in schoolyards and playgrounds (CDCP, 2011). Moreover, reflective pavement surfaces with a light color can cause glare and visual pollution, which can harm eyesight after a long period of exposure. Reflection from light-colored surfaces can disturb occupants of taller neighboring buildings when applied to roofs (LBNL, online source), make pedestrians on nearby sidewalks suffer when applied to walls (Marvin, 2013), and provide less lane demarcation due to the poor visibility of white lines when applied to light-colored roads, potentially increasing driving risks (City of Chula Vista, 2012).

3.6. LIGHT POLLUTION

With its high reflectivity, a high-albedo roof or pavement reflects not only radiation in daytime but also visible lights from artificial illumination at nighttime. In natural environments, stray and obtrusive lights at night, regardless of their purpose, are generally referred to as light pollution. Shaflik (2007) notes that 35% to 50% of all light pollution is estimated to be attributable to roadway lighting and that 95% of light directed toward pavements is reflected upwards at reflectance rates that range from 6% for asphalt to 25% for concrete. A recent study by the International Dark-Sky Association at the Brecon Beacons National Park found asphalt surfaces can reduce the upward light reflected by half when compared to concrete surfaces, regardless of luminaire light distribution (James, 2013). Reflective pavement materials are expected to increase the upward reflected light, which is likely to result in less visibility of the night sky and stronger light pollution.

4. POTENTIAL ENERGY COST CONSIDERATIONS

Both cooling savings and heating penalties are widely accepted as consequences of reflective roofs. However, their relative magnitude, which serves as a crucial parameter in evaluating the performance of reflective roofs, is unclear. To determine the actual impacts of reflective roofs on energy costs, model simulations have been conducted to compare cooling savings to heating penalties.

In favor of cool roofs, LBNL states that reflective roofs reduce more energy in cooling than they increase in heating. Akbari et al. (1999) used the DOE-2 building energy simulation program to model reflective roofs in 11 U.S. metropolitan statistical areas and found 2.6 TWh annual electricity savings, $194 million net annual savings and 1.7 GW peak electricity demand savings after subtracting the heating penalties. Levinson et al. (2005) concluded that cool roofing on a prototypical California nonresidential (NR) building with a low-sloped roof yielded average annual cooling energy saving of approximately 3.2 kWh/m^2, average annual natural gas deficits of 1.56 kWh/m^2, average annual source energy savings of 8.33 kWh/m^2, and average peak demand savings of 2.1 Wh/m^2 from DOE-2.1E simulations. Levinson and Akbari (2009) combined building energy simulations, local energy prices, local electricity emission factors, and local estimates of building densities to characterize local per-CRA (conditioned roof area) and per-LA (land area) annual rates of energy cost savings in the U.S. after installation of a cool roof. Using the DOE-2.1E building energy model with a roof assembly heat transfer module, they predicted that a cool roof almost always reduced the annual cooling load more than it increased the annual heating load per-CRA, with the greatest saving in Hawaii and the least in Alaska. With TRNSYS thermal simulation software, Synnefa et al. (2007) found that application of a cool coating lead to a larger cooling load reduction (9 to 48 kWh/m^2/year) than heating penalty (0.2 to 17 kWh/m^2/year) for the 27 cities studied around the world.

Contrary to LBNL's work, several studies reported larger heating penalties than cooling savings. Matter (2008) pointed out that heating (29%) accounted for more energy consumed within a building than cooling (6%) based on the building energy data book and concluded that dark-colored membrane roof systems were at least 10% more energy efficient per year based on the DOE-2 energy calculator. Reale (2009) illustrated that heating was a much more significant factor in energy usage than cooling through a comparison of heating degree days (HDD) and cooling degree days (CDD) at three major U.S. cities: Boston; Grand Rapids, Mich.; and Albuquerque, N.M. Using the DOE's cool-roof calculator, the results were respectively 5,841 HDD versus 646 CDD in Boston, 7,153 HDD versus 508 CDD in Grand Rapids and 4,361 HDD versus 1,211 CDD in Albuquerque.

It is noteworthy to point out that all comparisons of energy usage above were all based on the DOE-2 program. DOE-2 is a building energy analysis program that performs hourly simulations of the building and estimates energy bills depending on the building layouts, constructions, operating schedules, conditioning systems (lighting, HVAC, etc.) and utility rates provided by the user, along with weather data. Therefore the gap in the conclusion above can be resulted from various aspects, such as building structures, meteorological forcings, etc. Though the program is validated and widely used by many professional societies and industry groups, DOE-2 is a single-building-based model that neglects physical interactions between buildings and the surrounding microclimate in the built environment; the same premise holds for experiments discussed in the cool roof benefits section. With that being said, all conclusions drawn from DOE-2 simulations come with the implicit assumption that the impact of the surrounding environment and microclimate on building's energy consumption is insignificant. However, this assumption is questionable.

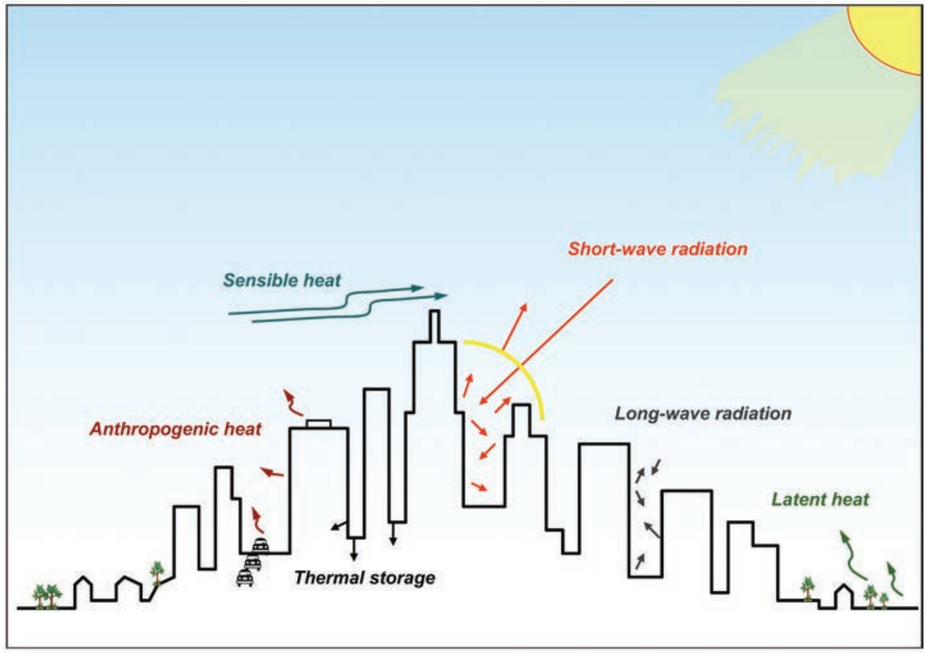

Figure 1. Schematic of surface heat budgets in a built environment (USEPA, 2008). Note that in particular the solar (short-wave) radiation experiences multiple reflections between adjacent urban facets, which results in the so-called "radiative trapping" phenomenon in urban areas.

Urban areas feature dense structural confines that impact heat transfer from and to pavement surfaces in various ways (see Figure 1). Obviously, one effect is the blocking and reflecting solar radiation during daytime. Energy is transported in this process between adjacent walls, roofs, and roads. And the transferring mechanism varies throughout the day with the solar elevation angle. Another important factor is heat released from pavement surfaces. Anthropogenic heat release serves as an additional heating source in urban areas that increases surrounding air temperature and consequently the cooling load of nearby buildings. Therefore, energy cost estimation by DOE-2 simulations, without consideration of thermal interactions in the built environment, is suspicious and inadequate to support large-scale deployment of reflective pavements; it requires further and more thorough investigations. This phenomena is supported by Lynn et al. (2009) who identifies that increasing pavement albedo is not a prudent UHI mitigation strategy due to the roughness (multiple reflections) of typical cityscapes.

In real situations, optimization of building energy usage in urban areas is a complicated problem that requires understanding of the complex interaction between urban morphology, materials, and climates. Intuitively, while reflective roofs may reduce building cooling loads by minimizing the transfer of heat through a relatively thin membrane in an elevated urban spatial location, the same is not necessarily true with regards to pavements as they function in different spatial locations (at grade), often are obscured by urban geometry (e.g., large buildings), and do not directly transfer heat into a building. Yaghoobian et al. (2010) applied a three-dimensional heat transfer model (TUF3D) and found a substantial reduction in short-wave radiative heat transfer from ground to building by using low-albedo ground surfaces. This reduction leads to a consequent savings in the daily design cooling load of nearby buildings by 17% using low-albedo pavements. Later in 2012, Yaghoobian and Kleissl (2012) adopted a three-dimensional building-to-canopy model (TUF-IOBES) to investigate the effects of reflective roofs on energy usage. Focusing on the physical interactions between buildings and surrounding microclimate in the urban canyon, the study found that increasing ground pavement solar reflectivity from 0.1 to 0.5 near a four-story office building (1,820 m^2 floor area, 47% window-to-wall ratio) in Phoenix would increase annual cooling loads up to 11% (33.1 kWh/m^2). These results illustrate the potential of increased cooling loads in adjacent buildings by reflected solar radiation from high-albedo reflective surfaces. Additionally, Ryu and Baik (2012) identified heat radiating from building walls as having a greater impact on nighttime temperatures than heat radiating from horizontal surfaces. If reflective pavements add to heat storage in vertical surfaces, this effect would be intensified.

After taking inter-building interactions into consideration, the estimates of energy costs need to be re-evaluated when comparing the impact of reflective pavement mitigation strategies as reflective pavements have been shown to increase adjacent building cooling energy loads. These current research findings warrant a much closer look at the impact of pavement albedo on heat transfer, especially to adjacent buildings.

5. LARGE-SCALE IMPACTS ON THE ENVIRONMENT

Benefits and limitations of reflective pavements summarized above are mainly at building and local (neighborhood) scales, without consideration of the interaction with surrounding environments and microclimates. As mentioned in the introduction section, recent studies have revealed the unintended consequences of large-scale cool roof deployments that should not be neglected. The impacts on a large scale, is of greater importance to the public concern and thus is discussed separately here. A pioneering study to quantify the possible meteorological impacts of large-scale increases in surface albedo and vegetative fraction is conducted by Taha et al. (1999) from LBNL on 10 U.S. regions with a three-dimensional Eulerian mesoscale meteorological model (CSUMM). In the model, albedo was increased from 0.25 to 0.55 for residential roofs and from 0.25 to 0.70 on office roofs. Vegetation increase was modeled as an additional three trees per residential or commercial unit. They focused only on temperature and found the increase in albedo and vegetation can offset the urban heat island intensity in most of the study areas by about 1 to 2 °C. Cooling savings were found to exceed heating penalties in most of the regions.

However, a later simulation by Oleson et al. (2010) showed that reflective roofs increased winter interior heating more than they decreased summer air conditioning with respect to the global annual average. In addition, the mitigation effect of reflective roofs on urban heat island was found to be less effective at high latitudes during winters determined by the coupled urban canyon model (CLMU), Community Land Model (CLM 3.5), and Community Atmospheric Model (CAM 3.5). Menon et al. (2010) performed simulations with the land component (CLSM) of the NASA GEOS-5 climate model to quantify the change in radiative forcing and land surface temperature due to increased albedo in urban areas. Meteorological forcings were collected from GSWP-2 and were not allowed to respond to changes in surface albedo. Results showed that an 0.1 increase in urban albedos for all global land areas would increase the global average outgoing radiation by 0.5 Wh/m^2 and the surface temperature would decrease by ≈0.008 K during the boreal summer (June-July-August). For the continental United States, the average outgoing radiation would increase by 2.3 Wh/m^2 and the surface temperature would decrease by ≈0.03 K for the same increase in urban albedo. In these studies, urban areas were not explicitly resolved and feedbacks between land and atmosphere were incomplete.

From a different perspective, Akbari et al. (2009) from LBNL investigated the possibility of offsetting global warming effect caused by CO_2 through large-scale deployment of reflective pavement materials. By increasing roof and pavement albedo respectively an additional 0.25 and 0.15 across all urban areas on the Earth, they estimated a change in global radiative forcing (RF) of about -4.0×10^7 kW using a conceptual Earth radiation balance model. Based on former studies and reports, Akbari et al. (2009) estimated an average RF change of 0.91 kW per tonne of CO_2 and adopted the European CO_2 price of \$25 per tonne for the economic calculation. Given these estimates, increasing the world wide urban albedo could offset about 44 Gt of CO_2 emissions annually, which is worth approximately \$1.1 trillion. Nevertheless, the fantastic savings demonstrated are dependent on unrealistic assumptions used in the study and are of great uncertainty. First, shading effects by trees, adjacent buildings, and other sources are ignored. A limited analysis by Levinson et al. (2008) showed that shadows can reduce the annual incidence of sunlight on residential roofs by 10% to 25%. Although no similar studies were reported, this number is most likely to increase on pavement surfaces simply due to their lower elevations. Without incidence of sunlight, reflective materials cannot function as designed with their high albedos. Therefore the equivalent potential of reflective surfaces and its concomitant benefits tends to reduce by a considerable percentage.

Moreover, the estimation of RF change by increasing urban albedo is inaccurate. Using the Earth radiation balance model, the increase in urban albedo is converted to equivalent global albedo change before calculation. This conversion is not reliable as meteorological and geographical conditions are vastly different on the Earth's surface. Factors such as cloud cover, elevation, and especially aerosols over cities play an important role in determining RF change; these conditions need to be accounted for to ensure a better estimation. Third, complex mechanisms and various assumptions of atmospheric modeling lead to great uncertainties and potential errors in model results. Therefore the RF change of CO_2 per tonne used in this study is highly sensitive and varies within a wide range. Last but not least, the trading price for CO_2 emission changes rapidly and stands a good chance of decreasing with a larger amount of CO_2. Multiplying the amount of CO_2 emission by its price per tonne oversimplifies the economic process and results in unreasonable savings expectations.

More recently, researchers have focused on addressing the impact of reflective pavement materials on local and regional hydroclimate. Millstein and Menon (2011) employed a regional atmospheric model (WRF) with a fully coupled representation of land-surface and atmospheric system to investigate the regional climate impact of large-scale cool roof deployment. They found that the adoption of cool roofs and pavements over the continental U.S. decreased afternoon summertime temperatures in urban locations but increased temperatures at some rural areas by up to 0.27 °C. The increased temperature was associated with lower soil moisture, fewer or thinner clouds, and less precipitation. The reduction of cloud formation and precipitation has been observed by other researchers. Doughty et al. (2011) concluded that increased agricultural albedo over land interfered with and decreased cloud formation and precipitation at low latitudes from the Community Atmosphere Model (CAM 3.0) coupled with the Community Land Model (CLM 3.0).

Bala and Nag (2012) reported a significant decrease in global land-mean precipitation (13.38%), runoff (22.31%), and soil water content due to albedo increase over land using an atmospheric general circulation model (NCAR CAM 3.1) coupled with a slab ocean model. Georgescu et al. (2012) indicated that implementation of cool roofs reduced evapotranspiration throughout the calendar year and decreased accumulated precipitation by 4% in maximum Sun Corridor expansion scenario using WRF. Simply increasing worldwide roof albedo from 0.12 to 0.65 with no other change, Jacobson and Ten Hoeve (2012) concluded that there is localized cooling but overall global warming for reflective roofs. A ≈0.02 K decrease in the population-weighted air temperature with a ≈0.07 K increase in global temperature were observed from the one-way-nested (from coarser to finer domains) global-regional gas, aerosol, transport, radiation, general circulation, mesoscale, and ocean model (GATOR-GCMOM). With better simulation of interaction and feedbacks between land and atmosphere, these studies illustrate that large-scale installation of reflective roofs and pavements will lead to serious unintended consequences in local and regional hydroclimate.

6. FIELD STUDIES INDICATE REFLECTIVE PAVEMENTS HAVE LITTLE IMPACT ON AIR TEMPERATURES

The literature reviewed in this study indicates that high-albedo reflective materials lower surface temperature at both building and city scales. Based on this mechanism, numerous studies deduce that reflective pavements are able to reduce overlying air temperature significantly. On the contrary, our field experiment in Arizona finds that reflective pavement surfaces have only limited influences on overlying air temperatures. In our experiment, six types of ground cover are deployed on a site: landscape gravel, green turf, concrete, pervious concrete, asphalt, and porous asphalt. The averaged diurnal cycles of surface temperature and air temperature at 5 feet above each surface from Dec. 1 to Dec. 10, 2012, are shown in Figure 2.

Figure 2(a), demonstrates significant deviation in surface temperature over different ground covers due to their albedo. The maximum surface temperature is found at the green turf and the minimum is at the concrete surface. The maximum difference is more than 10°C around noon. On the other hand, it is shown in Figure 2(b) that the air temperature profiles at 5 feet above the different surfaces are almost identical throughout the day. This result indicates that the presence of turbulent mixing near surface weakens the impact of surface albedo of individual pavement patches, which results in a flux aggregation at certain blending heights with the effect of albedo on the atmosphere being effectively annihilated. In the instances shown in Figure 2, air temperature at 5 feet above the ground is almost independent to the direct underlying pavement materials.

In addition, Figure 2(a) also illustrates potential thermal properties that help to mitigate UHI besides albedo. One important variable is the heat capacity. The surface temperature exhibits a different trend during the night. At nighttime, concrete and asphalt pavements, both possessing greater capacity to retain heat, exhibit higher surface temperatures, while surface temperatures over green turf and gravel dropped rapidly. Another effective variable is the porosity of pavement materials. Compared to concrete, pervious concrete has higher temperatures during daytime. However, being permeable to air flow through its pores, pervious concrete is able to dissipate the heat comparatively more quickly such that its surface temperature is lower at night. The difference between asphalt and porous asphalt shows the same trend. Besides, permeable materials can hold condensed liquid water during nighttime and cool the surface temperature by evaporation, which also has a positive effect on stormwater management and reducing UHI (Boyer, 2011). Overall, modifying heat capacity and porosity, both resulting in nighttime cooling, can be an efficient way to mitigate UHI, rather than relying upon the questionable effects of high reflectivity alone. Because the UHI phenomenon is more prominent at night, a nighttime-cooling effect should be the norm, rather than an exception, for any potential UHI mitigation strategy.

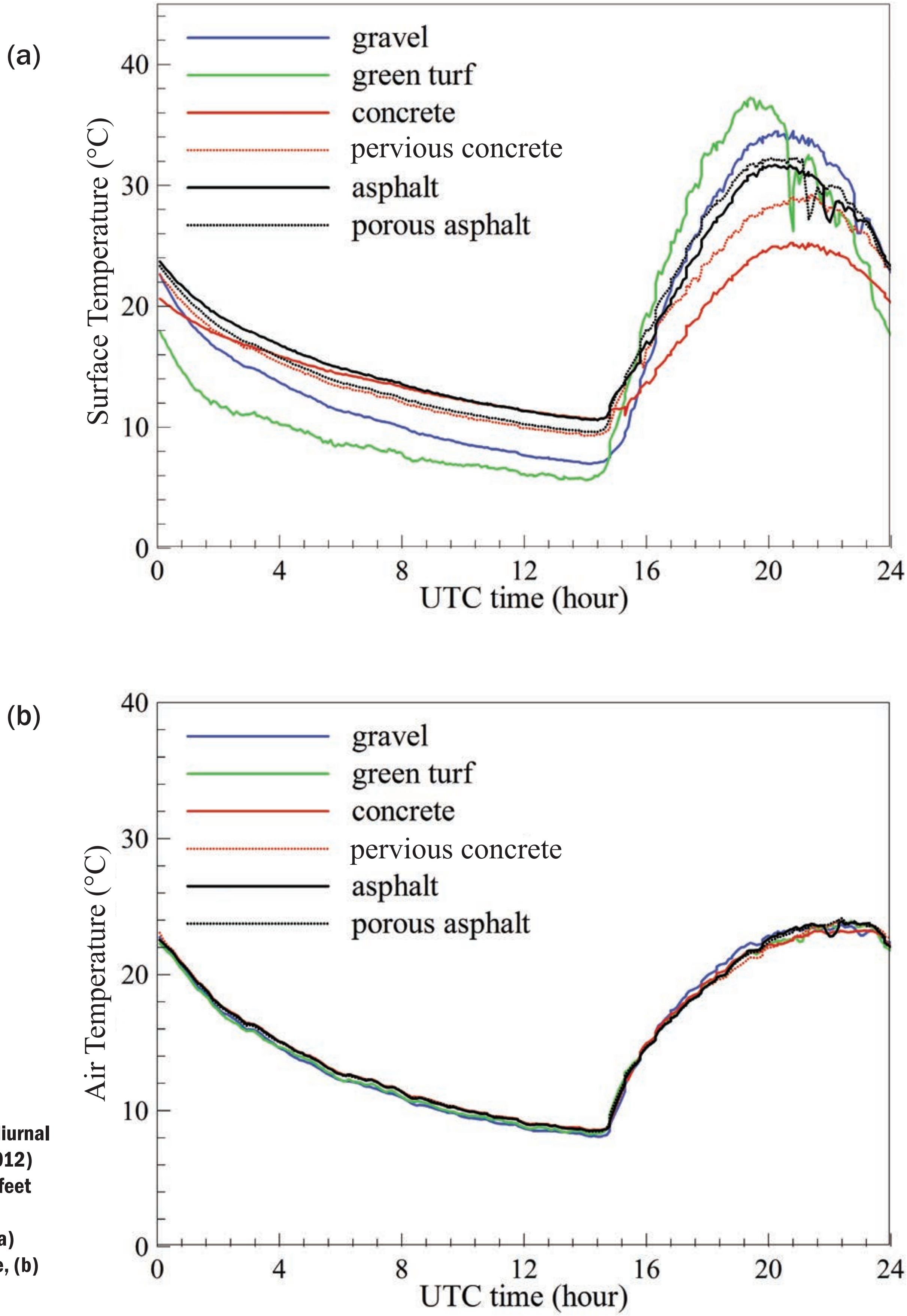

Figure 2. Averaged diurnal cycle (Dec. 1–10, 2012) of temperature at 5 feet over frequently used urban land covers: (a) surface temperature, (b) air temperature.

7. CONCLUSIONS

While reflective pavement is becoming an increasingly popular option in our urban planning today for mitigating the UHI effect, the unintended consequences it brings along are not clearly understood. In this paper we reviewed, compared, and summarized historical studies and latest research advances to provide a comprehensive overview for guidance on implementation of reflective pavements, on a variety of scales.

With high albedo, reflective materials redirect more radiation and reduce surface temperatures. However, a change in surface temperature has only limited effects on the overlying air layers such that overall benefits of reflective pavements and roofs can be less than expected. Meanwhile, reflected solar radiation from these surfaces can increase the temperature and consequently increase the cooling load of the surrounding built environment, accelerate the heat aging of membranes, increase damages, and increase heat discomfort. And reductions in surface temperature can produce adverse effects related to condensation, snow and ice buildup, and a heating penalty in winter. Harmful reflected UV radiation and glare, and additional unintended consequences of reflective pavements, require special consideration as to the impact on human health.

We reiterate here that within the scope of this review, it is still unclear whether large-scale deployment of reflective pavements can achieve overall energy savings. Although the modeling studies developed by LBNL and others promote reflective materials, neglect of physical interactions between buildings and the surrounding microclimate in the urban environment in their modeling simulations makes the conclusions quite suspect. Based on unrealistic assumptions, LBNL's inference that reflective pavement deployment can save hundreds of billions of dollars is unreliable.

With different spatial locations, reflective materials on different surfaces in urban areas can lead to opposite effects with regards to energy consumption. At large scales, models show that local cooling by deployment of reflective pavements can cause regional warming in other places or even contribute to global warming. Significant reduction in precipitation, runoff, and soil water content requires special attention where installation locations are in water-shortage regions. Among all scales, primarily due to complex urban geometry, it is essential to study the effect of reflective pavements separately by geographical location to obtain accurate simulations and meaningful conclusions.

In summary, though specific outcomes of experimental and modeling results with high-albedo pavements are uncertain, based on the comprehensive review presented in this white paper, it is suggested that the unintended consequences of specifying reflective pavements should be given serious consideration by city planners and policy makers. Without further detailed investigation, larger-scale deployment of highly reflective pavements to mitigate UHI is premature.

REFERENCES

Akbari H. 2003. Measured energy savings from the application of reflective roofs in two small non-residential buildings. *Energy*, 28(9):953–967. doi:10.1016/S0360-5442(03)00032-X

Akbari H, Konopacki S. 2005. Calculating energy-saving potentials of heat-island reduction strategies, *Energy Policy*, 33(6):721–756. doi:10.1016/j.enpol.2003.10.001

Akbari H, Konopacki S, Pomerantz M. 1999. Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States. *Energy*, 24(5):391–407. doi:10.1016/S0360-5442(98)00105-4

Akbari H, Levinson R, Rainer L. 2005. Monitoring the energy-use effects of cool roofs on California commercial buildings. *Energy and Buildings*, 37(10):1007–1016. doi:10.1016/j.enbuild.2004.11.013

Akbari H, Menon S, Rosenfeld A. 2009. Global cooling: increasing world-wide urban albedos to offset CO_2. *Climatic Change*, 94(3-4): 275–286. doi:10.1007/s10584-008-9515-9

Asphalt Roofing Manufacturers Association. 2011. *ARMA White Paper: Low-slope cool roofing*. http://www.asphaltroofing.org/sites/default/files/ARMA%20Low%20Slope%20Cool%20Roof%20White%20Paper%20Nov11.pdf

Bala G, Nag B. 2012. Albedo enhancement over land to counteract global warming: impacts on hydrological cycle. *Clim. Dyn.*, 39(6):1527–1542. doi:10.1007/s00382-011-1256-1

Bianchi MVA, Miller WA, Desjarlais AO, Petrie TW. 2007. Cool roofs and thermal insulation: Energy savings and peak demand reduction. *Thermal Performance of the Exterior Envelopes of Buildings X, proceedings of ASHRAE THERM X*, Clearwater, FL, Dec. 2007.

Bludau C, Zirkelback D, Kunzel HM. 2009. Condensation problems in cool roofs. *Interface*, 27(7):11–16.

Boyer M. 2011. Preliminary analysis of summertime heat storage in traditional versus pervious concrete systems. Master's thesis, Washington State Univ.

Brender D, Lindsey T. 2008. Effect of rooftop exposure in direct sunlight on conduit ambient temperatures. *IEEE Transactions on Industry Applications*, 44(6):1872–1878. doi:10.1109/TIA.2008.2006301

Canadian Center for Occupational Health and Safety. Skin Cancer and Sunlight. http://www.ccohs.ca/oshanswers/diseases/skin_cancer.html

Carter M, Stangl R. 2012. Considerations for building design in cold climates. *Whole Building Design Guide*. http://www.wbdg.org/resources/bldgdesigncc.php?r=env_roofing

California Energy Commission (CEC). 2008. *2008 Building Energy Efficiency Standards for Residential and Nonresidential Buildings*, Publication Number CEC-400-2008-001-CMF. California Energy Commission, Sacramento, CA.

Centers for Disease Control and Prevention. 2011. *Shade planning for America's schools*. http://www.cdc.gov/cancer/skin/pdf/shade_planning.pdf

City of Chula Vista. 2012. *Cool roof study final report*.

Heat Island Group, Lawrence Berkeley National Laboratory. *Cool science: Cool roofs*. http://heatisland.lbl.gov/coolscience/cool-science-cool-roofs

Dregger P. 2012. "Cool" roofs cause condensation-Fact or fiction? *Western Roofing*, January/February:48–62.

Doughty CE, Field CB, McMillan AMS. 2011. Can crop albedo be increased through the modification of leaf trichomes, and could this cool regional climate? A letter. *Climatic Change*, 104(2):379–387. doi:10.1007/s10584-010-9936-0

Energy Information Administration. 2003. *Commercial Buildings Energy Consumption Survey*. U.S. Energy Information Administration.

Enlink Geoenergy. 2012. *Overview of geothermal heat pump systems*. U.S. Green Building Council, Nevada.

Ennis M, Kehrer M. 2011. The effects of roof membrane color on moisture accumulation in low slope commercial roof systems. *Proceedings of the 2011 International Roofing Symposium*, Washington, DC, Sept. 7–9. http://staticcontent.nrca.net/masterpages/technical/symposium/pdf/25_ennis_paper.pdf

Georgescu M, Mahalov A, Moustaoui M. 2012. Seasonal hydroclimatic impacts of Sun Corridor expansion. *Environ. Res. Lett.*, 7(3):034026. doi:10.1088/1748-9326/7/3/034026

Hutchinson TW. 2008. A matter of opinion: A roofing industry professional shares his views about current issues facing the industry. *Professional Roofing*, October:32–38.

Hutchinson TW. 2009. Challenging what's cool: Is the exponential growth of cool roofing an impending catastrophe. *eco-structure*, January/February:38–41. http://www.ecobuildingpulse.com/cool-roofing/challenging-whats-cool.aspx

Hutchinson TW. 2013. Questioning cool roofs. *Commercial Building Products*, 11(1):19–21.

Ibrahim S. 2012. Black vs. White: Energy Performance and Cold Climate Concerns. *International Roofing Expo*, Anaheim, CA, Feb. 22–24.

Ibrahim S. 2013. White roofs, green myth? *The Huffington Post*. http://www.huffingtonpost.com/samir-ibrahim/white-roofs-green-myth_b_2901288.html

Jacobson MZ, Ten Hoeve JE. 2012. Effects of urban surfaces and white roofs on global and regional climate. *J. Climate*, 25(3):1028–1044. doi:10.1175/JCLI-D-11-00032.1

James HP. 2013. *Brecon Beacons National Park International Dark Sky Reserve lighting management plan*. http://www.darksky.org/assets/Night_Sky_Conservation/BBNPA%20LMP%20complete.pdf

Levinson R, Akbari H, Pomerantz M, Gupta S. 2008. Estimating the solar access of typical residential rooftops: A case study in San Jose, CA. *Solar 2008*, American Solar Energy Society, San Diego CA, May 3–5.

Levinson R, Akbari H. 2009. Potential benefits of cool roofs on commercial buildings: conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants. *Energy Efficiency*, 3(1):53–109. doi:10.1007/s12053-008-9038-2

Levinson R, Akbari H, Konopacki S, Bretz S. 2005. Inclusion of cool roofs in nonresidential Title 24 prescriptive requirements. *Energy Policy*, 33(2):151–170. doi:10.1016/S0301-4215(03)00206-4

Li H. 2012. Evaluation of Cool Pavement Strategies for Heat Island Mitigation. PhD dissertation, Univ. of California, Davis.

Liscum CL. 2013. Unintended consequences of a white roof. *Perspectives: A quarterly information source from Benchmark Inc.* 75(1) http://www.benchmark-inc.com/article/253/Benchmark%20Pespectives%20Newsletters/volume-75-march-2013-unintended-consequences-of-a-white-roof.html

Lynn BH, Carlson TN, Rosenzweig C, Goldberg R, Druyan L, Cox J, Gaffin S, Parshall L, Civerolo K. 2009. A Modification to the NOAH LSM to Simulate Heat Mitigation Strategies in the New York City Metropolitan Area. *J. Appl. Meteor. Climatol.* 48(2):199–216. doi:10.1175/2008JAMC1774.1

Marvin S. 2013. Reflective pavement, solution or direction? *League of California Cities Planning Commissioners Academy*, Pasadena, CA, Feb. 27–Mar. 1.

Matter T. 2008. Energy efficiency: more than a simple black-and-white issue. *Interface*, 26(11):25–30.

Menon S, Akbari H, Mahanama S, Sednev I, Levinson R. 2010. Radiative forcing and temperature response to changes in urban albedos and associated CO_2 effects. *Environ. Res. Lett.*, 5(1):014005. doi:10.1088/1748-9326/5/1/014005

Millstein D, Menon S. 2011. Regional climate consequences of large-scale cool roof and photovoltaic array development. *Environ. Res. Lett.*, 6(3):034001. doi:10.1088/1748-9326/6/3/034001

Minnesota Department of Transportation (MnDOT). 2013. *MnDOT District 1 2013 Winter State Highway Maintenance White Paper — Fact Sheet*. http://www.dot.state.mn.us/d1/images/WinterMaintenanceWhitePaper2012-2013winterseason.pdf.

Oke, TR. 1982. The energetic basis of the urban heat islands. *Q.J.R. Meteorol. Soc.*, 108(455): 1–24. doi:10.1002/qj.49710845502

Oleson KW, Bonan GB, Feddema J. 2010. Effects of white roofs on urban temperature in a global climate model. *Geophys. Res. Lett.*, 37(3):L03701. doi:10.1029/2009GL042194

Pearlmutter D, Berliner P, Shaviv E. 2006. Physical modeling of pedestrian energy exchange within the urban canopy. *Build. Environ.*, 41(6):783–795. doi:10.1016/j.buildenv.2005.03.017

Pierce HH. 2012. Unintended consequences! Keeping alert to protect single-ply roofs. *Interface*, 30(2):20–24. http://www.rci-online.org/interface/2012-02-pierce.pdf

Reale R. 2009. A white roof isn't always the right roof. *Miller-McCune*. http://www.psmag.com/blogs/news-blog/white-roof-isnt-always-right-roof-3711/

Ryu YH, Baik JJ. 2012. Quantitative analysis of factors contributing to urban heat island intensity. *J. Appl. Meteor. Climatol.*, 51(5):842–854. doi:10.1175/JAMC-D-11-098.1

Shaflik C. 2007. Environmental effects of roadway lighting. Univ. of British Columbia, Department of Civil Engineering, Vancouver. http://www.darksky.org/assets/documents/is125.pdf

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. doi:10.1016/j.enbuild.2007.01.004

Taha H, Konopacki S, Gabersek S. 1999. Impacts of large-scale surface modifications on meteorological conditions and energy use: a 10-region modeling study. *Theor. Appl. Climatol.*, 62(3-4):175–185. doi:10.1007/s007040050082

TranSafety. 1997. Using Salt and Sand for Winter Road Maintenance. *Road Management & Engineering Journal*. http://www.usroads.com/journals/p/rmj/9712/rm971202.htm

United States Environmental Protection Agency (USEPA). 2008. *Reducing urban heat islands: Compendium of strategies*. http://www.epa.gov/heatisland/resources/compendium.htm

Wray C, Akbari H. 2008. The effects of roof reflectance on air temperatures surrounding a rooftop condensing unit. *Energy and Buildings*, 40(1):11–28. doi:10.1016/j.enbuild.2007.01.005

Yaghoobian N, Kleissl J, Krayenhoff ES. 2010. Modeling the thermal effects of artificial turf on the urban environment. *J. Appl. Meteor. Climatol.*, 49(3):332–345. doi:10.1175/2009JAMC2198.1

Yaghoobian N, Kleissl J. 2012. Effect of reflective pavements on building energy use. *Urban Climate*, 2:25–42. doi:10.1016/j.uclim.2012.09.002

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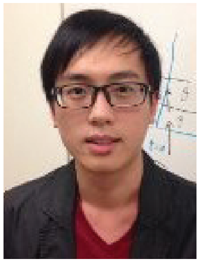

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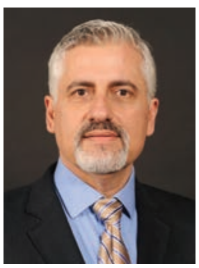

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