Global cooling: effect of urban albedo on global temperature

H. Akbari
Lawrence Berkeley National Laboratory, USA

S. Menon
Lawrence Berkeley National Laboratory, USA

A. Rosenfeld
California Energy Commission, USA

ABSTRACT

In many urban areas, pavements and roofs constitute over 60% of urban surfaces (roof 20-25%, pavements about 40%). The roof and the pavement albedo can be increased by about 0.25 and 0.10, respectively, resulting in a net albedo increase for urban areas of about 0.1. Many studies have demonstrated building cooling-energy savings in excess of 20% upon raising roof reflectivity from an existing 10-20% to about 60%. We estimate U.S. potential savings in excess of $1 billion (B) per year in net annual energy bills. Increasing albedo of urban surfaces can reduce the summertime urban temperature and improve the urban air quality.

Increasing the urban albedo has the added benefit of reflecting more of the incoming global solar radiation and countering the effect of global warming. We estimate that increasing albedo of urban areas by 0.1 results in an increase of 3x10^-4 in Earth albedo. Using a simple global model, the change in air temperature in lowest 1.8 km of the atmosphere is estimated at 0.01K. Modelers predict a warming of about 3K in the next 60 years (0.05K/year). Change of 0.1 in urban albedo will result in 0.01K global cooling, a delay of ~0.2 years in global warming. This 0.2 years delay in global warming is equivalent to 10 Gt reduction in CO2 emissions.

1. INTRODUCTION

For more than two decades, the Heat Island Group (HIG) at Lawrence Berkeley National Laboratory (LBNL) has performed research to quantify the effect of increasing urban albedo on reducing cooling energy use, cooling urban areas, and improving urban air quality. In many urban areas, pavements and roofs constitute over 60% of urban surfaces (see Table 1; roof 20-25%, pavements about 40%) (Akbari et al., 2003, Rose et al., 2003, Akbari and Rose 2001a, Akbari and Rose 2001b).

Table 1: Urban fabric

<table>
<thead>
<tr>
<th>Metropolitan Areas</th>
<th>Vegetation</th>
<th>Roofs</th>
<th>Pavements</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt Lake City</td>
<td>33.3</td>
<td>21.9</td>
<td>36.4</td>
<td>8.5</td>
</tr>
<tr>
<td>Sacramento</td>
<td>20.3</td>
<td>19.7</td>
<td>44.5</td>
<td>15.4</td>
</tr>
<tr>
<td>Chicago</td>
<td>26.7</td>
<td>24.8</td>
<td>37.1</td>
<td>11.4</td>
</tr>
<tr>
<td>Houston</td>
<td>37.1</td>
<td>21.3</td>
<td>29.2</td>
<td>12.4</td>
</tr>
</tbody>
</table>

Source: Rose et al., 2003

Many studies have demonstrated building cooling-energy savings in excess of 20% upon raising roof reflectivity from an existing 10-20% to about 60%. We estimate U.S. potential savings in excess of $1 billion (B) per year in net annual energy bills (cooling-energy savings minus heating-energy penalties). Increasing albedo of urban surfaces (roofs and pavements) can reduce the summertime urban temperature and improve the urban air quality (Taha 2002; Taha 2001; Taha et al. 2000; Rosenfeld et al. 1998; Akbari et al. 2001, Pomerantz et al. 1999). The energy and air quality savings resulting from increasing urban surface abedo in the U.S. can exceed $2B per year.

Increasing the urban albedo has the added benefit of reflecting more of the incoming global solar radiation and countering the effect of global warming (Kaarsberg and Akbari, 2006). Here we quantify the effect of increasing albedo of urban areas on the global temperature.

2. ESTIMATING GLOBAL URBAN AREAS

Figure 1 lists the area densities for the 100 largest metropolitan areas of the world (Wikipedia, 2006). The median area density is about 430 m² per urban dweller. The 100 largest metropolitan areas (with a total population of 670 M) comprise about 0.26% of the Earth land area. Assuming that about 3B people live in urban areas, total urban area of the globe is estimated at about 1.2% of land.
3. POTENTIALS FOR URBAN ALBEDO CHANGE

Rose et al. (2003) have estimated that the fractions of the roof and paved surface areas in four U.S. cities. The fraction of roof areas in these four cities varies from 20% for less dense cities to 25% for more dense cities. The fraction of paved surface areas varies between 29% to 44%. Many metropolitan urban areas around the world are less vegetated than typical U.S. cities. For this analysis, we consider an average area fraction of 25% and 40% for roof and paved surfaces, respectively.

Akbari and Konopacki (2005) have reviewed the solar reflectance of typical roofing materials used on residential and commercial buildings in many U.S. regions. A solar-reflective roof is typically light in color and absorbs less sunlight than a conventional dark-colored roof. Less absorbed sun light means a lower surface temperature, directly reducing heat gain from the roof and air-conditioning demand. Typical albedo values for low- and high-albedo roofs can be obtained from the cool roofing materials database (CRMD, 2007) developed at LBNL.

For the sloped-roof residential sector, available highly reflective materials are scarce. White asphalt shingles are available, but have a relatively low albedo of about 0.25. Although it can be argued that white coatings can be applied to shingles or tiles to obtain an aged albedo of about 0.5, this practice is not followed in the field. Some highly reflective white shingles are being developed, but are only in the prototype stage. Recently, one U.S. manufacturer has developed and marketing cool-colored fiberglass asphalt shingles with a solar reflectance of 0.25. Some reflective tiles and metal roofing products with greater than 50% reflectivity are also available. Conversely, highly reflective materials for the low-slope commercial sector are on the market. White acrylic, elastomeric and cementitious coatings, as well as white thermoplastic membranes, can now be applied to built-up roofs to achieve an aged solar -reflectance of 0.6.

The albedo of typical standard roofing materials ranges from 0.10-0.25; one can conservatively assume that the average albedo of existing roofs does not exceed 0.20. The albedo of these surfaces can be increased to about 0.55 to 0.60.

Pomerantz et al. (2000a, 2000b, 1997) and Pomerantz and Akbari (1998) have documented the solar reflectance of many standard and reflective paved surfaces. They report that the solar reflectance of a freshly installed asphalt pavement is about 0.05. Aged asphalt pavements have a solar reflectance between 0.10-0.18, depending on the type of aggregate used in the asphalt mix. A light-color (low in carbon content) concrete can have an initial solar reflectance of 0.35-0.40 that will age to about 0.25-0.30. Pomerantz et al. also reviewed the solar reflectance of other paving materials such as chip seal, slurry coating, light-color coating.

Akbari et al. (2003) provide estimates for two scenarios for potential changes in the albedo of roofs and paved surfaces (See Table 2). Based on this data, we assume that roof albedo can increase by 0.25 for a net change of 0.25x0.25=0.06. The pavement albedo can increase by 0.10 for a net change of 0.40x0.10=0.04. Hence, the potential change in albedo of urban area is estimated at 0.10.

Table 2: Two albedo modification scenarios

<table>
<thead>
<tr>
<th>Surface-Type</th>
<th>Albedo Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Residential Roofs</td>
<td>0.3</td>
</tr>
<tr>
<td>Commercial Roofs</td>
<td>0.4</td>
</tr>
<tr>
<td>Pavements</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Source: Akbari et al. (2003)

Increasing albedo of urban areas by 0.1 results in an increase of 3x10^-4 in Earth albedo.

4. THE EFFECT OF CHANGING URBAN ALBEDOS ON GLOBAL TEMPERATURE

In his book, Harte (1998) presents a simplified method to estimate the effect of a change in the albedo on the globe on the Earth equilibrium temperature. Using Hart’s simple global model, the change in air temperature in the lowest 1.8 km of the atmosphere is estimated at 0.01K. This estimate is corroborated by calculations of Hansen et al. (1997).

We have also carried out preliminary general circulation model (GCM) simulations to estimate the changes in the average globe temperature by changing the albedo of the all urban land surfaces. Currently, general circulation models (GCMs) are too coarse to estimate the effects of increased urban albedo. Most GCMs simulate the global climate with grid sizes larger than 2.5 degree (approximately 250 km; area of 62500 km^2). Most metropolitan urban areas are about 3000 – 5000
km² or about 1/100 of a typical GCM grid size. A change in the urban albedo of about 0.1, would reflect a change of 0.001 in the albedo of the grid. Such a small change in the albedo may not produce a significant feedback and hence the results of the GCM simulations may be questionable.

Several groups have performed general circulation model (GCM) simulations to investigate various aspects of global warming related to land-use changes (e.g. Hansen et al. 1998, Bettes 2001, Levy et al. 2004, Chase et al. 2000, Jacobson, 2002, Oyama and Nobre 2004, to name a few). However, effects of urban albedos on climate have usually not been investigated. Some of the reasons are the coarse-grids of GCMs that are unable to resolve urban landscape features.

With current computational advances, it has become feasible to run a GCM at scales of 50 to 100 km with sub-grid adaptations of particular processes. Newer developments in land-surface schemes, based on satellite retrieved land-surface properties such as emissivity, are being incorporated in land-surface models that could be coupled to a GCM (Jin and Liang 2006; Jin and Shepherd 2005). Our preliminary simulations using the NASA GISS GCM, that has a horizontal resolution of 4x5 degrees, predicts a decrease in global surface temperatures of about 0.03K (See figure 2.)

These results were based on two sets of simulations: (1) A control run with prescribed present-day sea-surface temperatures called CtrlA; and (2) a simulation similar to CtrlA but with modified surface albedos, referred to as Exp. In simulation Exp, we assumed that the surface albedo of all urban land surfaces (2% of land surfaces) is purely reflective (set at 1) and the albedo of the rest of the land surfaces (98%) are not changed and are dependent on surface type, vegetation etc. as in the CtrlA version. The results from the two simulations, CtrlA and Exp, are averaged for three years after a spin-up of one year and are shown in Fig. 2. However, given the small changes we impose, and the coarse grid of the model, the signal to noise ratio is not strong and at best, the surface temperature changes given in Fig. 2 are preliminary values. We are investigating methods to more accurately estimate the effect of an albedo increase on global warming.

5. GLOBAL COOLING: CO2 EQIVALENCY

Modellers predict a warming of about 3K in the next 60 years (0.05K/year). Change of 0.1 in urban albedo will result in 0.01K global cooling, a delay of ~0.2 years in global warming. The World’s current rate of CO2 emissions is about 25 G tons/year (4.1 tons/year per person). The World’s rate of CO2 emissions averaged over next 60 years is estimated at 50 G tons/year. Hence, the 0.2 years delay in global warming is worth 10 Gt CO2.

In Europe CO2 is currently traded at ~$10/ton. A 10 Gt CO2 reduction for changing albedo of roofs and paved surfaces is worth $100 billion. The contribution of cooler roofs to this CO2 savings is worth $60B.

6. CONCLUSIONS

Using cool roofs and cool pavements in urban areas, on the average, can increase the albedo of the urban areas by 0.1. An increase of 0.1 in urban albedo can cool the Earth by about 0.01K. This cooling can compensate for 0.2 years of the world’s CO2 emissions; a saving of 10 Gt CO2, valued at $100B. Cool roofs also save air
conditioning energy use at about $10B per year; $600B over the next 60 years. Given these potential savings, we would like to recommend establishing an international organization where the developed countries offer $1 million per large city in a developing country, to trigger a cool roof/pavement program in that city.

7. ACKNOWLEDGEMENT

This work was supported by the California Energy Commission (CEC) through its Public Interest Energy Research Program (PIER), and by the Assistant Secretary for Energy Efficiency and Renewable Energy under Contract No. DE-AC02-05CH11231.

REFERENCES


Status of cool roof standards in the United States

H. Akbari and R. Levinson
Lawrence Berkeley National Laboratory, USA

ABSTRACT

Since 1999, several widely used building energy efficiency standards, including ASHRAE 90.1, ASHRAE 90.2, the International Energy Conservation Code, and California’s Title 24 have adopted cool roof credits or requirements. We review the technical development of cool roof provisions in the ASHRAE 90.1, ASHRAE 90.2, and California Title 24 standards, and discuss the treatment of cool roofs in other standards and energy-efficiency programs. The techniques used to develop the ASHRAE and Title 24 cool roof provisions can be used as models to address cool roofs in building energy standards worldwide.

1. INTRODUCTION

Roofs that have high solar reflectance (high ability to reflect sunlight) and high thermal emittance (high ability to radiate heat) stay cool in the sun. The same is true of low-emittance roofs with exceptionally high solar reflectance. Roofs that stay cool in the sun are referred to as “cool roofs.”

Low roof temperatures lessen the flow of heat from the roof into the building, reducing the need for electricity for space cooling in conditioned buildings. Since building heat gain through the roof peaks in mid-to-late afternoon, when summer electricity use is highest, cool roofs can also reduce peak electricity demand. Energy savings are greatest for buildings located in climates with long cooling and short heating seasons, particularly those buildings that have distribution ducts in the plenum (Akbari 1998; Akbari et al. 1999; Konopacki and Akbari 1998).

Cool roofs transfer less heat to the outdoor environment than do warm roofs (Taha 2001). The resulting lower outside air temperatures can slow urban smog formation and improve human health and outdoor comfort. Reduced thermal stress may also increase the lifetime of cool roofs, lessening maintenance and waste (Akbari et al. 2001).

Many studies have measured daily air-conditioning energy savings and peak power demand reduction from the use of cool roofs on nonresidential buildings in several warm-weather climates, including California, Florida, and Texas. Cool roofs typically yielded measured summertime daily air-conditioning savings and peak demand reductions of 10% to 30%, though values have been as low as 2% and as high as 40% (Konopacki et al. 1998). For example, Konopacki et al. (1998) measured summer daily air-conditioning savings of 67, 39, and 4 Wh/m² (18, 13, and 2%) for three California nonresidential building. Hildebrandt et al. (1998) measured summer daily air-conditioning savings of 23, 44, and 25 Wh/m² (17, 26, and 39%) in an office, a museum, and a hospice in Sacramento, CA. Konopacki and Akbari (2001) estimated summer daily cooling average energy savings of 39 Wh/m² (11%) and peak power reduction of 3.8 W/m² (14%) in a large retail store in Austin, TX. Parker et al. (1998) measured summer daily energy savings of 44 Wh/m² (25%) and a peak power reduction of 6.0 W/m² (30%) for a school building in Florida. Parker et al. (1997) measured summer daily energy savings of 81 Wh/m² (25%) and peak power reduction of 6.4 W/m² (29%) in seven retail stores within a Florida strip mall.

Building energy efficiency standards typically specify both mandatory and prescriptive requirements. Mandatory requirements, such as practices for proper installation of insulation, must be implemented in all buildings covered by the standard. A prescriptive requirement typically specifies the characteristics or performance of a single component of the building (e.g., the thermal resistance of duct insulation) or of a group of components (e.g., the thermal transmittance of a roof assembly).

All buildings regulated by a particular standard must achieve either prescriptive or performance compliance. A proposed building that meets all applicable mandatory and prescriptive requirements will be in prescriptive compliance with the standard. Alternatively, a proposed building can achieve performance compliance with standard if (a) it satisfies all applicable mandatory requirements and (b) its annual energy use does not exceed that of comparable design (a.k.a. standard design) building that achieves prescriptive compliance.

Prescribing the use of cool roofs in building energy efficiency standards promotes the cost-effective use of cool roofs to save energy, reduce peak power demand, and improve air quality. Another option is to credit, rather than prescribe, the use of cool roofs. This can allow more flexibility in building design, permitting the use of less energy-efficient components (e.g., larger windows) in a building that has energy-saving cool roofs. Such credits are energy neutral, but may still reduce peak power demand and improve air quality. They may also reduce the first cost of the building.
This paper reviews the technical steps in developing the cool roof provisions in the ASHRAE 90.1, ASHRAE 90.2, and California Title 24 building energy efficiency standards, and discusses the treatment of cool roofs in several other standards and energy-efficiency programs.

2. DEVELOPMENT OF STANDARDS

2.1 ASHRAE Standard 90.1

Recognizing the potential for cool roofs to reduce the conditioning energy use of commercial buildings, the ASHRAE Standard 90.1 committee organized a task force in 1997 to analyze the energy-saving benefits of cool roofs in different climates, and to propose modifications to the standard to account for the effect of roof solar reflectance (Akbari et al. 1998).

A cool roof reduces the flow of heat from the roof into the building’s conditioned space. This can decrease the need for cooling energy in summer, and increase heating-energy use in winter. The winter heating-energy penalty is usually smaller than the summer cooling-energy savings, because in winter the sun is low, the days are short, the skies are often cloudy, and most heating occurs either in early morning hours or early evening hours. Roof insulation also impedes the flow of heat between the roof and the conditioned space, slowing both heating of the building when the roof is warmer than the inside air and cooling of the building when the roof is cooler than the inside air. One can develop an energy-neutral tradeoff between the roof’s solar reflectance and the thermal resistance of its insulation.

ASHRAE Standard 90.1 permits both prescriptive and performance (“energy cost budget”) compliance. ASHRAE Standard 90.1-1999 includes two forms of credits for a cool roof, defined as one with a minimum initial solar reflectance of 0.70 and a minimum thermal emittance of 0.75. For performance compliance, a cool roof on a proposed building is assigned a solar absorptance of 0.55 (solar reflectance of 0.45). (We believe this may be a typographical error, because the analysis used to develop this standard assigned to a cool roof an aged solar absorptance of 0.45 [aged solar reflectance of 0.55]). A noncool roof on a proposed building and the roof on the design building are each assigned a solar absorptance, or possibly a solar absorptance of 0.35; the standard’s language is ambiguous. A noncool roof on a proposed building is assigned its actual solar absorptance, or possibly a solar absorptance of 0.35; the standard’s language is ambiguous. A noncool roof on a proposed building is assigned its actual solar absorptance, or possibly a solar absorptance of 0.35; the standard’s language is ambiguous. A noncool roof on a proposed building is assigned a solar absorptance of 0.20 (solar reflectance of 0.80).

For prescriptive compliance, ASHRAE Standard 90.1-1999 increases the maximum acceptable thermal transmittance of a roof assembly under a cool roof surface. This has the effect of reducing the required thermal resistance of insulation beneath a cool roof. The standard includes the following adjustment to the thermal transmittance of the roof assembly with a cool surface:

\[ U_{\text{roof adj}} = U_{\text{roof proposed}} \times F; \]

where \( U_{\text{roof adj}} \) is the adjusted roof thermal transmittance for use in demonstrating compliance; \( U_{\text{roof proposed}} \) is the thermal transmittance of the proposed roof, as designed; and \( F \) is the roof thermal transmittance multiplier from Table 1. ASHRAE Standard 90.1-2001 (ASHRAE 2001) retains the same provisions for cool roof credits. The current version of this standard, ASHRAE Standard 90.1-2004 (ASHRAE 2004a) tabulates thermal transmittance multipliers by U.S. climate zones (see Table 2).

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Rooftop U-Factor Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.77</td>
</tr>
<tr>
<td>2</td>
<td>0.83</td>
</tr>
<tr>
<td>3</td>
<td>0.85</td>
</tr>
<tr>
<td>4 - 8</td>
<td>1</td>
</tr>
</tbody>
</table>

2.2 ASHRAE Standard 90.2

The procedure for incorporating the effect of roof solar reflectance in the ASHRAE Standard 90.2 residential standards was similar to that followed for ASHRAE Standard 90.1 (Akbari et al. 2000). ASHRAE Standard 90.2-2004 permits both prescriptive and performance (“energy cost budget”) compliance. The standard includes two form of credits for cool roofs, defined as a roof with either (a) a minimum initial solar reflectance of 0.65 and a minimum thermal emittance of 0.75, or (b) a solar reflectance index (SRI) of at least 75 calculated in accordance with ASTM Standard E1980 under medium wind speed conditions (ASTM 1998). SRI is defined to be 0 for a clean black roof (solar reflectance 0.05, thermal emittance 0.90) and 100 for a clean white roof (solar reflectance 0.80, thermal emittance 0.90); thus, warm surfaces have low SRI, and cool surfaces have high SRI. For performance compliance, a cool roof on a proposed building is assigned its actual solar absorptance, or possibly a solar absorptance of 0.35; the standard’s language is ambiguous. A noncool roof on a proposed building and the roof on the design building are each assigned a solar absorptance of 0.20 (solar reflectance of 0.80). However, the authors believe the latter to be a typographical error; the logical value would be a solar absorptance of 0.80 (solar reflectance of 0.20).