Global Cooling: Increasing World-wide Urban Albedos to Offset CO_2

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ABSTRACT

Modification of urban albedos reduces summertime urban temperatures, resulting in a better urban air quality and building air-conditioning savings. Furthermore, increasing urban albedos has the added benefit of reflecting some of the incoming global solar radiation and countering to some extent the effects of global warming. In many urban areas, pavements and roofs constitute over 60% of urban surfaces (roof 20-25%, pavements about 40%). Using reflective materials, both roof and the pavement albedos 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% (a U.S. potential savings in excess of $1 billion (B) per year in net annual energy bills).

On a global basis, our preliminary estimate is that increasing the world-wide albedos of urban roofs and paved surfaces will induce a negative radiative forcing on the earth equivalent to removing ~22 - 40 Gt of CO_2 from the atmosphere. Since, 55% of the emitted CO_2 remains in the atmosphere, removal of 22 - 40 Gt of CO_2 from the atmosphere is equivalent to reducing global CO_2 emissions by 40 - 73 Gt. At ~$25/tonne of CO_2, a 40 - 73 Gt CO_2 emission reduction from changing the albedo of roofs and paved surfaces is worth about $1,000B to 1800B. These estimated savings are dependent on assumptions used in this study, but nevertheless demonstrate considerable benefits that may be obtained from cooler roofs and pavements.

1 INTRODUCTION

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). 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 a 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 the 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 abedos in the U.S. alone can exceed $2B per year.

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

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 m^2 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, the total urban area of the globe is estimated at about 1.2% of the land area.

As an independent verification for the estimate of urban areas, we used the data from Global Rural-Urban Mapping Project (GRUMP) Urban Extent Mask (CIESIN 2007). The Urban Extent Mask combines National Oceanic and Atmospheric Administration measurements of nighttime lights with the US Defense Mapping Agency Digital Chart of the World's Populated Places to assess the geographic extents of rural and urban areas (Balk et al. 2004). Equal-area sinusoidal projection of the 30-arc-second urban extent mask indicates that of the Earth's 149 million km^2 of land area, 128 million km^2 is rural and 3.5 million km^2 is urban. The 3.5 million km^2 of urban land represents 2.4% of global land area and 0.7% of global surface area. Most of the 17.5 million km^2 of unclassified land lies in Antarctica (14 million km^2) or Greenland (2.2 million km^2). The GRUMP estimate of 2.4% is twice the estimate of 1.2%. [1] Furthermore, the analysis from McGranahan et al., (2005) shows that the urban areas account for 2.8% of the land area. We expect that the GRUMP estimate is closer to reality, since the population densities in the world's 100 largest cities are probably higher than in other urban areas. In our calculations, we conservatively assume that urban areas are 1% of the land area.

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 35% 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 cementatious 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 as well as the solar reflectance of other paving materials such as chip seal, slurry coating, light-color coating. 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

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[1] We note that a USGS analysis of 1992 data shows a value of 0.17% for the fraction of the urban areas to the total land surface area (USGS 1999). This number is 7 to 16 times smaller than the other three estimates shown above.

initial solar reflectance of 0.35-0.40 that will age to about 0.25-0.30.

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 0.15 for a net change of 0.35x0.15=0.04. Hence, the net potential change in albedo for urban areas is estimated at 0.10. Increasing the albedo of urban areas by 0.1 results in an increase of $3\text{x}10^{-4}$ in the Earth's albedo.

4 THE EFFECT OF CHANGING URBAN ALBEDOS ON GLOBAL RADIATIVE FORCING

We estimate the CO_2 equivalency of cool urban surfaces using data from prior studies as indicated in Table 3. Hansen et al. (1997a) estimate a $2\text{x}CO_2$ adjusted top-of-atmosphere (TOA) radiative forcing (RF) of 4.19 W/m^2. This agrees with the results from Myhre (1998), where RF $[W/m^2] = 5.35\ ln(1+ \Delta C/C) = 5.35 * ln2 = 3.71\ W/m^2$. Using the Hansen et al. (1997a) estimate of radiative forcing, the total global radiative forcing is $2.13\text{x}10^{15}$ W. Doubling of CO_2 relative to the pre-industrial era increases the atmospheric CO_2 by 275 ppm. It is estimated that 1 Gt of CO_2 increases the atmospheric CO_2 concentration by 0.128 ppm (Broecker 2007). Hence, doubling the atmospheric CO_2 concentration to 550 ppm is equal to increasing the atmospheric CO_2 by 2010 Gt of CO_2. The radiation change per tonne of CO_2 is then estimated as [$2.1 \text{ x } 10^{15}$ W] / [2010 Gt CO2] = 1 kW/ tonne CO_2 (airborne**)**.

Hansen et al. (1997a) also estimate an adjusted RF for changing the albedo of 'Tropicana' by 0.2 as -3.70 W/m^2. In our analysis, we estimate that Tropicana is 22% of the land area (a major portion of land area between 22°S to 30°N and 20°-50°E indicated in Fig. 1 of Hansen et al. (1997b)); or about 1/16th of the global surface. For the reflected surfaces, the radiative forcing per 0.01 unit change in albedo as estimated by Hansen et al. (1997a) is -2.92 W per m^2 of Tropicana land. We note that the RF for albedo change is a strong function of the cloud cover. The higher the cloud cover, the lower the RF resulting from changes in surface albedo. Assuming that of the radiation incident on clouds 50% is absorbed and 50% is reflected, we can use a simple multiple reflection and absorption model to estimate the effect of cloud cover on RF given as

$$dRF / d\rho = I(1-c)^2 / (1-\rho c/2)^2$$

where I is the average annual solar radiation at TOA, ρ is the albedo of the surface (assumed 0.4 for Tropicana and 0.2 for urban areas) and c is the cloud cover. Using this equation and the RF of -2.92 W/m2 for Tropicana, we calculate a cloud cover of 9% for Tropicana. This 9% cloud cover is consistent with satellite (International Satellite Cloud Climatology Project (ISSCP)) estimates of annual mean cloud cover (Rossow and Schiffer, 1991). For the urban areas, assuming an albedo of 0.2 and an annual mean cloud cover range of 0.2 to 0.4, we estimate a RF of -1.22 to -2.25 per 0.01 change in albedo. Using 1 kW per tonne of CO_2, we estimate a CO_2 equivalent of -1.2 to -2.3 kg of CO_2 per m^2 of urban areas for a 0.01 change in albedo (see Table 4). For cool roofs with a proposed albedo change of 0.25, the CO_2 equivalent is then estimated at -31 to -57 kg CO_2 per m^2 of roof area. For cool pavements with a proposed albedo change of 0.15, the CO_2 equivalent is equal to -18 to -34 kg CO_2 per m^2 of pavement area.

5. GLOBAL COOLING: CO_2 EQUIVALENCE

In our calculations, we estimate that urban areas are at least 1% of the Earth's land area of about $1.5\text{x}10^{12}$ m^2 (see Table 5). The roof area is $3.8\text{x}10^{11}$ m^2. The paved surface area is $5.3\text{x}10^{11}$ m^2. Hence, the global atmospheric CO_2 equivalent potentials for cool roofs and cool pavements are in the range of 12-22 Gt of CO_2 and 10-18 Gt of CO_2, respectively, giving a total global atmospheric CO_2 equivalent potential range of 22-40 Gt of CO_2. IPCC (2007) estimates that only 55% of the emitted CO_2 stays in the atmosphere. Hence, the total global emitted CO_2 equivalent potential for cool roofs and cool pavements is 40-73 Gt of CO_2. This

40-73 Gt CO_2 is about one to two years of the 2025 projected world-wide emission of 37 Gt of CO_2 per year (EIA 2003).

Currently, in Europe CO_2 is traded at ~$25/tonne. A 40-73 Gt CO_2 emission reduction from changing the albedo of roofs and paved surfaces is worth about $1000-1800 B. The contribution of cooler roofs to this CO_2 savings is thus worth $1300??B.

6 DISCUSSION

Although our study indicates considerable benefits in offsetting CO_2 from changing urban albedos, we note that there are several underlying assumptions/approximations made in this study that may affect the projections of CO_2 savings and benefits from increasing urban albedos listed as follows:

~~1)~~ Our calculations for radiative forcing changes do not account for the effect of multiple scattering or absorption of radiation within the atmosphere due to the increased reflectance from urban surfaces. This may then result in increased absorption of radiation by some species such as black carbon that may increase the heating within the atmospheric layer, especially in areas where black carbon concentrations are relatively high. However, the relative effects of these changes are hard to estimate without using a detailed radiative transfer model coupled to a chemical transport model (outside the scope of this work), and may to some extent be offset by the additional benefits of reduced smog formation. For example it has been shown that reflective surfaces in general result in cooler urban temperatures, in turn slowing the formation of smog and decreasing the urban boundary layer thickness. Observations and simulations of smog concentration versus ambient temperature have also shown that on the net cool urban surfaces have a dramatic effect in reducing urban smog (Taha 2005, 2008a&b). Also, most non-metallic surfaces (independent of their solar reflectance) absorb over 90% of the incoming UV light (Levinson et al. 2005a&b) and thus, we do not expect any UV-related effect on photochemical urban smog because of reflective urban surfaces.

2) For locations of urban areas outside tropical regions, such as 'Northland" (areas located at < 55°N) in Hansen et al. (1997b), the value for RF of -2.15 W/m^2 is lower than that obtained for 'Tropicana'. Thus, depending on the location of all urban areas considered, the RF values would have to be scaled accordingly.

3) In most urban areas, residential and suburban areas constitute the majority of the surface areas (the fraction of areas with tall buildings are fairly small). A limited analysis for the effect of shading of roofs by trees and adjacent buildings shows that shadows from all sources reduce the annual incidence of sunlight on residential roofs by about 10 - 25%, depending on tree cover. (Reference: Levinson and Akbari: Tree Shade paper under preparation). This tends to reduce the equivalent potential of cool surfaces by a similar 10-25%.

We note that converting to cool urban surfaces does not address the underlying problem of global warming, that is the emissions of greenhouse gases and absorbing particles. Here we note that the cool urban surfaces, particularly cool roofs, yield significant energy savings and hence reduction in GHG emissions. The global cooling effect of increasing urban solar reflectance is an added benefit that is quantified here.

7 CONCLUSIONS

Using cool roofs and cool pavements in urban areas, on an average, can increase the albedo of urban areas by 0.1. We estimate that increasing the albedo of urban roofs and paved surfaces will induce a negative radiative forcing equivalent to removing 22 - 40 Gt of CO_2 from atmosphere. Removal of 22 - 40 Gt of CO_2 from atmosphere is equivalent to reducing global CO_2 emissions by 40 - 73 Gt. A 40 - 73 Gt of CO_2 emission reduction from changing the albedo of roofs and paved surfaces is worth about $1000-1800 B. The contribution of cooler roofs to this CO_2 savings is worth $1300B. We emphasize that these calculations and estimates are preliminary in nature. Our future study will include detailed calculations from climate model simulations.

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Table 1: Urban fabric

Metropolitan Areas	Vegetation	Roofs	Pavements	Other
Salt Lake City	33.3	21.9	36.4	8.5
Sacramento	20.3	19.7	44.5	15.4
Chicago	26.7	24.8	37.1	11.4
Houston	37.1	21.3	29.2	12.4

Source: Rose et al., 2003.

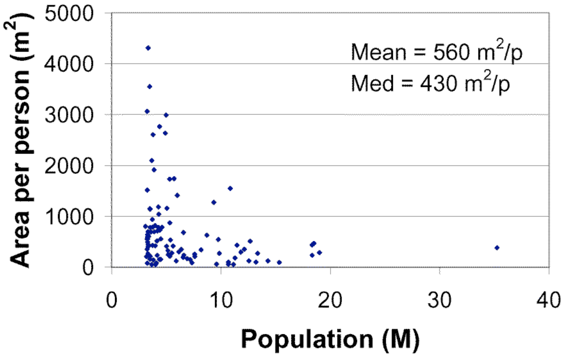

Figure 1: Area density for the 100 largest cities in the world. 670 million people live in these cities.

Table 2: Two albedo modification scenarios

Surface-Type	Albedo Change		
	High	Low	This Study
Residential Roofs	0.3	0.1	0.25
Commercial Roofs	0.4	0.2	0.25
Pavements	0.25	0.15	0.15

Source: Akbari et al., 2003.

Table 3: Radiative forcing and CO_2 equivalence

Row	Item	Value
1.	$2XCO_2$ TOA radiative forcing (RF)[a]	4.19 W/m^2
2.	Increase in atmospheric concentration by doubling CO_2	275 ppm
3.	Increases in atmospheric concentration by adding 1Gt of CO_2[b]	0.128 ppm
4.	Increase in atmospheric $CO_2$by doubling concentration [Row 2/Row 3]	2.15×10^{12} tonne
5.	Surface area of the Earth	5.08×10^{14} m^2
6.	Total radiative forcing on the Earth [Row 1 x Row 5]	2.13×10^{15} W
7.	Earth surface radiation change per tonne of atmospheric CO_2 [Row 6/Row 4]	≈ 1 kW / tonne CO_2

a: Hansen et al., 1997.

b: Broecker (2007) estimates that for each 4 Gt of fossil carbon burned, the atmospheric CO_2 content rises by about 1 ppm. Each tonne of carbon produces 3.67 tonne of CO_2. Also, about 52% of the CO_2 emitted stays in the atmosphere. Hence, we then estimate that each Gt of CO_2 emitted increases the atmospheric CO_2 by 0.128 ppm.

Table 4: Radiative forcing of changing the roofs and pavements and their CO_2 equivalent

Row	**Item**	**Value**
1.	TOA radiative forcing (RF) by changing albedo of 'Tropicana' by 0.20[a]	-3.70 W/m^2
2.	Assumed change in the albedo of 'Tropicana' [a]	0.20
3.	Earth RF for a Δ albedo of 0.01 [0.01xRow 1 / Row 2]	-0.185 W/m^2 of Earth
4.	Fraction of land to Earth surface area	0.29
5.	Tropicana fraction of land area[b]	0.22
6.	Tropicana fraction of Earth surface area [Row 4 x Row 5]	0.063
7.	Tropicana RF for a Δ albedo of 0.01 [Row 3 / Row 5] [c]	-2.92 W/m^2 of Tropicana
8.	Estimated annual cloud cover in most populated areas[d]	20% - 40%
9.	Range of RF for a Δ albedo of 0.01of populated areas	-2.26 to -1.22 W/m^2
10.	Urban areas CO_2 equivalent for a Δ albedo of 0.01 [Row 9 / Row 7 Table 3]	-2.26 to -1.22 kg CO_2/m^2 of urban areas
11.	Proposed change in the solar reflectance of roofs	0.25
12.	CO_2 equivalent of cool roofs [Row 8 x Row 9]	-57 to -31 kg CO_2/m^2 of roof area
13.	Proposed change in the solar reflectance of pavements	0.15
14.	CO_2 equivalent of cool pavements [Row 8 x Row 11]	-34 to -18 kg CO_2/m^2 of paved area

a: Hansen et al., 1997.

b: Estimated by the authors. The 'wonderland' model has 276 cells (12x23) of which 17.5 cells are Tropicana. Hence, the ratio of Tropicana land to the Earth surface is 0.063, or 22% of land surface area.

c: Assuming that of the radiation incident on clouds 50% is absorbed and 50% is we reflected, we can use a simple multiple reflection and absorption model to estimate the cloud cover for the Tropicana to be about 9%. This 9% cloud cover is consistent with ISCCP estimates (Rossow and Schiffer 1991).

d: Source: ISCCP : http://isccp.giss.nasa.gov/products/browsed2.html

Table 5: CO_2 equivalency of increasing the albedo of roofs and pavements in all major hot cities of the world.

Row	Item	Value
1.	Area of the Earth	508×10^{12} m^2
2.	Land Area (29% of Earth area)	147×10^{12} m^2
3.	Dense and developed urban areas (1% of land area)	1.5×10^{12} m^2
4.	Roof area (25% of urban area)	3.8×10^{11} m^2
5.	Paved surface area (35% of urban area)	5.3×10^{11} m^2
6.	Potential atmospheric CO_2 reduction of cool roofs [Row 4 x Row 12 Table 4]	12 - 22 Gt CO_2
7.	Potential atmospheric CO_2 reduction of cool pavements [Row 5 x Row 14 Table 4]	10 - 18 Gt CO_2
8.	Total potential atmospheric CO_2 reduction of cool roofs and cool pavements [Row 6 + Row 7]	22 - 40 Gt CO_2
9.	Fraction of emitted CO_2 that remains in the atmosphere	0.55
10.	Total potential of CO_2 emission reduction for cool roofs and cool pavements [Row 8 / Row 9]	40 -73 Gt CO_2
11.	Projected 2025 world CO_2 emission[a]	37 Gt CO_2

a: EIA. 2003. International Energy Outlook. Energy Information Administration. Washington D.C.