J3.1 MITIGATION OF URBAN HEAT ISLANDS – RECENT PROGRESS AND FUTURE PROSPECTS

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1. INTRODUCTION

The urban heat island (UHI) phenomenon has been the subject of intense study over the past several decades. Initial focus on the causes of the UHI has led to a basic understanding of the factors affecting heat island development and magnitude. Related research into the effects of elevated urban temperatures on air quality, energy consumption, and human health has provided motivation for reducing the magnitude of the UHI. The information resulting from this body of research has paved the way for development of strategies to mitigate urban heat islands. These strategies generally fall into two categories – increasing urban albedo (reflectivity to solar radiation) and increasing evapotranspiration. Albedo increases are generally accomplished through high albedo roofing and paving technologies. Increase in evapotranspiration is accomplished through a combination of decreasing the fraction of impervious surfaces and planting vegetation in urban areas (shade trees, vegetated walls, and rooftop gardens/ecoroofs).

This paper provides a brief overview of the recent history of UHI research and discusses in detail recent efforts at UHI mitigation. These efforts range from the development of mitigation technologies to computer modeling of their impacts and in situ evaluation of their performance. This paper builds on past efforts to summarize heat island mitigation progress (Estes, 2000), but attempts to be more comprehensive and more up to date. The presentation will conclude with a look at what the future might hold for heat island mitigation.

2. URBAN ENERGY BALANCE

In order to investigate potential mitigating strategies that might be useful in combating the urban heat island it is helpful to first develop a basic understanding of the urban energy balance. The discussion here is intentionally brief as it is intended simply to lay the foundation for understanding mitigation strategies. A more comprehensive discussion of the urban energy balance can be found in (Oke, 1978; Landsberg, 1981).

As illustrated in Fig. 1 the urban energy balance is driven by shortwave radiative input from the sun. In midlatitudes the summer midday shortwave flux may exceed 1000 W/m^2. As the shortwave radiation reaches surfaces in the urban environment it is partially absorbed and partially reflected. The ratio of reflected to total incoming solar radiative heat flux is referred to as the albedo. It is important to note that solar radiation spans the frequency spectrum with most of the sun's energy content being concentrated in the shortwave (0.4 to 0.7 μm) visible range. Hence high albedo surfaces are *generally* characterized by being light in color, or white. One key cause of heat islands is that cities tend to have lower albedos than the unbuilt surroundings (Oke, 1982). Compounding this albedo difference is the underlying morphology of cities (see Golany, 1996). When solar radiation is reflected from a street surface some of it escapes the urban canopy, but some (depending upon the sky view factor) is intercepted and partially absorbed by exterior building walls. So, the effective albedo of a city can be significantly lower than that of the rural countryside and even lower than the albedo of any individual component surface (Sailor and Fan, 2002).

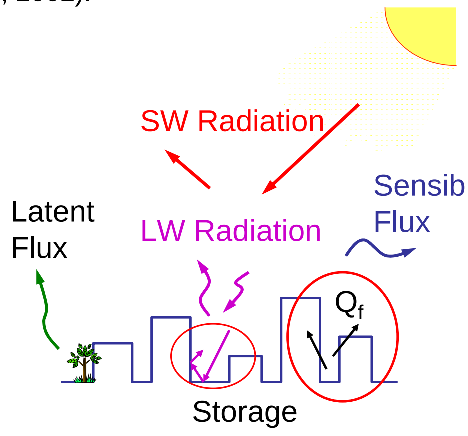

Figure 1. A simplified model of the urban energy balance including anthropogenic heating as a source term (Q_f).

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The surface complexity introduced by urban morphology also affects long wave radiative exchange. All surfaces emit radiation as a function of their absolute temperature (raised to the 4^{th} power). For surfaces with temperatures typically encountered in the urban environment (e.g., 0 to 60 ^{o}C) this energy is concentrated in the longwave spectrum (peaking at wavelengths of about 10 μm). Longwave radiative emission is a key mechanism whereby surfaces cool themselves at night. In an urban setting, however, longwave emission from one surface is often intercepted by many other urban surfaces. The net effect is that urban surfaces with their reduced sky view factor tend to cool off slowly at night.

Another key component of the urban energy balance is the prevalence of impervious surfaces and general lack of vegetation in urban settings. The result of these factors is increased heat storage (Asaeda et al., 1996) a reduction in available substrate moisture and corresponding reduction of latent heat flux from evaporation and transpiration processes (Avissar, 1996).

The complexity of urban canyons also has a complex effect on localized wind speeds, and hence on sensible (convective) heat loss of surfaces. Convective heat transfer from some surfaces is enhanced due to the wind channeling effect through urban canyons. Some surfaces, however, will be located in regions of relative stagnation and have significantly reduced convective heat loss.

In addition to these surface-related differences between urban and rural energy balances urban areas are also subject to significant waste heat emissions that can cause local elevation in air temperatures. This anthropogenic heating can be on the order of 10's of W/m^2 when averaged over a large metropolitan area; 100's of W/m^2 when averaged over a city; and can rival the peak solar load when averaged over just the central business district of a large city (Sailor and Fan, 2004).

This overview of the urban energy balance and identification of key causes of the UHI effect points to possible mechanisms for mitigation. Specifically, mitigation strategies should either increase effective albedo, augment latent heat flux processes, reduce storage, or reduce anthropogenic heating of the urban environment.

3. MITIGATION STRATEGIES

As noted above the urban heat island exists in both summer and winter seasons. In fact, it is generally largest in the winter when it has some beneficial characteristics related to reducing the demand for heating energy. In summer, however, the existence of the heat island has negative implications in three key areas – air quality, human health, and energy consumption for air conditioning. It is this summertime heat island that generally spawns an interest in mitigation. Hence, mitigation strategies are generally focused on reducing summertime heat island magnitudes and may have less desirable effects during the winter.

3.1 Albedo

The primary surfaces in the urban environment that are amenable to albedo increase are rooftops, roadways, and parking lots. In order to assess potential for albedo modification, various studies (Akbari et al., 1999) have estimated the composition of the urban fabric. This composition varies for different landuse subtypes within a city and depends upon whether one is concerned with plan view data (as seen from a plane) or with the actual composition under the canopy. With respect to the plan view composition of cities these studies typically find that roughly 20% of a city's surface is rooftop, 30% is pavement and the remainder is a combination of vegetation canopy, and other surfaces. It is this underlying composition that limits the potential effectiveness of any albedo-related mitigation strategy.

3.1.1 Roofing

There are a wide range of materials used for roofing. In general the residential market is dominated by asphalt and wood shingles and clay/composite tiles. Many homes have black or grey asphalt shingles that range in albedo from 0.05 to 0.12. It is important to note that asphalt shingles are, in fact, currently available in many shades that are much more reflective to solar radiation. For example, the Cool Roofing Material Database (http://eetd.lbl.gov/CoolRoofs) compiled by Lawrence Berkeley National Labs indicates that light gray to white asphalt shingles with albedos ranging from 0.22 to 0.36 exist in the marketplace.

More options exist for commercial roofing systems. This is due in large part to the prevalence of unseen flat roofs that are not as subject to aesthetic concerns. Rubber-like EPDM materials and coatings can be black (albedo ~ 0.05 to 0.10) or white (albedo > 0.60) with little impact on aesthetics or cost (see Fig. 2). Metal roofs can often have albedo in the 0.60 to 0.70 range. At the same time, however, metals tend to have a relatively low emissivity. The thermal emissivity is the parameter that dictates how effectively a hot surface cools itself by radiating energy to the environment. Most roofing materials (asphalt tiles, EPDM, clay tiles, wood shingles, etc) have emissivities that are approximately 0.90. In contrast, an aluminum roof may have an emissivity of only 0.25 and a galvanized steel roof may have an emissivity of only 0.04. Hence, metal roofs will typically not perform as well as an alternative with comparable albedo. For further details regarding albedo, emissivity, and related properties of a wide range of roofing materials the interested reader is referred to the Cool Roofing Material Database (http://eetd.lbl.gov/CoolRoofs).

Figure 2. Workers apply a cool roof coating on a rowhouse in Baltimore, MD (courtesy EPA HIRI web site).

It is important to note, however, that reflective roofs become less reflective with age, due in large part to soiling from soot and other particulates (Berdahl et al., 2002). Much of the original albedo can be recovered, however, through periodic washing of the roof surface.

Convective characteristics of roofing systems can also play a role in their overall effectiveness as a mitigation strategy. Roofing systems with larger surface areas exposed to the outside air (e.g. wood shake systems) can enhance convection.

3.1.2 Paving

Paved surfaces including parking lots and roadways often constitute a significant fraction of the urban fabric. Although there is typically more paved surface area than rooftop area, changes in pavement albedo are complicated by a lower skyview factor. That is, some of the radiation reflected from a paved surface is intercepted by building walls. Furthermore, a non-trivial fraction of paved surfaces are commonly covered by vehicles, thus reducing the effectiveness of any pavement albedo modification strategy.

Levinson and Akbari (2002) provide a fairly comprehensive analysis of the albedo characteristics of cements of varying composition. They found that after curing the albedo of various concrete mixes ranged from 0.41 to 0.77, suggesting a significant opportunity to engineer reflectivity of concrete surfaces. They also found, however, that after simulated weathering the cement albedo decreased by as much as 0.19 (e.g., from 0.77 down to 0.58). Regardless, their key finding is that white-cement mixtures could be made with albedos that were significantly higher than the most reflective gray-cement mixtures.

3.2 Vegetation and Pervious Surfaces

Vegetation augmentation and reduction of impervious surface cover in urban environments can be accomplished through residential and municipal tree planting programs, addition or expansion of ecoroofs, and implementation of pervious pavements.

Gomez et al., (1998) investigated the role that green areas play in affecting the thermal climate in Valencia, Spain. What they found provides one basis for assessing the potential large-scale effects of intensive tree-planting campaigns. At part of this work they provide an early attempt to link spatial patterns in vegetative cover with spatial patterns in the observed heat island.

While many studies focus on the evapotranspiration benefits of urban trees it is important to note that trees also affect wind patterns within cities (Heisler, 1989). By thus changing wind patterns trees may alter the effectiveness of cooling breezes and can play an important role in dispersion processes as well as pollutant removal by deposition.

3.2.1 Shade trees

Shade trees are a common mitigation strategy for a variety of reasons. First, they provide direct shade to buildings and pedestrians. At the same time, however, they improve the thermal environment through evapotranspiration processes. While albedo is typically not a high priority when considering shade trees for mitigation it should be pointed out that many tree species will have albedo values in excess of 18%. Hence, the addition of shade trees can also result in a net increase in albedo over that of some paving surfaces (e.g., asphalt roads and parking lots).

In addition to these aspects, urban vegetation also offers a number of other environmental benefis that are often difficult to quantify: they are aesthetically pleasing; they can provide habitat; and they help to reduce stormwater runoff.

American Forests is a non-profit association that provides a variety of tools and regional tree guides to help develop appropriate tree lists and to measure the economic benefits of trees in urban settings. Many resources relevant to shade tree mitigation can be found at their web site: www.americanforests.org.

3.2.2 Ecoroofs

As noted by Beckman et al., (1997) and Solomon (2003) ecoroofs (or green roofs) offer many benefits to the urban environment. They provide habitat and species biodiversity within cities. They provide aesthetically pleasing environments that can be made accessible to the public. They can retain stormwater, thus alleviating the loading of combined sewerage and water systems (DeNardo et al., 2003; Liptan, 2004). In fact, it is this suite of benefits that often drives the ecoroof implementation decision process. Researchers are also working to quantify the direct building energy benefits of ecoroofs (Del Barrio, 1998; Niachou et al., 2001). Clearly, though, ecoroofs, like their surface-based shade-tree counterparts also have the potential to mitigate the urban heat island (Sailor, 2004).

Ecoroofs have long been commonplace in Europe and have only recently made significant market penetration in the US. Scientific and popular articles illustrating the range of ecoroof implementations are becoming more common (Miller, 2002; Johnson, 2003; Wong et al., 2003; Eisenman, 2004; Lubell, 2004). Along with the growing popularity of ecoroofs comes an interest in developing standards for implementation and assessing performance (Anon, 2002; Wark and Wark, 2003).

3.2.3 Pervious Pavements

Impervious surfaces lead to runoff of available moisture and limit the ability of cities to be cooled by evapotransporation processes. While replacing impervious surfaces with vegetated soil surfaces is generally desirable it is not always practical. In many situations it is reasonable, however, to replace traditional pavements with pervious pavements that allow moisture transport into and out of the substrate. An example of a pervious pavement application in a parking lot is illustrated in Fig. 3.

3.3 Direct and Indirect Effects of Mitigation

These mitigation strategies can have impacts that range from localized effects to effects that are manifested at scales as large as the city. For example, implementing a high albedo roof on a commercial building has the direct effect of reducing the solar load on the building, and hence reducing summertime energy demand for that building. The same roof, however, also plays a small role in the urban climate system as a whole. Since the rooftop surface is cooler there is less convective heating of the air that flows over the building. The presence of many high albedo roofs within a city can, in theory, indirectly benefit the entire city through the combined air temperature reduction effects. While the direct effects can generally be measured the indirect effects must typically be estimated through large scale atmospheric model simulations (e.g., Sailor, 1998; Taha et al., 1999; Kikegawa et al., 2004).

Figure 3. A pervious lot in Fair Oaks, California's Miller Park with 23 mature Olive trees, which provide shade and give the parking lot a natural look (courtesy, US EPA, HIRI web site).

4. IMPLEMENTATION ISSUES

4.1 Cool Roofing

The commercial roofing market is largely composed of flat roofs that are relatively isolated from the public view. As a result, roof color tends not to be much of an aesthetic issue in the commercial market. The residential market, however, with its traditional sloped roofs must consider aesthetics as a key implementation barrier (Bretz et al., 1998). Darker roofs ranging from black asphalt shingles to wood shakes are often preferred by residential customers. This is likely due in part to their ability to hide dirt, moss, and other weathering characteristics. In many cases these darker surfaces also serve to help blend the house into the natural setting (e.g. cedar shingles). Light-colored residential roofs as illustrated in Fig. 4, while not common in the US, have been used widely elsewhere in the world – and in mediteranean countries, in particular.

In a demonstration project involving a 10,000 sq. foot roof on a commercial building in Florida researchers at Florida Solar Energy Research Center increased roof albedo from 0.23 to 0.68. In comparing pre and post modification energy consumption they found up to a 35% reduction in peak (mid-afternoon) electricity demand (Parker et al., 1996).

In many cases cool roofing strategies have no upfront cost differential compared with the traditional alternative. As an example, in the commercial roofing market Elastomeric and EPDM ethylene propylene diene terpolymer) rubber roofing materials can be ordered in color choices from black (albedo < 0.10) to white (albedo > 0.70). It is also important to note, however, that since cool roofing materials endure less thermal cycling there is reason to believe that they will last longer as well.

Figure 4. Example of a lone high albedo roof in an otherwise dark-roofed residential neighborhood in New Orleans (photo by D.J. Sailor).

The Cool Roof Rating Council (CRRC) is an independent and non-biased organization that has established a system for providing Building Code Bodies, Energy Service Providers, Architects & Specifiers, Property Owners and Community Planners with accurate radiative property data on roof surfaces that may improve the energy efficiency of buildings while positively impacting our environment (www.coolroofs.org).

4.2 Cool Paving

A common concern with implementing cool paving technologies is the potential glare associated with driving over highly reflective surfaces. Personal experience suggests that this concern may be overstated. For example, in daily driving routines it is relatively common to drive over dark asphalt (albedo ~ 0.05 to 0.08) and newer concrete (albedo ~ 0.20 to 0.30) in the same trip. Anecdotal evidence suggests that most drivers do not notice whether their trip involved concrete, asphalt, or both surfaces. Of course, as transportation agencies consider implementing very high albedo surfaces (albedo > 0.50) the glare issue may require further investigation.

On the flip side of the glare issue is the likelihood that highly reflective paving surfaces may significantly improve evening/nighttime visibility and/or reduce requirements for street lighting.

Also, roadway surfaces are subject to extreme weathering conditions which include dirt/soil, oil/other automotive fluids, and tire tread marks. As a result, weathering may significantly reduce the effectiveness of high albedo paving within months or weeks of installation.

4.3 Shade trees

Along with many benefits, shade trees introduce a host of cost issues. The cost of planting a new tree is proportional to the initial size/age of the tree. While smaller trees can be planted at relatively low cost they are also less likely to survive to maturity. Also, maintaining a tree requires routine pruning – particularly if planted alongside existing above-ground utility lines. Depending upon the species and climate some initial irrigation and fertilizer application may be required. Trees also are vulnerable to extreme winds, insects, and diseases posing a risk to nearby structures and utility lines which can be damaged by falling limbs. Likewise the root structure of trees can damage sidewalks and streets.

Additionally, vegetation emits isoprene and monoterpenes which play a role in the formation of photochemical smog. Through careful choice of vegetative species it is possible to obtain many of the benefits of vegetation with relatively low emissions of hydrocarbons (Corchnoy et al., 1992; Benjamin et al., 1996). A database of trees that are particularly amenable to application in the climate of southern California is given at: http://selectree.cagr.calpoly.edu.

Another useful reference for tree planting guidelines is the USDA Forest Service Western Center for Urban Forest Research and Education. Its web pages provide information on research and products related to urban forestry in general, and evaluations of the effectiveness parking lot shade tree ordinances. http://wcufre.ucdavis.edu.

4.4 Ecoroofs

Although ecoroofs function similarly to shade trees – both shading building surfaces and providing evapotranspiration benefits to the city, they differ significantly with respect to implementation issues. First, ecoroofs are commonly installed with a soil layer that is no more than 6 inches (15 cm) deep. In such installations the root system of the vegetation is severely limited, and, in fact, many ecoroofs are populated with sedum and similar vegetative species that inherently require little water. As a result, the evapotranspiration benefits of such systems are relatively small. With shallow root structures comes the general need for irrigation and maintenance of more water-intensive species. Ecoroofs with deeper soil systems, capable of more extensive vegetation schemes are possible but require that the building infrastructure be built to support the added weight. This issue is somewhat moderated by the fact that ecoroof soils tend to have very low mass densities.

5. EXAMPLE MITIGATION INITIATIVES

There are numerous examples around the world where researchers, local agencies and governments have explored small and large scale implementation of heat island mitigation. In some cases these studies are limited to computer modeling, in other cases they involve actual modification at scales ranging from individual buildings to entire cities. The following case studies provide a context for understanding the range of mitigation efforts that have been undertaken. While this section is not intended to be comprehensive, it is believed that most major heat island mitigation efforts to date are represented herein.

5.1 U.S. EPA's HIRI

The Heat Island Reduction Initiative (HIRI) at the US EPA supports research to advance the scientific understanding and adoption of heat island reduction strategies in U.S. cities. One aspect of HIRI seeks to improve understanding of the impacts that heat island reduction strategies have on urban meteorology, air quality, energy demand, and human health. Another thrust of HIRI activities focuses on translating research results into outreach materials and guidance that provide communities with information to develop programs, policies, codes, and ordinances that incorporate heat island reduction strategies. HIRI is partnering with the cities shown in Fig. 5.

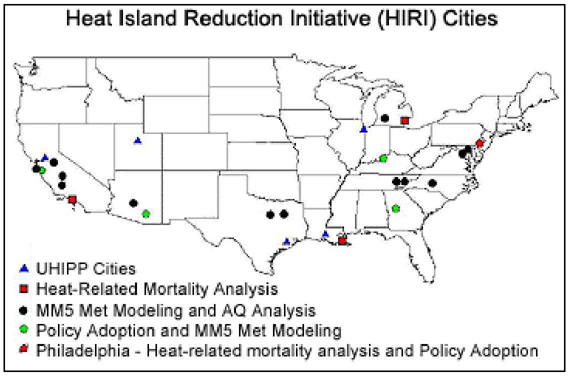

Figure 5. Map showing cities with which the US EPA's HIRI program has partnered (courtesy US EPA HIRI web site).

5.1.1 UHIPP

In 1998, as part of the Heat Island Reduction Initiative (HIRI), the US EPA launched the Urban Heat Island Pilot Project (UHIPP) Full details on UHIPP can be found at www.epa.gov/heatisland. UHIPP's primary goals are to: assist cities in efforts to adopt and evaluate heat island reduction strategies; encourage research, education, and communication; demonstrate and document successful heat island reduction projects that may be adopted in other communities; and build community support and understanding of heat island reduction measures. Pilot cities included in the UHIPP investigations include Baton Rouge, Chicago, Houston, Sacramento, and Salt Lake City. Figure 6 shows a UHIPP team measuring the thermal characteristics of a high albedo commercial roof installed in Salt Lake City.

Figure 6. Measuring the albedo of a cool roof in Salt Lake City, UT. (US EPA HIRI web site).

5.1.2 MIST

Out of the EPA-sponsored research into UHI mitigation strategies grew a need to be able to convey the research results to the urban planning and public policy communities in a meaningful way. While detailed modeling was simply not financially feasible for the large number of cities where UHI mitigation may hold promise, it was determined that some level of interpolation and extrapolation is possible based on the modeling that had been performed. So, a web-based screening tool was developed that integrates the results of EPA-supported modeling efforts. The user of the screening tool can select from any of over 200 US cities for which to conduct a UHI mitigation analysis. The mitigation strategies investigated include increasing of vegetative cover and increasing of urban albedo. The user can test a range of albedo scenarios, vegetation scenarios, or combined scenarios. In addition users can simply specify a nominal urban air temperature reduction associated with some undetermined set of mitigation actions. The mitigation impact screening tool (MIST) then extrapolates results from a set of detailed meteorological model simulations for 20 cities across the US. These meteorological impacts are combined with energy and ozone impact models to estimate the impact that the specified mitigation action may have on the selected city. The results presented by MIST include a high degree of uncertainty and are intended only as a first-order estimate that urban planners can use to assess the viability of heat island mitigation strategies for their city. The tool should be accessible at the EPA UHI website (www.epa.gov/heatisland) by early 2006.

5.1.3 Heat Island Reduction Guidebook

As part of its outreach efforts, the EPA HIRI is also in the process of developing a comprehensive heat island mitigation guidebook. This guidebook will serve as a resource for communities that are interested in learning about heat island issues and developing strategies and specific measures to mitigate heat island impacts. Goals of the guidebook include: assisting stakeholders in understanding causes and consequences of heat islands; identification of strategies for reducing or eliminating heat islands; explain how strategies work and illustrate the various strategies through examples drawn from mitigation efforts within the US; and to provide guidance for individuals, agencies, and governments with respect to implementing heat island mitigation within their own communities. At the present time this guidebook is in review and expected to be published by April 2006. Further information regarding the guidebook will be published on the EPA UHI website (www.epa.gov/heatisland) as it becomes available.

5.2 ICLEI

In cooperation with EPA's HIRI the International Council on Local Environmental Initiatives (ICLEI) has been developing and distributing information to local governments on heat island reduction strategies. ICLEI has developed a policy package that contains: fact sheets on urban heat island reduction; a sample resolution for local governments interested in adopting urban heat island reduction policies; model ordinance language to help practitioners modify development standards and planning, landscape, and building codes; and other resources including product lists, and links to scientific studies, and successful mitigation programs.

In October 2001, ICLEI initiated the Urban Heat Island Mitigation Policy Adoption and Peer Exchange Initiative. Together with the EPA they selected five cities to participate: San Jose, CA; Tucson, AZ; Philadelphia, PA; Atlanta, GA; and Louisville, KY. Each city committed to developing, adopting, and implementing reduction strategies within their jurisdictions. More details on ICLEI's heat island mitigation efforts can be found at www.iclei.org.

5.3 U.S. Department of Energy

The US Department of Energy was one of the early players in the field of heat island mitigation. Led by efforts within the Lawrence Berkeley National Laboratory and in cooperation with the US EPA the Department of Energy has developed technologies for heat island mitigation, conducted analyses of the effectiveness of measures, and been a leading advocate of legislation, policies, and standards that promote heat island mitigation strategies.

5.3.1 ORNL

Oak Ridge National Laboratory (ORNL) has been involved in heat island mitigation research with a focus of cool roofing technologies. They have conducted studies looking into the effectiveness of cool roofs as installed, and after weathering. They provide a wealth of information related to energy efficient design of walls and roofs at www.ornl.gov/sci/roofs+walls. From this site one can also explore ORNL's cool roof calculator which is an easy-to-use tool that allows users to assess the likely savings of replacing a traditional roof with a cool roof. A similar tool with a spruced up user interface is available from the EPA's Energy Star program at: http://roofcalc.cadmusdev.com. To use either tool one must enter information regarding the building's location and construction, heating fuel, and performance characteristics for its HVAC equipment. The tool then estimates energy savings of a cool roof relative to that of a reference black roof.

5.3.2 LBNL

The Heat Island Research group at Lawrence Berkeley National Laboratory (LBNL) has been studying mitigation strategies since the late 1980's. In 1992 they published one of the first guidebooks for urban heat island mitigation (Akbari et al., 1992).

Researchers at Lawrence Berkeley National Laboratory were among the early advocates of using highly reflective roof surfaces for urban heat island mitigation (Akbari et al., 1995). This group led the way with respect to building energy simulations relating high albedo roofing to energy savings. Of particular note is their 11-city modeling study in which they estimated savings for metropolitan areas in a variety of climates within the US (Akbari et al., 1999). The total savings for all 11 MSAs studied were: annual electricity savings, 2.6 terawatt hours (TWh); net annual savings, $194 M; and peak electricity demand savings, 1.7 gigawatt (GW). The Heat Island Research group at LBNL has an extensive web site (http://eetd.lbl.gov/HeatIsland/) that includes discussion of the fundamental physics of heat islands, results from many past mitigation studies, and many resources related to mitigation technologies.

5.4 NASA

Researchers led by NASA's Marshall Space Flight Center were instrumental in bringing the technology of remote sensing to bear on this problems of urban heat island assessment and mitigation (Quattrochi et al., 2000).

A highlight of NASA's heat island research efforts is Project Atlanta. Project ATLANTA (ATlanta Land-use ANalysis: Temperature and Air-quality) was initiated with funding from the NASA EOS Interdisciplinary Science (IDS) program in 1996 (see www.ghcc.msfc.nasa.gov/atlanta for details). The goals of this project were to observe, measure, model, and analyze how the rapid growth of the Atlanta, Georgia metropolitan area since the early 1970's has impacted the region's climate and air quality. The objectives included: 1) modeling the relationship between Atlanta urban growth, land cover change, and the development of the urban heat island phenomenon through time; 2) investigating the relationship between urban growth and land cover change on air quality through time; and 3) modeling the overall effects of urban development on surface energy budget characteristics across the urban landscape. By addressing these objectives NASA researchers were able to arrive at an improved understanding of how land cover changes associated with urbanization can affect local and regional climate, surface energy flux, and air quality characteristics.

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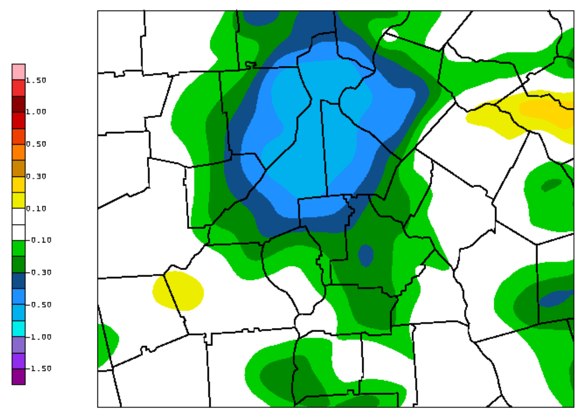

Figure 7. Simulation results for urban heat island mitigation impacts on 2-meter air temperatures in Atlanta GA relative to a baseline scenario (courtesy of NASA MSFC).

In more recent work NASA researchers are partnering with stakeholder focus groups coordinated by Georgia Cool Communities (www.coolcommunities.org) to assess relationship between future growth scenarios for the Atlanta region and the resulting heat island signature. They have defined UHI mitigation scenarios to represent conditions attainable by 2030 given strong support from local governments. The three strategies considered are: use of high albedo roof materials; use of high albedo paving materials; and increasing vegetative cover through tree planting initiatives. All scenarios were developed with detailed consideration of existing surface cover and likely future development patterns. A sample result from this work is illustrated in Fig. 7. This figure shows that it may be possible to cool most of metropolitan Atlanta by about 0.5 °C (in mid afternoon during the summer).

5.5 Mitigation Efforts in US Cities

Examples of mitigation efforts in US cities are widespread. Some of these efforts have been introduced in the preceding sections that focused on large agency initiatives. Two additional examples of mitigation in US cities are presented below. These particular examples illustrate mitigation approaches that are largely driven by local agencies and governments.

5.5.1 Cool Houston

With support from the Brown Foundation, the Houston Endowment, Inc., and George P. Mitchell the Houston Advanced Research Center (HARC) has published a document referred to as the "Cool Houston Plan". This document is similar in some respects to the EPA Heat Island Reduction guidebook. It is unique in that it focuses on Houston and is more of a Strategic Planning document. While this plan includes basic information related to heat island physics, and available mitigation strategies, it is particularly useful in that it also includes detailed data related to current inventories of land use, roof area, paving area, etc. This plan is available for download at the HARC website (www.harc.edu --> search for "Cool Houston Plan").

5.5.2 Portland Oregon, USA

In Portland, Oregon, city planners are particularly interested in the stormwater reduction potential of green roofs. Faced with the high cost of solving its politically charged Combined Sewer Overflow problem, the City's Bureau of Environmental Services (BES) is looking into using eco-roofs to retain stormwater on developments. The Central City Plan has a roof garden bonus, allowing new developments an extra square foot of building for each square foot of roof garden. To qualify for this bonus the developer must cover at least half of the roof with a garden, 30 percent of which must be vegetation (Beckman et al., 1997).

In a related effort funded by multiple city agencies Portland pursued a unique comprehensive study of the potential of a very large scale ecoroof redevelopment plan to reduce stormwater runoff, save building energy, and mitigate the urban heat island. While this study was preliminary in nature it illustrated the importance of considering co-benefits of mitigation strategies (Sailor, 2004). While the heat island mitigation aspects of this study are relatively modest in impact the study does provide a useful foundation for similar analyses in other cities.

Ecoroof development in Portland is expanding rapidly with several high profile examples, including the Multnomah County building with an 1100 m^2 ecoroof and the Broadway housing building on the Portland State University campus which has the largest ecoroof in the city at approximately 1400 m^2 (see Fig. 8).

Figure 8. A student makes performance measurements on an ecoroof on the Portland State University campus (photo by D.J. Sailor).

5.6 Mitigation Efforts in Canada

Local governments and organizations in several cities across Canada have initiated research into implementing heat island mitigation strategies. In Toronto, a business coalition known as Green Roofs for Healthy Cities intends to install and monitor green roofs on two city-owned buildings. Their measurements will focus on energy savings and stormwater reduction benefits of the green roofs. One of the demonstration sites is located on the 464 m^2 roof of the Eastview Community Centre, the other is on a 557 m^2 portion of the roof of City Hall.

5.7 Mitigation Efforts in Japan

Researchers in Japan have played a major role in understanding the urban heat island. Their efforts have included laboratory investigations (Jie et al., 1997; Saitoh and Yamada, 2000), observations (Tamiya and Ohyama, 1981; Nakatsuji et al., 1997; Saitoh and Yamada, 2000), and computational modeling (Uno et al., 1989; Kimura and Takahashi, 1991; Mochida et al., 1997; Ichinose et al., 1999; Kikegawa et al., 2003).

With respect to mitigation efforts much of the work in Japan has focused on numerical simulation. For example, Ichinose et al., (1999), Kikegawa et al., (2003), Kikegawa et al., (2004) and Tamura et al., (2006) all sought to evaluate how various aspects of the urban environment in Japanese cities impact the urban climate or building energy consumption.

In 2000 the city of Tokyo created a building design guidance document that encourages larger new public and private commercial developments to cover at least 20 percent of any flat roof area with an ecoroof. While this guidance is not binding it represents a first step toward establishing some mandatory ecoroof requirements for future construction.

5.8 Mitigation Efforts throughout Europe

While heat island mitigation using urban vegetation is an emerging phenomenon in the US, ecoroof technology has been widespread throughout Europe for decades. The various European efforts (only a few of which are summarized here) provide a powerful example of how governments can assist the implementation of mitigation strategies on a very large scale.

Germany has been at the forefront of ecoroof implementation and legislation for decades. Many German cities possess by-laws that ensure that industrial buildings incorporate a green roof. Stuttgart subsidizes by up to 50% the cost of green roof installation on industrial buildings (Beckman et al., 1997). The policy requires that green roofs be installed on new or altered low slope roofs. The policy compensates developers and building owners for the additional expense by allowing higher densities and building heights (Beckman et al., 1997).

Throughout Germany, planning polices that require or encourage green roofs have had significant impact. It is estimated that 43 percent of German cities offer financial incentives for roof greening (Osmundson, 1999) and that more than 10 percent of all flat roofs in Germany incorporate some level of ecoroof (Beckman et al., 1997). This translates into over 55 million square meters of ecoroof implementation (through 1997).

Netherlands is another leader in adopting environmental legislation. Ecoroofs can be seen in such prominent locations as the Schipol International Airport and throughout the entire community of Ecolonia. The Ecover manufacturing plant in Belgium has been hailed as “the world’s first ecological factory.” It contains more than two acres of rooftop native grasses and wildflowers (Thompson, 1998). The Swiss have taken an aggressive approach to green roof implementation in that they require all new buildings to relocate the green space covered by the building’s footprint at grade to the rooftop, and existing buildings, regardless of age or roof slope, to green 20 percent of their roofscape (Pedersen, 2001). The city of Linz, Austria has implemented a similar roof greening program that requires developers to compensate for any green space lost in development by covering an equivalent amount of space with greenery.

6. FUTURE PROSPECTS

6.1 Co-benefits

In many cases the success of heat island mitigation strategies will hinge on the ability to demonstrate co-benefits in areas other than the urban climate. A good example is the ecoroof which has direct effects on the building by providing additional insulation in summer and winter, but also provides habitat, aesthetic beauty, stormwater runoff reduction, and air quality benefits. As a general rule it is important to perform relatively comprehensive life-cycle cost-benefit analyses of mitigation strategies to evaluate their true value.

6.2 Climate change

It is possible, and perhaps likely that global climatic variations are amplified in urban settings through various feedback mechanisms. One such positive feedback mechanism is a result of the relationship between air conditioning demand and air temperature. As the air warms demand for air conditioning increases. The waste heat (or anthropogenic heat) from increased air conditioning further raises the ambient air temperature. So, under conditions of regional/global climatic change the UHI may increase in both magnitude and importance. The added stress of climate change combined with long term changes in various socio-economic factors may also impact the relative benefits of various mitigation strategies. For example, under increased competition for limited water resources albedo-based mitigation strategies may gain some competitive advantage over vegetation-based strategies, although both approaches may still yield net benefits.

6.3 New technologies

It has long been recognized that albedo and urban vegetation along with more traditional technological advances will be crucial components of addressing the UHI problem (Rosenfeld et al., 1997). It is likely that the future will hold technological advances that will lessen barriers to implementing UHI mitigation strategies, while simultaneously making them more effective. One example is in the area of high albedo surface coatings. Researchers are already working on new roof and paving systems that have increased overall albedo while being only moderately reflective in the visible spectrum. This engineering of the spectral reflectivity of surface coating systems holds great promise for breaking the implementation barriers in the residential roofing market. Figure 9 is a qualitative representation of two important aspects of spectral reflectivity. The top panel of this figure illustrates how two surfaces may be engineered in such a way that they have similar albedo, but very different reflectivities in the visible spectrum. Specifically, material B would be darker in visible color, yet have similar albedo as A. The lower panel of this figure illustrates how two materials with a similar visible color (same spectral reflectance in the 0.4 to 0.7 μm wavelength range) can be engineered such that one (material D in this case) has a much higher albedo. So, if a consumer wants a grey roofing shingle they may one day be able to choose from a traditional shingle with an albedo of less than 0.15 or one with the same gray color, but an engineered albedo in excess of 0.30.

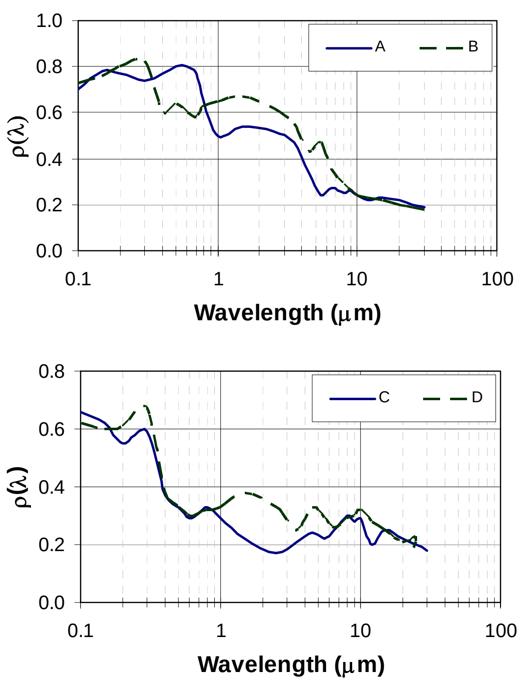

Figure 9. A plot of the spectral reflectivity of hypothetical surfaces. Surfaces A and B have similar albedo but different color. Surfaces C and D have the same color but different albedo.

6.4 Standards and Legislative Momentum

Various researchers have promoted the development of incentive programs, product labeling, and standards to facilitate the rapid deployment of urban heat island mitigation strategies (Akbari, 1998; Akbari et al., 2001). The results to date have been encouraging. Many municipalities have implemented incentive programs and ASHRAE has included reflective roofing in their building energy standards (Akbari et al., 1998; ASHRAE, 2001). As more local governments implement incentives and legislation the number and variety of successful models grows, facilitating the spread of further legislation and incentive programs.

7. CONCLUSIONS

This paper has provided a summary of the physical mechanisms responsible for the urban heat island phenomenon. These mechanisms motivate the development of mitigation strategies that incorporate aspects of increasing albedo, increasing vegetative cover, decreasing the areal coverage of impervious surfaces, and decreasing waste heat from anthropogenic activities.

The various mitigation strategies that are commonly employed for heat island mitigation have been presented along with a discussion of limitations and barriers to widespread implementation. The conclusion of this aspect of the present summary is that it is important to consider the wide range of costs and benefits of any heat island mitigation strategy. This includes undesirable wintertime penalties as well as unintended co-benefits. Likewise, full life-cycle cost-benefit analyses are important to fully assess the merits of any mitigation strategy.

Finally this paper provides a brief assessment of the future of heat island mitigation. It appears from the work done to date that there is significant momentum and potential for ongoing and expanded large-scale mitigation projects in the future. Some of the current barriers to implementing these strategies are being addressed by aggressive research programs and a grass-roots efforts within communities and local governments to establish incentives, standards, and legislation to further promote implementation of UHI mitigation strategies.

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REFERENCES

Akbari, H., 1998. Cool roofs save energy. ASHRAE Transactions 104.

Akbari, H., Davis, S., Dosano, S., Huang, J., Winnett, S. 1992. Cooling our communities: A guidebook on tree planting and light-colored surfacing. pp. also Lawrence Berkeley National Laboratory Report # LBL-31587.

Akbari, H., Konopacki, S., Pomerantz, M., 1999. Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States. Energy (Oxford) 24 (5) 391-407.

Akbari, H., Konopacki, S. J., Eley, C. N., Wilcox, B. A., Van Geem, M. G., Parker, D. S., 1998. Calculations for reflective roofs in support of standard 90.1. ASHRAE Transactions 104 976-987.

Akbari, H., Pomerantz, M., Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy 70 (3) 295-310.

Akbari, H., Rose, L. R., Taha, H. 1999. Characterizing the fabric of the urban environment: a case study of Sacramento. pp. LBNL-44688.

Akbari, H., Rosenfeld, A. H., Taha, H., 1995. Cool construction materials offer energy savings and help reduce smog. Standardization News 23 (11) 32.

Anon, 2002. ASTM established green roof standards task group. Interface (Raleigh, North Carolina) 20 (1) 12.

Asaeda, T., Ca, V. T., Wake, A., 1996. Heat storage of pavement and its effect on the lower atmosphere. Atmospheric Environment 30 (3) 413-427.

ASHRAE 2001. Standard 90.1-2001 (S-I edition) -- Energy Standard for Buildings Except Low-Rise Residential Buildings (IESNA cosponsored; ANSI approved; Continuous Maintenance Standard), SI Edition.

Avissar, R., 1996. Potential effects of vegetation on the urban thermal environment. Atmospheric Environment 30 (3) 437-448.

Beckman, S., Jones, S., Liburdy, K., Peters, C. 1997. Greening our cities: An analysis of the benefits and barriers associated with green roofs. 51 pp.

Benjamin, M. T., Sudol, M., Bloch, L., Winer, A. M., 1996. Low-emitting urban forests: a taxonomic methodology for assigning isoprene and monoterpene emission rates. Atmospheric Environment 30 (9) 1437-1452.

Berdahl, P., Akbari, H., Rose, L. S., 2002. Aging of reflective roofs: Soot deposition. Applied Optics 41 (12) 2355-2360.

Bretz, S., Akbari, H., Rosenfeld, A., 1998. Practical issues for using solar-reflective materials to mitigate urban heat islands. Atmospheric Environment 32 (1) 95-101.

Corchnoy, S. B., Arey, J., Atkinson, R., 1992. Hydrocarbon Emissions from Twelve Urban Shade Trees of the Los Angeles, California, Air Basin. Atmospheric Environment 26B (3) 339-348.

Del Barrio, E. P., 1998. Analysis of the green roofs cooling potential in buildings. Energy and Buildings 27 (2) 179-193.

DeNardo, J. C., Jarrett, A. R., Manbeck, H. B., Beattie, D. J., Berghage, R. D., 2003. Stormwater Detention and Retention Abilities of Green Roofs. World Water and Environmental Resources Congress 2003, Jun 23-26 2003, Philadelphia, PA, United States, American Society of Civil Engineers.

Eisenman, T., 2004. Sedums over Baltimore: how a green roof made a rehabilitated building more sustainable [Montgomery Park Business Center]. Landscape architecture 94 (8) 52.

Estes, M. G., Jr., 2000. Urban heat island mitigation strategies. Planning Advisory Service Memo (May) 1-4.

Golany, G. S., 1996. Urban design morphology and thermal performance. Atmospheric Environment 30 (3) 455-465.

Gomez, F., Gaja, E., Reig, A., 1998. Vegetation and climatic changes in a city. Ecological Engineering 10 (4) 355-360.

Heisler, G. M. 1989. Effects of Trees on Wind and Solar Radiation in Residential Neighborhoods. pp. ANL-058719.

Ichinose, T., Shimodozono, K., Hanaki, K., 1999. Impact of anthropogenic heat on urban climate in Tokyo. Atmospheric Environment 33 3897-3909.

Jie, L., Arya, S. P., Snyder, W. H., Lawson, R. E., Jr., 1997. A laboratory study of the urban heat island in a calm and stably stratified environment. Part II: velocity field. Journal of Applied Meteorology 36 (10) 1392-1402.

Johnson, L., 2003. Meadows above: a rooftop plant community in downtown Toronto. Landscape architecture 93 (8) 22.

Kikegawa, Y., Genchi, Y., Kondo, H., Ohashi, Y., 2004. Yearlong evaluation of urban heat island countermeasures from the viewpoints of thermal environment mitigation and urban energy conservation. 5th Symposium on the Urban Environment, Aug 23-26 2004, Vancouver, BC, Canada, American Meteorological Society, Boston, MA 02108-3693, United States.

Kikegawa, Y., Genchi, Y., Yoshikado, H., Kondo, H., 2003. Development of a numerical simulation system toward comprehensive assessments of urban warming countermeasures including their impacts upon the urban buildings' energy-demands. Applied Energy 76 (4) 449-466.

Kimura, F., Takahashi, S., 1991. The effects of land-use and anthropogenic heating on the surface temperature in the Tokyo Metropolitan area: a numerical experiment. Atmospheric Environment, Part B 25 B (2) 155-164.

Landsberg, H. E. 1981. The Urban Climate, Academic Press.

Levinson, R., Akbari, H., 2002. Effects of composition and exposure on the solar reflectance of portland cement concrete. Cement and Concrete Research 32 (11) 1679-1698.

Liptan, T., 2004. Stormwater retention of ecoroofs - Hamilton building data. Portland OR.

Lubell, S., 2004. New York's Javits Center design shows off world's largest green roof. Architectural record 192 (8) 30.

Miller, C., 2002. Updating the sod roof: a German-style ecoroof finds a home in suburban Pennsylvania. Landscape architecture 92 (11) 30.

Mochida, A., Ooka, R., Sugiyama, H., Murakami, S., Ojima, T., Kim, S., 1997. CFD analysis of mesoscale climate in the Greater Tokyo area. Journal of Wind Engineering and Industrial Aerodynamics 67-68 459-477.

Nakatsuji, K., Yamaji, A., Minami, H., Sato, A., Muraoka, K., 1997. Effects of urbanization on ground surface temperature in the Kansai District, Japan - based on meteorological data. Journal of Global Environment Engineering 3 183-197.

Niachou, A., Papakonstantinou, K., Santamouris, M., Tsangrassoulis, A., Mihalakakou, G., 2001. Analysis of the green roof thermal properties and investigation of its energy performance. Energy and Buildings 33 (7) 719-729.

Oke, T. R. 1978. Boundary Layer Climates. London, Methuen.

Oke, T. R., 1982. The Energetic Basis of the Urban Heat Island. Quarterly Journal of the Royal Meteorological Society 108 1-24.

Osmundson, T. 1999. Roof Gardens: History, design, and construction. New York, W. Norton & Company.

Parker, D. S., Sherwin, J. R., Sonne, J. K., Barkaszi Jr., S. F. 1996. Demonstration of Cooling Savings of Light Colored Roof Surfacing in Florida Commercial Buildings: Our Savior's School. pp. FSEC-CR-904-96.

Pedersen, K., 2001. Meadows in the Sky - contemporary applications for eco-roofs in the Vancouver region. School of Architecture. Vancouver, University of British Columbia 113.

Quattrochi, D. A., Laymon, C. A., Howell, B. F., Luvall, J. C., Rickman, D. L., Estes, M. G., Jr., 2000. A decision support information system for urban landscape management using thermal infrared data. Photogrammetric Engineering and Remote Sensing 66 (10) 1195-1207.

Rosenfeld, A. H., Romm, J. J., Akbari, H., Lloyd, A. C., 1997. Painting the town white - and green. Technology Review 100 (2) 52-59.

Sailor, D., 2004. Ecoroofs and the Urban Climate. Second Annual Greening Rooftops for Sustainable Communities Conference, Portland, OR.

Sailor, D. J., 1998. Simulations of annual degree day impacts of urban vegetative augmentation. Atmospheric Environment 32 (1) 43-52.

Sailor, D. J., Fan, H., 2002. Modeling the diurnal variability of effective albedo for cities. Atmospheric Environment 36 (4) 713-725.

Sailor, D. J., Fan, H., 2004. The importance of including anthropogenic heating in mesoscale modeling of the urban heat island. 84th annual meeting of the AMS, Symposium on Planning, Nowcasting, and Forecasting in the Urban Zone, Seattle.

Saitoh, T. S., Yamada, N., 2000. Experimental observation and numerical simulation of heat island plume in urban surface layer. 35th Intesociety Energy Conversion Engineering Conference, Jul 24-Jul 28 2000, Las Vegas, NA, USA, Institute of Electrical and Electronics Engineers Inc., Piscataway, NJ, USA.

Solomon, N. B., 2003. Vegetation systems atop buildings yield multiple environmental benefits. Architectural record 191 (3) 149-152.
Taha, H., Konopacki, S., Gabersek, S., 1999. Impacts of large-scale surface modifications on meteorological conditions and energy use: A 10-region modeling study. Theoretical and Applied Climatology 62 (3-4) 175-185.
Tamiya, H., Ohyama, H., 1981. Nocturnal heat island of small town, its manifestation and mechanism. Geographical Review of Japan 54 (1) 1-21.
Tamura, H., Ishii, K., Yokoyama, H., Iwatsubo, T., Hirakuchi, H., Ando, H., Yamaguchi, T., Mikami, T., Ichino, M., Akiyama, Y., 2006. Numerical prediction of heat island mitigation effect on decrease in air temperature in Tokyo, Atlanta, GA, American Meteorological Society.
Thompson, J. W., 1998. Grass-roofs movement. Landscape architecture 88 (May) 47-51.
Uno, I., Ueda, H., Wakamatsu, S., 1989. Numerical modeling of the nocturnal urban boundary layer. Boundary-Layer Meteorology 49 (1-2) 77-98.
Wark, C. G., Wark, W. W., 2003. Green roof specifications and standards establishing an emerging technology. Construction Specifier 56 (8) 76-82.
Wong, N. H., Tay, S. F., Wong, R., Ong, C. L., Sia, A., 2003. Life cycle cost analysis of rooftop gardens in Singapore. Building and Environment 38 (3) 499-509.