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ScienceDirect

Solar Energy xxx (2014) xxx–xxx

SOLAR ENERGY

www.elsevier.com/locate/solener

Using remote sensing to quantify albedo of roofs in seven California cities, Part 2: Results and application to climate modeling

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Received 17 July 2014; received in revised form 11 October 2014; accepted 16 October 2014

Communicated by: Associate Editor Matheos Santamouris

Abstract

The albedo of a roof determines the fraction of incoming sunlight that is reflected, which affects heat transfer into the building and exchange of energy between the built environment and the atmosphere. While the albedo of individual roofs can be easily measured, roof albedo at the city scale is unknown. In this paper we characterize the albedos of roofs in seven cities in California: Los Angeles, Long Beach, Bakersfield, San Francisco, San Jose, Sacramento, and San Diego. The fraction of urban area covered by roofs ranged by city from 10% to 25%. City-wide average roof albedo ranged from 0.17 ± 0.08 to 0.20 ± 0.11 (mean $\pm$ standard deviation) for five of the cities; values were higher in Sacramento (0.24 ± 0.11) and San Diego (0.29 ± 0.15). Buildings with small roofs were found to constitute a large fraction of city roof area and to have low mean albedos. This suggests that efforts to increase urban albedo through the use of reflective roofs should include small roofs, which are presumably mostly residential. Roof albedos derived for Bakersfield were used in a regional climate model (Weather Research and Forecasting Model) to estimate temperature changes attainable by converting the current stock of roofs to "cool" high albedo roofs. It was found that seasonal mean afternoon (15:00 LST) temperatures could be reduced by up to 0.2 °C during both the summer and winter. Changes in precipitation were not significant at the 95% confidence level.

Keywords: Roof albedo; Solar reflectance; Cool roof; Heat island effect

1. Overview

In a companion paper (Ban-Weiss et al., 2015) we present a new method for deriving the bihemispherical albedo of roofs using aerial imagery. In this paper we apply the method to compute roof albedos in seven California cities: Los Angeles, Long Beach, San Diego, Bakersfield, Sacramento, San Francisco, and San Jose. First we show roof albedos projected onto maps of each city. The mean roof albedo and other statistics for each city are reported and discussed. Next, we estimate the minimum sample size required to characterize the mean albedo of the roofs in a city. This was accomplished using a Monte Carlo technique to randomly sample from the ~1.1 million roof albedos computed for Los Angeles. Next, using a large sample of duplicates we estimate the error (precision) in reported roof albedos for each city. We then examine the prevalence and mean albedos of roofs of different sizes; we also compute the fraction of large roofs that have high albedo. Lastly, roof albedo results for Bakersfield were used as inputs to a regional climate model to estimate changes in summer and wintertime temperature and precipitation that would

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http://dx.doi.org/10.1016/j.solener.2014.10.041
0038-092X/

result from replacing the current stock of roofs with "cool" high albedo roofs.

2. Results

2.1. Roof albedos for Los Angeles, Long Beach, Bakersfield, San Francisco, and San Jose

Maps for each city showing the mean albedo of individual roofs are shown in Panel a of Figs. 1–5. Panels b and c show histograms and cumulative distributions of roof albedos, respectively. In Panel b, N is the total number of roofs, while μ and σ are the city-wide mean and standard deviation of roof albedo weighted by roof surface area; see also Table 1. Note that roof surface area in this paper refers to the footprint area of the building. In Panel c, we show cumulative distributions of roof albedo that are both unweighted and weighted by roof area.

The roof count is lowest for San Francisco ($N = 82{,}941$) and highest for Los Angeles ($N = 1{,}130{,}120$). The area fraction of each city covered by roofs ranges from 10% (Bakersfield) to 25% (San Francisco) (Table 1). The area-weighted mean roof albedo (± standard deviation) for each city ranges from 0.17 ± 0.08 (Los Angeles) to 0.20 ± 0.11 (Bakersfield). In each city nearly all roofs have low albedo in the range of 0.05–0.25 (Panel b, Figs. 1–5). Roofs with albedo greater than 0.4 make up less than 3% of total roofs and 7% of total roof area in each city (Panel c, Figs. 1–5); Bakersfield has the largest area fraction of roofs with albedo greater than 0.4.

Fig. 6 presents a closer look at roof albedos in part of Los Angeles. Some large (presumably non-residential) buildings in this area have high albedo "reflective" roofs with values up to about 0.7. Many of these reflective roofs are likely the result of the Title 24 Building Energy Efficiency Standards (CEC, 2005), which includes a prescription that new or retrofitted low-sloped roofs on non-residential buildings should generally be white. Albedos of reflective roofs vary because of differences in (a) initial albedo of roofs when installed; (b) roof age; and/or (c) the resistance to soiling of a reflective roof, which varies by product (Sleiman et al., 2011).

2.2. Roof albedos in Sacramento and San Diego

2.2.1. Determining the number of roofs to manually trace

We were unable to acquire geographic information system (GIS) building outlines from local governments or commercial vendors for Sacramento and San Diego. We therefore manually traced buildings in ESRI ArcMap using techniques described in Ban-Weiss et al. (2015). The number of buildings needed to properly characterize the mean roof albedo of a city was determined using a statistical investigation of the population of ~1.1 million values computed for Los Angeles. A Monte Carlo technique was used to randomly select buildings in Los Angeles; as more randomly selected buildings were sampled, the variability in the (area-weighted) mean roof albedo decreased (Fig. 7a). The large fluctuation at small sample sizes ($N \leqslant 500$ roofs) occurs because for a small sample, the sample mean roof albedo is very sensitive to the inclusion or absence of large high albedo roofs. (Note that this figure analyzes one of many possible sets of randomly selected roofs; therefore the initial fluctuations would be different for another random set of roofs.) As the number of samples increases, the fluctuations diminish, and an asymptote is approached representing the (area-weighted) mean roof albedo for the city. The mean roof albedo is reached after sampling about 1000 roofs (Fig. 7a). This suggests that the mean roof albedo of Los Angeles can be characterized from the albedos of 1000 randomly sampled buildings. We expect that 1000 roofs overestimates the requirement for characterizing Sacramento and San Diego since these cities have fewer roofs than Los Angeles. This assertion is tested in Section 2.2.3.

We further investigated the effect of building sample size on city-mean roof albedo using a second set of Monte Carlo simulations. Random samples of N roofs were drawn from the total population of ~1.1 million roofs in Los Angeles. The distributions of calculated means for 100,000 such experiments are shown in Fig. 7b for sample sizes $N = 10$, 100, 1000, and 5000. Also shown are the grand means and standard deviations of sample means over the 100,000 simulated samples for each value of N. The main effect of larger sample size (N) is a narrower distribution of sample means with corresponding lower standard deviations. This shows that a randomly sampled collection of roofs is more likely to appropriately characterize the city-mean roof albedo if the sample size is larger. Our chosen sample size of 1000 roofs returns a standard deviation equal to 0.01, which is equivalent to an uncertainty with 90% confidence interval of 0.0005. This error is much smaller than the estimated error (accuracy) of the remotely sensed albedos for each roof, which is discussed in Ban-Weiss et al. (2015). Thus, the limited sample sizes in Sacramento and San Diego (1000 roofs each) are not expected to noticeably affect estimates of their city-wide mean roof albedos.

2.2.2. Roof albedos

The numbers of roofs sampled in Sacramento and San Diego (about 1000 each) are orders of magnitude lower than for the other cities (Table 1). The area-weighted mean roof albedos for Sacramento and San Diego are 0.24 ± 0.11 and 0.29 ± 0.15 (Table 1, Figs. 8 and 9). For the buildings sampled, roofs with albedo greater than 0.4 made up about 8% and 17% of roof area in Sacramento and San Diego; these represent 5% and 2% of roofs sampled.

2.2.3. Testing the sufficiency of 1000 building outlines

Monte Carlo simulations were again performed, this time randomly sampling from the approximately 1000 roof albedos for Sacramento and San Diego. The sample mean roof albedos for Sacramento and San Diego each converge