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Mitigation of urban heat islands: materials, utility programs, updates ☆

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Abstract

Elevated temperatures in urban 'heat islands' increase cooling energy use and accelerate the formation of urban smog. Urban shade trees and light-colored surfaces can offset or reverse the heat island and conserve energy. Implementation of heat island mitigation measures is now a prominent part of President Clinton's Climate Change Action Plan to control the emissions of greenhouse gases, necessitating a better understanding of the quantitative benefits of these control measures. We present recent measurements of the air-conditioning savings for houses in Sacramento and Florida, and air temperature measurements at White Sands National Monument, New Mexico. We also discuss the results of meteorological and smog simulations for the Los Angeles Basin. The albedo of a city may be increased gradually if high-albedo surfaces are chosen to replace darker materials during routine maintenance of roofs and roads. Such high-albedo surfaces may last longer than their conventional dark counterparts. Utility-sponsored incentive programs, product labeling, and standards could promote the use of high-albedo materials for buildings and roads, and several paint manufacturers have expressed interest in participating in a 'cool surfaces' labeling program. We examine the spectral reflectance of various white coatings and building materials that might be labeled in such a program.

Keywords: Urban heat islands; Utility programs; Air-conditioning electricity savings; Smog mitigation; Cool roofs; Cool roads

1. Introduction

Modern urban areas usually have dark surfaces and less vegetation than their surroundings. These differences affect the climate, energy use, and habitability of cities. At the building scale, exposed dark exterior surfaces become hot and thus raise the summertime cooling demands of buildings. Collectively, the dark surfaces and reduced vegetation warm the summer air over urban areas, leading to the creation of the summer urban 'heat island'. On a clear summer afternoon, the air temperature in a typical city is about 2.5 °C (5 °F) hotter than the surrounding rural area. Akbari et al. [1] have found that peak urban electric demand in five American cities (Los Angeles, CA; Washington, DC; Phoenix, AZ; Tucson, AZ; and Colorado Springs, CO) rises by 2–4% for each 1 °C rise in daily maximum temperature above a threshold of 15–20 °F. Thus, the additional air-conditioning use caused by this urban air temperature increase is responsible for 5–10% of urban peak electric demand, at a direct cost of several billion dollars annually.

The Heat Island Project at the Lawrence Berkeley Laboratory has examined both the building- and city-scale effects of the urban surface on energy use and

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climate. We find that increasing the albedo [6] of urban surfaces and planting trees in urban areas can limit or reverse the urban heat island effectively and inexpensively. Both of these improvements can be implemented by (i) rating and labeling roofing materials by their minimum midday temperature; (ii) adopting relatively mild standards (for example, that new roofs run cooler than halfway between the surface temperatures of typical white and black surfaces) and (iii) offering rebates on new roofs (or re-roofs) for beating the standards.

2. Building-scale effects

The direct effect of lowering the albedo of a surface and removing the surrounding vegetation is to increase its solar heat gain and thus its surface temperature. If the surface is the roof or wall of a building, the increased heat gain directly increases the cooling energy use and peak cooling demand of the building.

Fig. 1 shows the midday temperatures of various horizontal surfaces exposed to sunlight. For highly absorptive (low-albedo) surfaces, the difference between the surface and ambient air temperature, ΔT_{s-a}, may be as high as 50 °C (100 °F), while for less absorptive (high-albedo) surfaces, such as white paint, ΔT_{s-a} is about 10 °C. For this reason, shade trees (which reduce the insolation on a surface) and cool surfaces (which absorb little of the incident insolation) are effective means of direct cooling and reducing energy use. Through direct shading and evapotranspiration, trees reduce summer cooling energy use in buildings at about 1% of the capital cost of avoided power plants plus air-conditioning equipment [3]. Cool surfaces are more effective than trees, and cost little if color changes are incorporated into routine maintenance schedules. Also, the results from light-colored surfaces are immediate, while it may be ten or more years before a tree is large enough to produce significant energy savings. Akbari et al. [4] discuss the relative benefit/cost of white surfaces versus trees.

2.1. Measured energy savings from direct cooling in Sacramento

In the summers of 1991 and 1992, we conducted experiments to measure the impact of white roofs and shade trees on six buildings in Sacramento [5]. We collected data on air-conditioning electricity use, indoor and outdoor dry-bulb temperatures and humidities, surface temperatures of roof and ceiling, inside and outside wall temperatures, solar intensities, and wind speeds and directions.

To measure the impact of shade trees, we monitored two houses in a 'flip-flop' experiment, divided into three

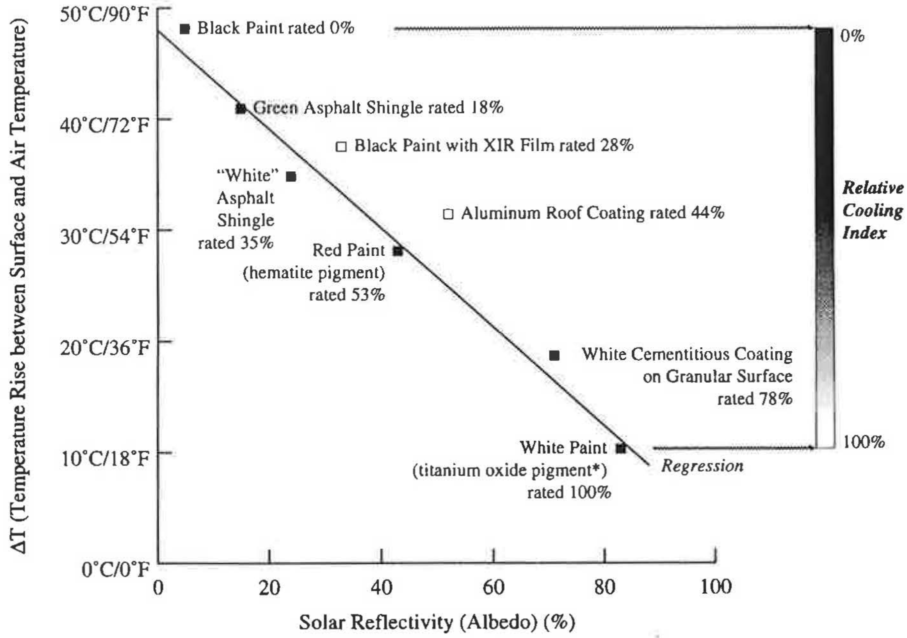

Fig. 1. The difference between surface and air temperatures vs. solar reflectivity of paints and roofing materials facing the sun. Note that white is 40 °C cooler than black. Metals (open squares) become hotter than similar colored paint because they radiate poorly (low emissivity). Before 1960, white shingles were cooler, but then industry made them darker to hide dirt. White acrylic paint is pigmented with titanium dioxide. Open squares are not included in the regression. Solar reflectivity is measured according to ASTM E903. Data from Ref. [2].

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[6] Albedo is defined as hemispherical reflectivity integrated over the solar spectrum. Low-albedo surfaces absorb a larger portion of the incident insolation and become hotter than high-albedo surfaces. Most high-albedo surfaces are light-colored, although selective surfaces which reflect a large portion of the infrared solar radiation but absorb some visible light may be colored, yet have relatively high albedos.

periods. In the first period, we monitored the cooling energy use of both houses in order to establish a base case relationship (see Fig. 2). In the second monitoring period, eight large and eight small shade trees were placed at one of the sites (site D) for a period of four weeks and then, for the third period, the trees were moved to the other site (site C). The cooling energy use of the site without trees indicates what the cooling energy use of the shaded site would have been were the trees not there. Fig. 2 shows savings of 35% of the median air-conditioning load of the unshaded houses.

To measure the impact of white roofs and walls, we monitored the cooling energy use of a house and two school bungalows. We monitored the house in its original condition to obtain pre-modification data. The albedo of the house roof at that time was 0.18. The next year, post-modification data were collected after the albedo of the roof had been increased to 0.73. Fig. 3 shows the daily cooling-energy use of the house plotted against daily average dry-bulb outdoor temperature. The daily average outdoor temperature that causes the air-conditioning unit to turn on has shifted upward by 2 °C. The lines on Fig. 3 are regression fits up to 25 °C. Past this point, it is difficult to compare pre- and post-modification data because there are no pre-modification data with comparable environmental variables. The seasonal cooling energy savings at this site are estimated to be 40% (330 kWh/yr).

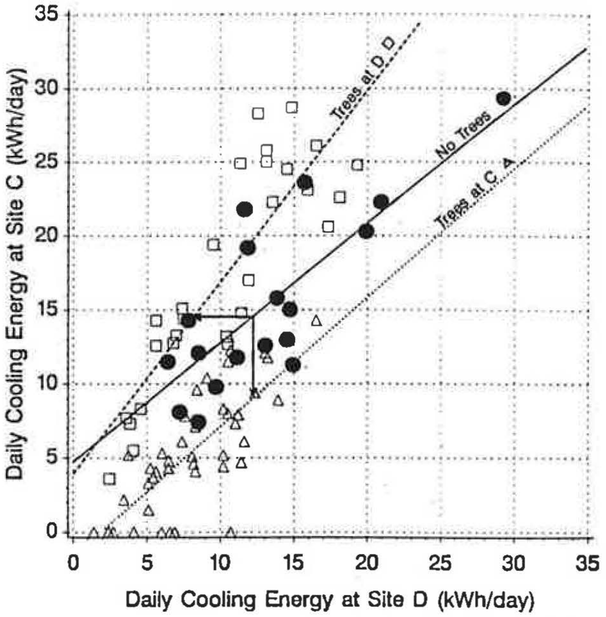

Fig. 2. Energy consumption changes due to shading by eight large and eight small trees of two houses in Sacramento, CA. Dots and their solid regression line represent 19 July base case days with no trees. Squares show the next 20 August days with Site D shaded. These data and their dashed regression move left about 35%. Triangles show 39 September and October days with the trees moved to site C. These data move down, again by about 35%. Shading saves 4–5 kWh/day.

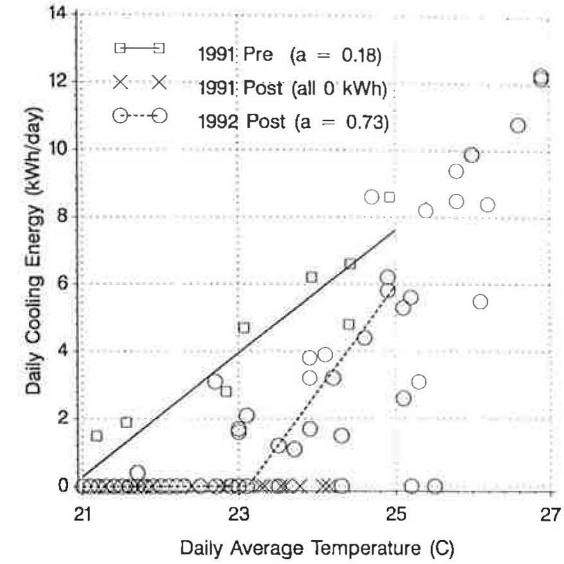

Fig. 3. Daily cooling energy use at a house in Sacramento, CA vs. daily average outdoor temperature. The squares and their solid regression line represent pre-modification conditions, when the roof was dark, with an albedo of 0.18. The Xs represent data collected after the roof albedo was raised to 0.78 with a high-albedo coating. No air-conditioning was used during this period. The circles, many of them at 0.0 kWh/day, represent the post-modification period when the roof was washed and its albedo restored to 0.73. The dotted line represents a regression to the data between 23 and 25 °C. Below this range, no cooling energy is used. Above this range, there are no pre-modification data. Lines indicate savings of 1.5 to 4 kWh/day [5].

At a school site, one of the two school bungalows was used as a control site and remained white roofed and walled all summer. The second building was monitored simultaneously in three different conditions: (1) unpainted metal roof and yellow walls, (2) brown roof and brown walls, and (3) white roof and white walls. Comparing the cooling energy use of the control building with the test bungalow in both conditions (1) and (2) revealed energy savings of 40–50%, and peak power reductions of 0.6 kW, or ~35%.

To estimate the energy savings which would result from a combination of albedo and tree shading modifications, we performed a series of simulations of the energy use of prototypical buildings. We used the DOE-2.1E building energy simulation program and building prototypes developed at the Lawrence Berkeley Laboratory. We simulated the effect of increasing the albedo of the roof and walls of the building in two increments, and increasing the number of shade trees at the site by one, two, four, or eight trees. Fig. 4 shows the percentage of annual base case air-conditioning use required by a residential building prototype under different combinations of albedo and tree shading modifications. This prototype represented common building practices by having R-30 insulation in the roof, R-11 insulation in the external walls, and double-glazed

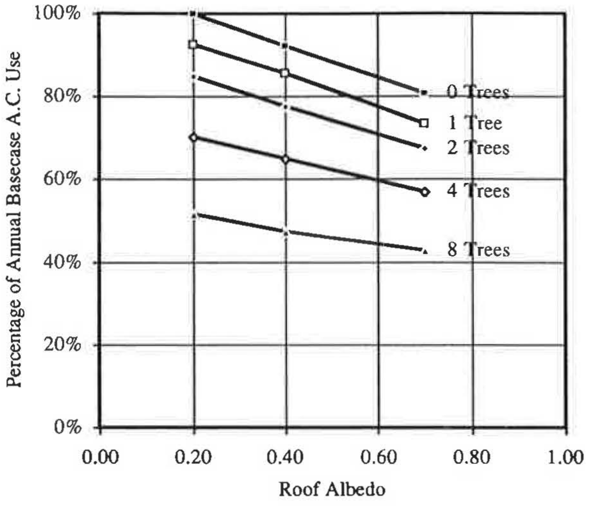

Fig. 4. DOE-2.1E simulation of the percentage of base-case annual air-conditioning energy used by a building prototype in Sacramento, CA for combinations of albedo modification and tree shading. The building prototype describes a new house with an R-30 roof, R-11 walls, double-glazed windows, a vaulted ceiling, and no duct system. Roof and wall albedos were increased from their initial values in two increments. The number of shade trees was increased from zero to eight trees in four increments. Weather data were obtained from the National Climate Data Center for a weather station at Sacramento Executive Airport.

windows. A combination of large albedo increase and extensive tree shading reduces annual air-conditioning use to 43% of base case values. The actual savings may be even higher. Another series of simulations were performed using the building descriptions of the buildings monitored in the experiment. A comparison of the simulation results and measured savings indicated that the building simulations underestimate the energy savings by as much as twofold.

2.2. Direct cooling in Florida

In 1991–1993, Parker et al. [6,7] of the Florida Solar Energy Center (FSEC) measured the impact of reflective roof coatings on air-conditioning energy use in six homes in central Florida. The roof insulations of the six homes, as summarized in Table 1, range from fully insulated (R-25 at site 1) to uninsulated (site 6) [7]. The roof albedos of these houses were raised to 0.61–0.73 from initial values of 0.08–0.31. Cooling-energy savings at the six homes averaged 9.2 kWh/day, or 23% of pre-modification use. The measured air-conditioning energy savings were approximately inversely related to roof insulation — from 11% savings in the R-25 house to 43% savings in the uninsulated house. The reported utility-coincident peak demand reductions between 5 and 6pm are 0.44–0.99 kW, averaging as 0.69 kW or 27% of pre-retrofit peak demand. Fig. 5 shows the roof air space temperature and the air-conditioning energy use before and after the application of reflective coating on the uninsulated house (site 6) on July 31, 1992. This study concluded that reflective coatings are particularly appropriate for existing Florida homes in which the roof structure makes insulation retrofitting difficult.

3. City-scale effects

When a region of dry, low-albedo, unshaded surfaces (i.e. a city) is exposed to sunlight, the surfaces become very hot, and in turn warm the air throughout the region. This climatic effect is quite substantial. Daytime summer urban heat islands with temperatures 2–3 °C higher than surrounding areas are found throughout the US. In Los Angeles, peak temperatures are ~3 °C higher than their 1940 levels, and are increasing faster than 1 °F (0.5 °C) per decade (Fig. 6). These high air temperatures strongly affect the energy use and air quality of a city. Fig. 7 shows the relationship between peak power for Southern California Edison (which supplies three-fourths of the electricity for the Los Angeles Basin), and temperature. For every rise of 1 °C in air temperature above 65 °F (18 °C), peak cooling demand in Los Angeles increases by 3.0%. For Atlanta's Hartfield International Airport, the increase is 6.0% per degree. The summer Los Angeles heat island thus accounts for 1.4 GW (gigawatt) of peak power [3]. Nationally, heat islands raise air-conditioning demand by about 10 GW, costing ratepayers several million dollars per hour, and a billion dollars annually [7].

3.1. Regional cooling by high-albedo surface at White Sands National Monument, New Mexico

To observe the large-scale effect of albedo on air temperature, we have begun to study the climate of White Sands National Monument, New Mexico. The surface of the Monument is composed of white gypsum sand, which has a high albedo (near the middle of the Monument the average albedo is 0.6) and little vegetation cover, since the soil is alkaline. The surrounding desert, at the same altitude of about 4000 ft, it sparsely vegetated with dry, low desert scrub and is characterized by an albedo of 0.26. Hence, the albedo difference between the Monument and the desert is about 0.35, comparable with the conceivable improvement in the albedo of large portions of a city like Los Angeles (but not dense high-rise downtown areas, like parts of Manhattan).

Fig. 8 shows the average difference in average hourly dry-bulb air temperature measurements made at weather stations installed over the light Monument and dark surroundings during August 1992 and June 1993.

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[7] The avoided cost of electricity is discussed in Section 4, just above Eq. (3).

Table 1
Roof characteristics, pre- and post-modification albedos, air-conditioning energy savings, and utility-coincident peak demand reductions for six homes in central Florida. All percentages are of pre-modification conditions [7]

Site	Roof type	Insulation	Albedo		Energy savings (kWh/day)	5–6 PM Load reductions (kW)
			before	after		
1	Asphalt shingles, concrete block	R-25 (ceiling)	0.22	0.73	4.0 (11%)	not measured
2	Gravel roof	R-11 (attic)	0.31	0.62	8.0 (15%)	0.44 (16%)
3	Asphalt shingles and flat gravel	R-11 (attic)	0.21	0.73	10.3 (25%)	0.66 (28%)
4	Tile roof	R-10 (attic)	0.20	0.64	11.6 (20%)	0.99 (23%)
5	Asphalt shingles [a]	~R-3 (ceiling)	0.08	0.61	5.6 (25%)	0.50 (30%)
6	Tar paper, flat roof	none	0.20	0.73	15.4 (43%)	0.86 (38%)
Average			0.20	0.68	9.2 (23%)	0.69 (27%)

[a] Only site without attic duct system.

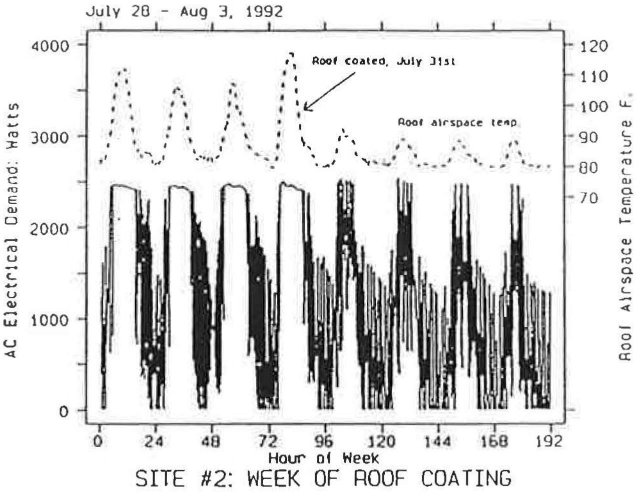

Fig. 5. Roof air space temperature and 15 min air-conditioning consumption of a test house with R-11 roof insulation in Florida between July 28 and Aug. 3, 1992. The roof was treated with a reflective roof coating on July 31st. Both roof temperatures and cooling energy consumption were substantially reduced. Air conditioning electricity use was decreased by 43% over periods with similar weather conditions [6].

In the morning hours, the air over the Monument is 3 °C cooler than the air over the dark surface. The air remains cooler throughout the daytime hours, although later in the day the amount of cooling is reduced because of increased upwelling.

3.2. Meteorological modeling of albedo modification in Los Angeles

To simulate the results of changing the albedo of an urban area, we used the Colorado State University Mesoscale Model (CSUMM) [8], modified to study the impacts of proposed surface changes in the Los Angeles Basin [10]. A rectangular region extending 325 km east–west and 200 km north–south was divided into 2600 surface grid cells, each 5 km by 5 km. A land-use database was used to characterize the surface of each cell.

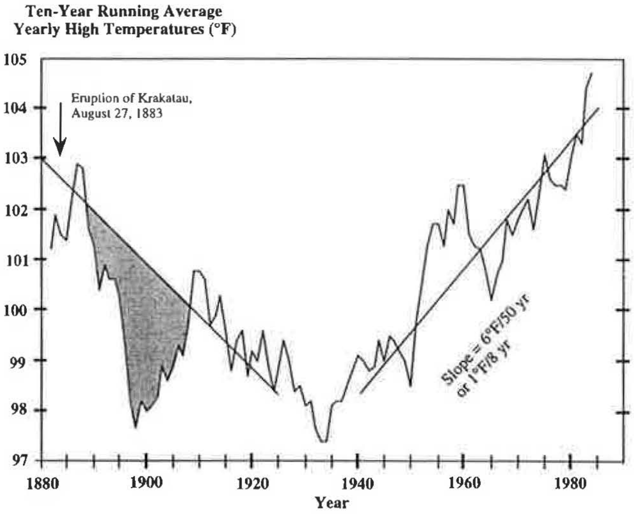

Fig. 6. Ten-year running average high temperatures in downtown Los Angeles, CA (1882–1984). With increasing irrigation and orchards, Los Angeles cooled 2 °C/year until the 1930s. Then, as asphalt replaced trees, Los Angeles warmed 3 °C (6 °F). The pronounced temperature depression in the late 1880s–90s is due to the eruption of the Krakatau volcano.

We identified 394 grid cells (about 10 000 km^2), in which over 20% of the land is covered by artificial surfaces, as 'developed areas' suitable for modification, shown in Fig. 9(a). An albedo modification was carried out on the urban surfaces in each cell as described in Table 2. This modification raised the average albedo of the developed areas by 0.13, from 0.13 to 0.26.

Fig. 9(b) shows the temperature changes resulting from the albedo modification with respect to the base case simulations for 9am. As shown in Fig. 9(c) for noon, the largest cooling, around 2 °C, occurs over

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[8] The CSUMM is a hydrostatic, incompressible, primitive-equation mesoscale meteorological model designed for simulation of airflows generated by differential surface heating and terrain irregularities. This model was originally developed by Pielke at Colorado State University. Over the past two decades, the CSUMM has been validated and applied in numerous situations. For a detailed description of the model, see Refs. [8] and [9].

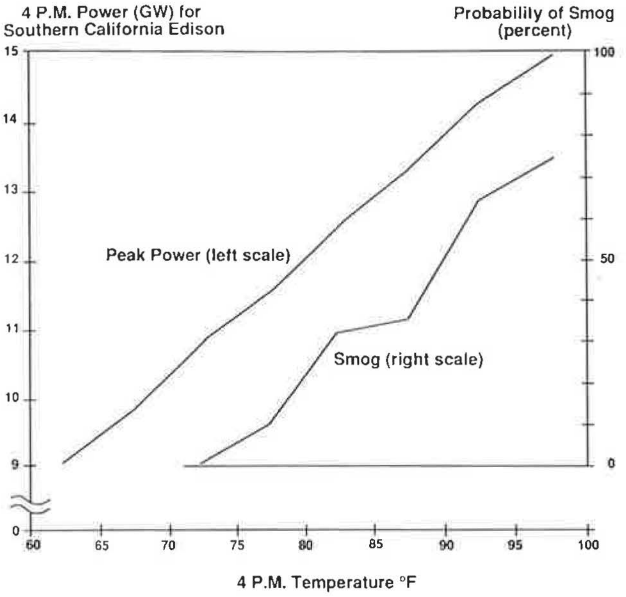

Fig. 7. Ozone levels and peak power for Southern California Edison vs. temperature in Los Angeles, CA. Peak power use rises by 3% for every 1 °C rise in temperature. Probability of smog increases by 6% for every 1 °C rise in temperature above 72 °F (22 °C) [3].

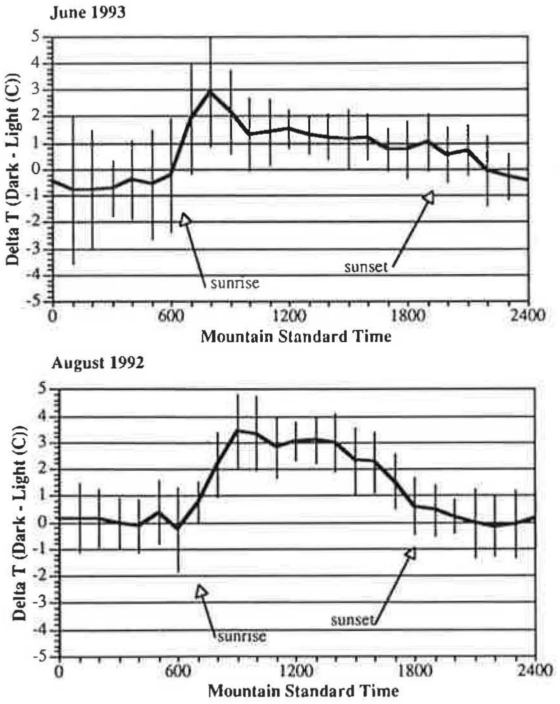

Fig. 8. Difference between dry-bulb air temperatures measured at weather stations installed over light and dark areas of White Sands National Monument averaged by hour for both June 1993 and August 1992. Vertical lines represent one standard deviation from the mean. Includes only non-rainy days. Temperature difference achieves a maximum of ~3 °C in the morning hours. Later in the day, the temperature difference drops as vertical upwelling increases.

downtown Los Angeles (an area with air-conditioning use). The peak impact occurs in the early afternoon. Fig. 9(d) illustrates that this potential cooling exceeds 3 °C at 3pm. We have conducted similar simulations under various initial conditions, all of which indicate peak summertime temperature reductions between 2 and 4 °C. According to Fig. 7, a cooling of this magnitude would reduce peak power consumption in Los Angeles by 0.6 to 1.2 GW (worth between $100 000/h and $200 000/h, based on a cost of 16.5 ¢/kWh derived in Section 4).

The albedo increase of 0.13 which we considered in the simulations does not imply a glaringly white city. This increase can be accomplished by brightening sloped roofs, which are visible to passers-by, to the brightness of light beige; brightening flat roofs, typically those of apartment and commercial, to bright white; and raising the albedo of asphalt roads to that of weathered concrete (Table 2). If whiter cities become popular, as they are traditionally in tropical regions and, recently, in Arizona, we could raise the average albedo by as much as 0.3. The average surface temperature resulting from this increase in albedo is 60 °C (140 °F). Such a city would be even cooler than the city described by our simulations.

Urban air temperatures can also be reduced substantially through a combination of albedo modification and tree planting. Although trees are dark, they cool the surrounding air by two processes. First, they help cool their surroundings by shading even darker surfaces. Second, the evapotranspiration of trees, drawing groundwater to the plant surface where the water evaporates, reduces sensible heating of the hot surrounding air and creates a cool 'oasis'. This regional oasis effect is evident in the weather records of cities built in arid environments. For example, in Los Angeles, the maximum air temperatures decreased during its early development, as dry arid regions were replaced with irrigated orchards and farmland (see Fig. 6). We believe that the cooling resulting from a combined albedo/tree program could mitigate or perhaps reverse the summertime heat island effect.

The results of the CSUMM model suggest the following relationship for the depression of summer peak temperature by increasing the albedo of a city:

$$\frac{\Delta T}{\Delta a} = \frac{(-3 \pm 1)\ ^\circ\mathrm{C}}{0.16} = -19 \pm 6\ (^\circ\mathrm{C})\ \text{[Los Angeses, model, max. } \Delta T\text{]} \quad (1)$$

where ΔT is the change in air temperature and Δa is the change in albedo. The measured temperature depression at White Sands yields a much smaller ratio:

$$\frac{\Delta T}{\Delta a} = \frac{(-2 \pm 1)\ ^\circ\mathrm{C}}{0.35} = -6 \pm 3\ (^\circ\mathrm{C})\ \text{[White Sands, measured, av. } \Delta T\text{]} \quad (2)$$

The difference between the simulation and measured results highlights the fact that the difference in climate

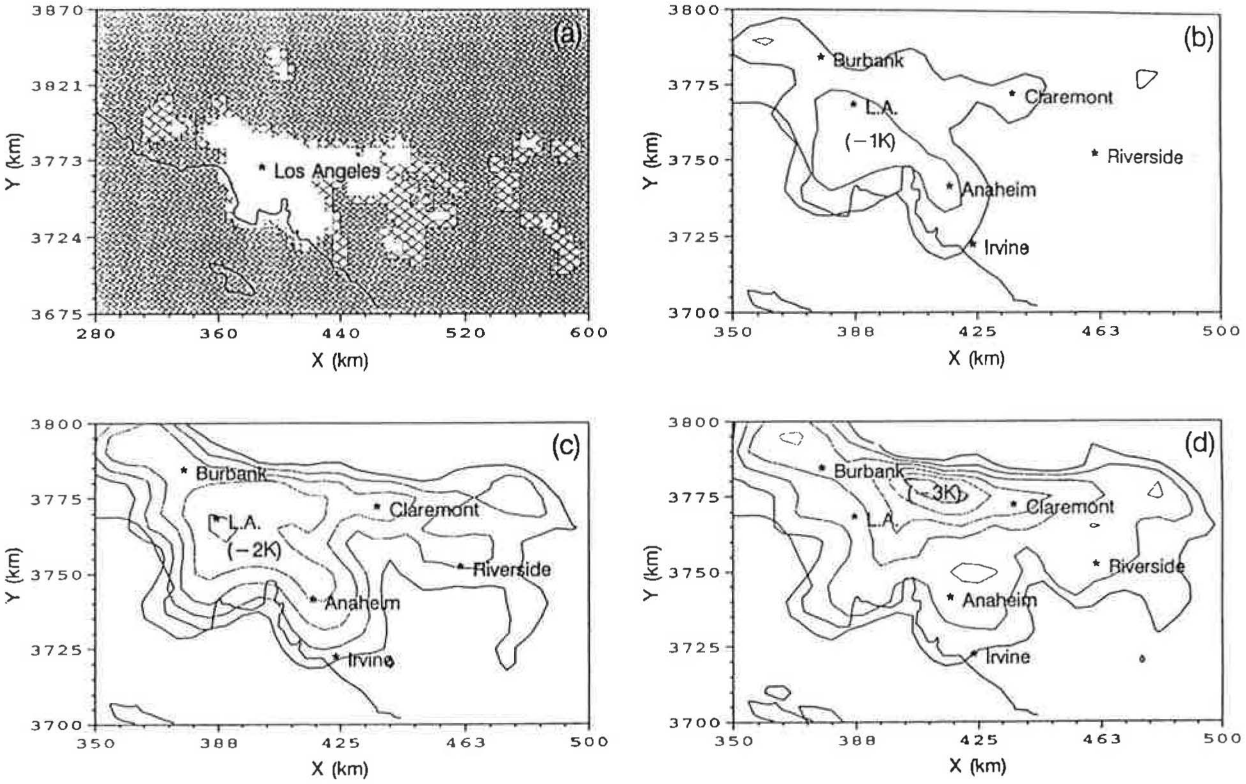

Fig. 9. Albedo modification results. (a) Regions within the modeling domain which have been identified for simulated albedo augmentation. Gray is unmodified, hashed is a modification of less than 0.10, and white is a modification in excess of 0.10. The maximum increase in albedo within each cell is 0.30. However, the average albedo increase over the 400 or so modified cells is 0.13. (b) The temperature difference between high-albedo case and base case simulation at 9 a.m. (c) Same as (b) except at noon. (d) Same as (b) except at 3 p.m. Contour increment in (b)–(d) is 0.5 °C.

Table 2
Albedo modifications for sloped roofs, flat roofs, and roads assumed in meteorological modeling of albedo modification in the Los Angeles Basin. Albedo of urban surfaces rises from 0.30 to 0.50. Average albedo change of developed cells is 0.13 [11]

Surface type	Fraction of land cover	Albedo		
		Before	After	Change
Sloped roofs	0.15	0.25	0.6 (light beige)	0.35
Flat roofs	0.15	0.25	0.75 (white)	0.5
Roads	0.30	0.15 (asphalt)	0.4 (concrete)	0.25

between the city and its surroundings results not only from the change in albedo, but from other differences in the surface characteristics. In addition to being dark, urban surfaces are also very rough (rectangular buildings, trees, and urban canyons), relatively impermeable to water, and sparsely vegetated. The urban surface also has a high heat storage capacity, and urban canyons reduce the ability of the surface to dissipate this stored heat (all of these characteristics are represented in the CSUMM model). Thus the measured results from White Sands cannot be extrapolated directly to urban areas.

To measure the actual climate effects of urban albedo modification and tree planting, we are seeking innovative developers to build half of their subdivisions conventionally, and half with shade trees and cool roofs and roads. We would then monitor these developments to observe the variation in air temperature and savings in air conditioning resulting from neighborhood-scale modifications [9].

3.3. Effect of heat islands on air quality

Heat islands have several effects on urban air quality. The power needed to compensate for heat islands requires significant additional generating capacity, which contributes to urban air pollution [10]. Further, elevated temperatures associated with heat islands accelerate the formation of smog. Fig. 7 shows that the probability of smog increases by 6% per °C in maximum daily

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[9] Danny Parker of FSEC informs us that this is being done in Homestead, FL, where homes destroyed by Hurricane Andrew in 1992 are being rebuilt with shade trees and cool roofs and roads by Habitat for Humanity. FSEC will compare the energy use of ten light-roofed homes to ten otherwise identical homes over the next 2–3 years.

[10] In the Los Angeles Basin, for example, most base load power is generated outside the Basin and does not contribute to urban air pollution. However, most peak power is generated within the Basin by inefficient gas-powered turbines.

temperature, above a threshold of 22 °C (72 °F). However, the urban heat island also raises the mixing height under which air is constantly mixed due to free convection and turbulence off the city surface. This increase in mixing height reduces smog by dispersing air pollutants in a larger volume of air.

We are actively studying the effect of heat island mitigation on urban air pollution. We insert the CSUMM results (such as those discussed above) into the Urban Airshed model to simulate the production of smog in the Los Angeles Basin. Preliminary results for a moderate change in albedo (half of that described in Table 2) indicate 20% reductions in peak smog in some parts of the city, but 10% increases in other [11]. The population-weighted reduction should be about 10%. This is equivalent to removing 10 million cars from Los Angeles roads (see Note Improve on p. 265).

4. Costs and potential savings

The costs of increasing the albedo and vegetation cover of a city are quite low. Albedo modifications may be very inexpensive if performed during routine maintenance. Roofs are typically refinished every 10–20 years, and cooler roofing material is either available or can be developed with little increase in cost. Cool pavement could be installed at the time of resurfacing. 'White topping' (resurfacing an asphalt pavement with concrete) produces a light-colored pavement with low maintenance costs and a long service life. Another light-colored pavement, popular in the UK is produced by rolling white chippings into the top surface of the pavement. Such light-colored surfaces show less damage caused by daily thermal expansion and contraction than dark ones and thus have longer service lives. UV damage to roofs and roads is also reduced, because this damage is caused by free radicals which interact more strongly the warmer the material. We are currently working with industry and other researchers to further develop durable high-albedo materials.

The potential reductions in energy consumption and costs, and carbon emissions are quite high. The national air-conditioning energy use in 1990 was around 420 BkWh [12]. We computed the projected national air-conditioning energy use for 1995–2015, assuming an annual rate of increase of 1% [13]. As shown in line 1(a) of Table 3, consumption rises to 540 BkWh by 2015.

Next we calculate the cost of a kWh of air-conditioning. According to the 1995 General Rate Case submitted by the Southern California Edison Company, marginal energy values are approximately 4 ¢/kWh for on-peak production (around 600 h per summer), and 3 ¢/kWh for mid-peak production. To this we add the marginal capacity values of 10 ¢/kWh for on-peak generation (i.e. capital costs of new equipment), and 1 ¢/kWh for mid-peak production. Thus, the total cost of peak power comes to 14 ¢/kWh, and that of non-peak power comes to 4 ¢/kWh. Assuming that a typical HVAC unit operates for 600 h during peak hours and for 1400 h during off-peak hours yearly, we find the average cost of air-conditioning electricity is

$$\text{Utility cost} = \frac{600\text{ peak hours} \times \dfrac{14¢}{\text{kWh}} + 1400\text{ off-peak hours} \times \dfrac{4¢}{\text{kWh}}}{2000\text{ total hours}}$$

$$= \frac{7¢}{\text{kWh}} \qquad (3)$$

To this utility cost, we add the HVAC equipment costs. We use the data of the PG&E ACT^2 Project, which finds that the marginal cost of one ton of HVAC equipment (including air handling and distribution systems) drawing 1 kW is \$800. Assuming a 10% capital recovery rate (CRR) for a 30-year service life, the annual cost of this equipment is ~\$50. Averaging the typical year operation time of residential HVAC units (1300 h) and commercial ones (2500 h), we estimate that the average HVAC unit operates for 2000 h yearly. Thus, we calculate the HVAC equipment cost of air-conditioning as

$$\text{HVAC unit cost} = \frac{(\text{cost of HVAC unit}) \times \text{CRR}}{(\text{hours of operation}) \times (\text{power of unit})}$$

$$= \frac{\$800 \times 10\%}{2000\text{ kWh}} = \frac{4¢}{\text{kWh}} \qquad (4)$$

Combining the utility costs in Eq. (3) and the equipment costs in Eq. (4), the total cost of air-conditioning is more than 10 ¢/kWh. Using 10 ¢/kWh, we calculated the costs (line 1(b)) of the annual US air-conditioning energy use (line 1(a)), shown in Table 3.

Finally, to compute line 1(c), the base case production of CO_2 due to air-conditioning use, we estimate that 250 g of carbon are associated with the marginal value of 1 kWh. Thus, the projected carbon emission from air-conditioning energy use rises from 110 MtC (million metric tons of carbon) in 1995 to 135 MtC in 2015.

Next, calculating the savings (lines 2(a)-(d)), we estimate that the widespread use of cool surfaces and vegetation in cities should be able to save 20% of cooling energy. Such savings would be achieved gradually, perhaps in a span of 20 years, as urban shade trees grow to maturity, and hot roofs and roads reach their scheduled maintenance. Thus, a nationwide heat island mitigation program begun in 1995 may achieve 5% of base case savings by 2000, 10% by 2005, 15%

Table 3
Base case US air-conditioning use and savings potential of cool surfaces and shade tree program assuming 20% of air conditioning is avoided by 2015 (some figures are rounded)

		1995	2000	2005	2010	2015
1	Base Case US a.c. use					
(a)	Electricity (BkWh)	441	464	488	512	539
(b)	\$ (utility + customer) cost [b]	\$44 B	\$46 B	\$49 B	\$51 B	\$54 B
(c)	CO_2 (MtC) [a]	110	116	122	128	135
2	Annual savings					
(a)	Fraction of base case (%)	0	5	10	15	20 [c]
(b)	Electricity (BkWh)	0	23	49	77	108
(c)	\$ (utility + customer) cost [b]	0	\$2.3 B	\$4.9 B	\$7.7 B	\$11 B
(d)	CO_2(MtC)	0	6	12	19	27

[a] MtC = million metric tons of carbon.
[b] Assuming 1 kWh costs 10 cents in 1994 dollars.
[c] Potential savings in 20 years when re-roofing is completed and trees have matured.

by 2010, and the saturation value of 20% by 2015. At this maximum value, we estimate annual savings of 108 BkWh, worth \$10 billion (in 1990 dollars), and preventing the emission of 27 Mt of carbon. For comparison, the recent Climate Change Action Plan released by the Clinton Administration calls for a 108 MtC reduction by the year 2000. A program of cool surfaces and shade trees can achieve 5% of this reduction in the year 2000, and 25% in 2015.

5. Policy steps to implement cool surfaces and shade trees program

Table 3 describes the potential savings. However, achieving this potential is conditional on the necessary Federal support. Programs for planting shade trees already exist, but to start an effective and comprehensive program requires the following seven outreach steps.

(1) Create test procedures, *ratings*, and labels for cool materials.

(2) Assemble a cool materials *database* made widely available to industry, utilities, contractors, architects, roofers, state and local procurement officers, consumers and communities.

(3) Incorporate cool roofs and shade trees into the *Building Energy Performance Standards* of ASHRAE, CABO, California Title 24, and Air Quality Management Districts. Standards can be relatively mild if accompanied by step (4).

(4) Offer *utility rebates* or other incentives to beat the standards. This will require support by the state public utility commissions.

(5) Begin *information programs* for all the groups mentioned in step (2), and distribute information by grassroots support networks to building owners and local governments.

(6) Demonstrate savings in selected '*Cool Communities*', including Federal facilities, particularly military bases. This will require support by the local utility.

(7) Establish aggressive policies for the *procurement of cool roofing materials* by Federal, state and local governments. Create 'purchasing co-ops' in the Cool Communities.

Let us expand on a few of these steps.

5.1. Ratings and labels

An effective heat island mitigation program requires a method of rating different paints and surfacing materials according to their summer mid-day surface temperature. This information must be readily available, since the albedo of a surface depends not only on its visible reflectivity (i.e. its intuitive visible brightness), but also on its reflection of IR light, which comprises about half of incident solar energy. Thus, a light-colored surface is not necessarily cool, and vice versa. For example, commonly used light-colored roofing materials such as 'white' asphalt shingles and galvanized steel run 63 °F (35 °C) and 78 °F (43 °C) hotter, respectively, than air temperature on a sunny day [11]. On the other hand, surfaces painted with red or green acrylic paint run only ~40 °F (22 °C) hotter, even though they are not visibly bright. Research is underway at LBL to create new cool surface materials, with a choice of colors, which would be highly reflective in the IR.

The rating of materials would avert the mistaken promotion of hot light-colored materials, and create a market for innovative cool surface materials. We are consulting with the paint/pigment, roofing, and pavement industries to create an accurate and simple test

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[11] White asphalt shingles are made quite dark so as not to show dirt and mildew. Unpainted galvanized steel gets hot because metals have low emissivities, which mean that they cannot cool by radiation.

procedure for heat island mitigation surfaces. Ratings would probably include the following information.

(1) An indicator of surface temperature at noon on a clear day under the midsummer sun, for example at the latitude of Los Angeles and Atlanta. Discussions with industry are focusing on the scale in Fig. 1. Thus, black acrylic paint is 0%, white paint 100%, and white cementitious coating about 70%.

(2) A second indicator of longevity of the high albedo, i.e. how well does a roof shed dirt, resist mold build-up, etc.? This would also use the scale in Fig. 1, measured after three years.

(3) Surface temperature under standard fire conditions (reflective materials offer better protection of roofs and walls from external fires).

(4) Service life (to credit the potentially longer lives of cool roofs and roads compared to surfaces exposed to diurnal thermal shock and ultraviolet radiation, and to identify low quality products).

Two workshops to further develop materials testing, ratings, labels, and a product database were held by LBL and the National Institute of Standards and Technology (NIST) in February and July 1994.

5.2. Standards for energy efficiency and air quality

As we have mentioned above, we recommend relatively mild standards which can be met without any significant change in the appearance of the buildings and pavements. Thus the California South Coast Air Quality Management District is circulating a draft plan proposing that new roofs (or re-roofs) must run cooler than some guideline, roughly halfway between white paint and black asphalt, and new roadways run as cool as weathered concrete. Another strategy is to encourage the conversion of low-use parking lots from hot asphalt to cool grass pavements [14]. As with ratings, national or international standards for improved energy efficiency and air quality would encourage the development and sale of new surface materials.

5.3. Utility incentives to beat the standards

Given the large savings potential of a cool surfaces and shade trees program, there is a large incentive for utilities to sponsor demand-side management (DSM) programs that promote the lightening and greening of cities. If, for example, utility DSM programs are credited with 50% of the savings achieved, and that public utility commissions permit utility stockholders to retain 10% of program savings, then Table 3 shows that in 2015 utility stockholders could earn $500 million/year. Further, if reductions in CO_2 are given a cash value (e.g. through avoided taxation), stockholder earnings could be even higher.

Implementation programs for white surfaces should be designed to emphasize roof types that cover the largest area in a city. Modified bitumen, asphalt shingles, and built-up roofing account for 44% of the residential roofing area in California, and 37% of the commercial area [15]. Built-up roofing and other materials can be installed with a white reflective coating for no additional cost, while adding a coating to modified bitumen may include a small incremental cost. Since the coating of asphalt shingles is an additional expense not included in installation, and voids the warranty on the shingles, it is necessary to induce shingle manufacturers to sell high-albedo shingles which shed dirt.

As an example, suppose a residential utility rebate program concentrates on large, poorly insulated, poorly shaded, dark-roofed buildings in hot climates. The annual air-conditioning bill for such a building may be $500. Replacing the dark roof with a cool one and planting shade trees around the building could perhaps save $200/year, half of which could be credited to standards. Thus a utility DMS program could save $100/year, with a discounted value of ~$1000. Thus, an appropriate utility rebate program might offer $500, approximately 10% of the cost of a new roof.

6. Conclusions

Raising the albedo of urban surfaces and increasing urban vegetation are easy ways to conserve energy, save money and probably to reduce air pollution. Experiments have shown 20–40% direct energy savings by increasing the albedo of a single building, and computer simulation indicates that the indirect effects of wide-scale albedo changes will nearly double the direct savings.

At its maximum potential, a vigorous cool surfaces and shade trees program could save annually $10 billion in energy and equipment costs, and eliminate 27 million metric tons of CO_2 emissions. To achieve this potential, several policy steps should be taken promptly. A simple ratings scheme and accurate test procedures should be established (recent workshops with the paint/pigment, roofing, and roadway materials industries have begun this task). Standards for new construction of buildings and roadways, and utility-sponsored incentive programs would promote the use of cool surfaces and shade trees and create new markets for their development and sale. Incentive programs should target asphalt shingle, modified bitumen, and built-up roofing. The albedo of these roofs may be changed at little or no additional cost at the time of routine maintenance. Such programs may generate earnings of $500 million/year for utility stockholders.

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Note added in proof

Since this paper was accepted, we have extended the modeling to include three shade trees per eligible house for a complete 'Cool Communities' strategies. The combined effect reduces the population-averaged smog by 20%. We have also compared these Cool Communities strategies for a smog episode modeled in Fig. 9 with the smog from all motor vehicles in the Basin; Cool Communities off-sets 50–90% of all these vehicules.