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Preparatory meteorological modeling and theoretical analysis for a neighborhood-scale cool roof demonstration

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A R T I C L E I N F O

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A B S T R A C T

Replacing dark conventional roofs with more reflective "cool" roofs has been proposed as a method to lower urban air temperatures. Many meteorological studies have simulated potential cool roof air temperature reductions. However, economic and logistical challenges make it difficult to perform the large-scale demonstrations needed to verify these model results. This work assesses whether a neighborhood-scale cool roof demonstration could yield an observable air temperature change. We use both an idealized theoretical framework and a meteorological model to estimate the air temperature reduction that could be induced by increasing roof albedo over ~1 km^2 area of a city. Both the idealized analysis and model indicate that an air temperature reduction could be detected, with the model indicating a reduction of 0.5 °C and the idealized analysis indicating a larger reduction of 1.3 °C. Follow-on modeling is recommended prior to design of a neighborhood-scale demonstration.

1. Introduction

"Cool" roofs reflect more of the sun's energy than do standard roofs. Increasing the albedo (solar reflectance) of a roof has been shown to save energy in a conditioned building, and to lower temperature in an unconditioned building (Gao et al., 2014). Urban climate models indicate that replacing a large portion of a city's standard roofs with cool roofs could reduce outside air temperature in that city (Rosenfeld et al., 1998; Millstein and Menon, 2011; Georgescu et al., 2014; Santamouris, 2014; Salamanca et al., 2016).

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As part of the CERC-BEE Cool Roofs & Urban Heat Islands project, we have investigated the potential of cool roofs to decrease building energy use in China "directly" by reducing the envelope's solar heat gain (Gao et al., 2014). Cool roofs may also save energy "indirectly" by decreasing the air temperature difference across the building envelope. In many cities, meteorological models have been used to estimate the potential cooling of outdoor air from the replacement of all standard roofs (e.g., aged albedo 0.12) with cool roofs (e.g., aged albedo 0.65). For example, meteorological modeling showed that average summer daytime temperature reductions of about 1 °C could be achieved in Guangzhou, China (Cao et al., 2015). However, there have been no demonstrations performed, in Guangzhou or elsewhere, that could verify the modeled predictions of cool-roof induced city-wide air temperature changes, hereafter referred to as the "cool roof effect". One partial exception to this statement is the analysis of cooling trends associated with the expansion of high-albedo greenhouse farming in a region in southeastern Spain (Campra et al., 2008). However, follow-on meteorological modeling indicated that only a portion of the historical temperature trends was likely associated with the expansion of high-albedo greenhouse farming; the remainder of the trend was unexplained (Campra and Millstein, 2013).

The reason that no field tests have been performed is the need to change a large portion of a city's roofing stock to produce a temperature signal large enough to observe—say, at least a few tenths of a degree Celsius. A small experiment encompassing a few buildings could quantify building cooling energy savings that result from reducing roof solar heat gain, but would not validate the meteorological models that show reductions to city-wide outside air temperatures.

On the other hand, expense and logistical challenges tend to make a city-wide test impractical. A demonstration would need to be larger than a few buildings but smaller than the scale of the city. This paper explores whether a neighborhood-scale (~1 km^2) demonstration of cool roofs could produce a measurable reduction to air temperature. First, we perform an idealized heat transfer analysis that indicates that at typical urban wind speeds, air must flow over about 1 km of modified surface to yield a measurable change in near-ground air temperature. Next, we apply a meteorological model to simulate the impact on air temperature of altering roof albedo across 0.77 km^2 sections of an urban area.

We employ a high-resolution regional weather and climate model (Weather Research and Forecasting, or WRF) to simulate ambient temperature changes from deployment of cool roofs to a small (0.8 km^2) neighborhood of Guangzhou, China. The simulation uses a single-layer urban canopy model; it does not include specific building characteristics or a multilayer urban canopy model. This effort simply tests whether deploying cool roofs to an area ~1 km^2 within the greater urban area of Guangzhou could produce significant temperature changes within a simple modeling framework. While we have chosen to simulate the city of Guangzhou, the general results—meaning the change in daytime temperature per change in albedo—are likely applicable to many, but not all, urban areas. To support this statement we point to the rough similarity in modeled temperature sensitivity across many U.S. cities (Millstein and Menon, 2011; Ban-Weiss et al., 2015) as well as Guangzhou China (Cao et al., 2015).

This test is necessary as modeling efforts to this date have generally been designed to evaluate large-scale, city-wide cool roof effects, but have not been designed to estimate changes from neighborhood-scale modifications. This exercise represents the first steps of developing a program to demonstrate the ability of reflective surfaces to cool cities. More complex modeling (such as work by Taleghani et al., 2016) should be pursued to increase the likelihood of the success of an actual demonstration. Specific suggestions for follow-on modeling are included in the concluding section of this paper.

2. Simplified heat transfer analysis

As air flows from a higher-albedo neighborhood to a lower-albedo neighborhood, the step change in surface albedo at the interface between neighborhoods will lead to a step change in surface temperature. Here we present a simple analytical model to estimate the air temperature change induced by a step change in the temperature of the surface over which it flows. We are particularly interested in the change in air temperature as a function of height above ground, and of distance from the point of the step change. This allows us to estimate the air flow distance needed to yield an observable change in air temperature at, say, 2 m above ground level. It thereby informs and complements our meteorological analysis.

This simplified analysis is provided only to estimate the characteristic length that air must travel over a surface for a step change in surface temperature to be detectable at a specified height above the surface. It models a