1.4 IMPACTS OF URBAN ALBEDO INCREASE ON LOCAL AIR TEMPERATURE AT DAILY THROUGH ANNUAL TIME SCALES: MODEL RESULTS AND SYNTHESIS OF PREVIOUS WORK

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1. INTRODUCTION

Urbanization gives rise to a variety of surface cover and land use modifications. As a result, urban areas tend to exhibit elevated temperatures relative to their non-urbanized surroundings, a phenomenon often referred to as “the urban heat island.” Urban heat islands impact urban residents in several ways (e.g. Oke 1997), including: modified energy demand (higher in summer, lower in winter), thermal stress on inhabitants, and increased air pollution formation rates.

Urban temperature more generally depends on local-scale and micro-scale processes in addition to the larger-scale (e.g., synoptic) weather patterns that provide the setting for local climates. Cities are logical sites for heat attenuation at these smaller scales through intentional surface modification, and due to their high population densities, they have become the foci of such efforts.

In this context, numerical models of urban surface-exchange processes have been applied to study neighborhood-scale (local-scale) urban heat mitigation options (e.g., Sailor 1995, Taha *et al*. 1999, Krayenhoff *et al*. 2003, Synnefa *et al*. 2008). These are often referred to as heat *island* mitigation studies, but it is absolute urban air temperature that is of relevance rather than its difference with a nearby “rural” site. The focus of these studies is usually the reduction of daytime or maximum diurnal “near-surface air temperature”; in contrast, the canopy layer urban heat island (i.e., the elevation of street-level air temperature relative to a nearby rural site) is typically best expressed during the evening and nighttime (Oke 1982). Hence, the motivation for urban heat mitigation strategies is considered here apart from the “urban heat island” framework. Such strategies simply take advantage of the concentrations within cities of relatively modifiable surfaces and especially of potential benefactors, that is, people and their associated energy use, comfort and health outcomes.

In this research, we focus on the sensitivity of near-surface air temperature to changes in roof albedo in neighborhoods with different degrees of urbanization. We use a simple 1-D modeling framework that parameterizes both the urban roughness sublayer and the boundary layer above, but ignores horizontal transport by wind (advection). The neglect of advection (i.e., the assumption of an “infinite city”) permits estimation of the maximum impacts of albedo modification on air temperature, as advection always serves to reduce the effect of the surface on the local climate. Said another way, this approach avoids any specificity in terms of advection strength, whereas most previous studies have focused on specific ‘hot’ episodes and used 3-D mesoscale models.

Subsequently, our modelled impacts are extended to seasonal and yearly time scales for a midlatitude city with distinct warm and cold seasons as well as a history of deadly heat waves (Chicago). We also compare our estimates of near-surface air temperature sensitivity to albedo with results from other modeling studies in the literature.

Degree-days are a simple measure of the cooling or heating energy expenditure required to maintain comfortable indoor temperature. Apart from Taha *et al*. (1999), most studies relating urban surface modification to local-scale thermal changes have focused on cities characterized by significant periods of elevated heat stress and/or air pollution episodes and a relatively high ratio of cooling degree-days (CDD) to heating degree-days (HDD). Therefore, an additional question that we begin to address is whether urban heat mitigation is beneficial in midlatitude cities that experience distinctly cold winters (with more HDD) as well as hot summers.

2. MODEL COMBINATION

We combine models to provide a simple but relatively complete description of boundary layer and canopy layer for clear sky conditions, and to permit simple radiative representation of clouds. We couple the Town Energy Balance (TEB) urban surface scheme (Masson 2000) with a 1-D column model originally by Troen and Mahrt (1986)—the non-local boundary-layer closure from the Oregon State University Coupled Atmosphere-Plant-Soil (OSU-CAPS) model—to simulate urban thermal climate. The two models are coupled such that they run interactively at each time step and require little outside forcing. The Roach and Slingo (1979) longwave scheme is added to the coupling and interacts with the boundary-layer model at each level. The coupled model output provides estimates of the urban surface radiation and energy balances and their impact on both the averaged canopy-layer atmosphere and the overlying atmospheric boundary layer. Finally, simple, relaxation-type advection is added to assess its importance. Krayenhoff and Voogt (2010) provide more details on the combined model and its evaluation and sensitivity.

3. ATMOSPHERIC SENSITIVITY TO ROOF ALBEDO

Chicago has recently been a focal point for municipal debates on the implementation of cool roofing technologies for urban heat mitigation (Gartland 2008). Hence, the coupled model is applied to study roof

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albedo impacts on near-surface air temperatures for two neighborhoods in this city: a dense downtown neighborhood (Urban Climate Zone 1; Oke 2006) and a detached residential neighborhood (Urban Climate Zone 3).

a. Simulation Design

i. Clear-sky simulations

Input parameters and initial conditions are found in Krayenhoff and Voogt (2010). Chicago roof parameters are provided by professional roofers (Dupuis, personal communication), and hence the sensitivity of the results to roof thermal parameters is not considered. Initial roof albedo (α_r) is 0.06 in both neighborhoods. We test the impacts resulting from α_r of 0.25, 0.32, and 0.65. These albedos originate from the U.S. Environmental Protection Agency's Energy Star Program, the 2001 proposed revision to the City of Chicago Energy Code and subsequent compromises with the roofing industry (Dupuis and Graham 2005, Gartland 2008), and represent a standard gravel–asphalt roof (0.06), gravel–asphalt roofs with lighter-colored aggregate (0.25, 0.32), and a high-reflectivity roof membrane (0.65).

Simulations are conducted for clear-sky conditions in three seasons. Each clear-sky case consists of a 2-day simulation that begins with an observed sounding of atmospheric temperature, humidity, and wind speed representative of clear weather conditions for the season under consideration (summer, spring, winter). Clear skies and a clean atmosphere are assumed throughout the simulation, maximizing the impact of solar radiation on the surface-layer climate. Simulations are conducted assuming no advective influences on the 1-D boundary layer to assess the maximum impacts of roof albedo change on the atmosphere. One additional simulation includes an estimate of cooling due to lake-breeze advection, given Chicago's proximity to Lake Michigan.

ii. Seasonal and annual integration

To provide seasonal and annual estimates of the average impact on near-surface temperature of roof albedo modifications, the likelihood of clear weather must be accounted for. We represent the main effect of clouds through the use of solar radiation measurements rather than cloud measurements, which are more complex. Observations of solar radiation at the surface integrate the effects of clouds and solar angle, such that their combined impact can be represented by one simple measure: the fraction of clear-sky solar radiation arriving at the surface.

The residential study area is chosen for the seasonal assessment, as it better represents the most prevalent surface cover in the Chicago area. Simulations are run for three dates: 21 July, representing the period 21 April–20 August ("summer"); 21 March, representing the periods 21 February–20 April ("spring") and 21 August–20 October ("fall"); and 21 January, representing the period 21 October–20 February ("winter"). These times are selected on the basis of the annual progression of extraterrestrial solar radiation and are intended to provide a minimum number of simulations to assess the seasonal variability. The degree of albedo-induced cooling for several cloud types is modeled for each season, and subsequently weighted by the observed seasonal solar radiation climatology for Chicago. More detail is found in Krayenhoff and Voogt (2010).

During the winter period, we assume that the vegetated portion of the urban area is snow covered, but that streets and roofs are snow free. The potential seasonal impacts of rooftop snow are estimated by assuming that atmospheric temperature is unaffected by α_r for the periods 21 December–20 February (short snow season) or 1 December–31 March (long snow season) in the seasonal and annual assessments. No advection is incorporated in this seasonal and annual assessment.

b. Results

i. Neighborhood albedo

The overall change in neighborhood albedo (α_N), the albedo of the complete urban surface, is output from TEB, and represents snow-free conditions (Table 1). The changes to α_N (≈0.2-0.3) resulting from the increase in α_r to 0.65 are large relative to typical urban–rural albedo differences of 0.05 or less (Oke 1988). Therefore, the surface modifications considered here represent large intentional climate forcings that are outside of the range of normally observed conditions.

ii. Air temperature

The effect of changing α_r in the downtown area has a relatively large impact on the simulations without advection (Fig. 1). The roofs in this area are assumed to occupy over half (53%) of the land surface—a very high fraction likely only realistic for very limited portions of the city. Effects are somewhat smaller for the residential neighborhood due to the smaller building fraction (0.33). In the downtown simulation with a modeled breeze from Lake Michigan, the impacts of α_r are reduced by about 80% for the average and maximum temperatures (Fig. 1).

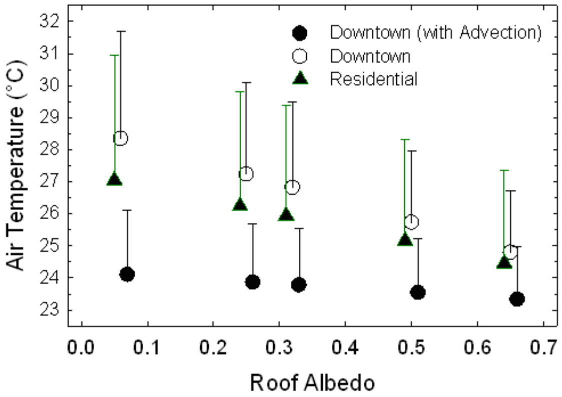
Table 1: Overall neighborhood albedo as output from TEB for each of the Chicago neighborhoods (snow free conditions), as well as the input (fixed) urban surface component albedos.

	Neighborhood Albedo (α_N)	
Roof	**Downtown**	**Residential**
0.06	**0.06**	**0.14**
0.25	**0.16**	**0.20**
0.32	**0.20**	**0.23**
0.65	**0.37**	**0.34**
Surface Component Albedos		
Vegetation	**Street**	**Walls**
0.24	0.15	0.31

On an annual basis, the impact of the full albedo implementation (0.06 to 0.65 for all roof area) results in a decrease in the average daily air temperature of approximately 1 °C for the residential area (Table 2). On a seasonal basis, the impacts are largest in the summer. Decreases in the summertime average daily maximum, average, and minimum temperatures are approximately 60% of those for an individual clear day. With full albedo implementation, snow-covered roofs reduce the average annual cooling by approximately 0.3 °C for the long snow season with a smaller reduction for the short snow season (not shown). Winter season temperature reductions are roughly half and one-third for the long and short periods, respectively. All results in Table 2 are considered high estimates of air temperature sensitivity to α_r due to the neglect of advection.

The impacts of roof albedo changes are expected to be most important during the daytime and in summer when higher solar elevation angles mean that roofs are important interceptors of solar radiation. Hence, reductions in maximum temperatures should exceed minimum temperature decreases. Indeed, ratios of maximum to minimum temperature reduction vary from ≈2 in summer to ≈3 in winter (Table 2), and are of similar magnitude to those of Oleson et al. (2010).

Figure 1: Summer clear-sky daily average (symbols) and maximum (bars) air temperatures for roof albedo simulations conducted in the downtown (with and without lake-breeze advection) and residential areas. Symbols are offset by up to 0.01 albedo units to prevent plotting over of symbols and error bars.



iii. Degree days and hot days

We assess the impact of the altered α_r on the cooling degree days and heating degree days for Chicago. The results apply to the residential area and do not incorporate advection; details of our methods are found in Krayenhoff and Voogt (2010). The full albedo implementation (0.65) yields a decrease of 302 CDD and an increase of 392 HDD (Table 3). The other albedo implementations also incur a net HDD penalty (i.e., HDD increase is larger than CDD reduction) although the difference is not large. These results assume no rooftop snow in winter. Rooftop snow cover serves to reduce the impact of α_r in winter and therefore reduce the increase in HDD (i.e., the snow-free simulations overestimate the impact on HDD). The HDD penalty effectively disappears for the short snow cover season; for the long snow season CDD reduction > HDD increase (Table 3). Advection would act to reduce the magnitude of both HDD and CDD changes.

The frequency of hot days is of greater relevance to mortality from heat waves. The frequency of maximum temperatures greater than 90 °F, or ≈32 °C, decreases by up to 75% with α_r = 0.65 (Fig. 2); again, these results ignore advection and represent maximum potential impacts.

Table 2: Change in the 15 m air temperature (°C) arising from the implementation of a 0.06 to 0.65 roof albedo change in the residential area without advection. Results are averaged seasonally and annually; "summer" represents the period 21 Apr – 20 Aug, and winter the period 21 Oct – 20 Feb. Results from a single clear summer day are included for comparison.

Parameter	**Annual (°C)**	**Summer (°C)**	**Winter (°C)**	**Clear Summer Day (°C)**
ΔT_{max}	**-1.6**	**-2.4**	**-0.7**	**-3.6**
ΔT_{avg}	-1.1	-1.6	-0.5	-2.6
ΔT_{min}	-0.5	-1.0	-0.2	-1.7
$\Delta T_{max}/\Delta T_{min}$	**2.9**	**2.4**	**2.8**	**2.1**

4. COMPARISON WITH PUBLISHED RESULTS

In Krayenhoff and Voogt (2010) we compare the ratio of the spatially averaged decrease in maximum temperature (ΔT_{max}) to the average neighborhood albedo increase ($\Delta\alpha_N$) across available modeling studies that report these quantities at the same spatial scale. We term this ratio the 'sensitivity' of atmospheric temperature to surface albedo. Several other modelling studies that examine albedo increases for urban heat mitigation but do not quantify both changes at the same scale are not included in this assessment.

Sensitivities are below 12 (i.e., 1.2 °C of cooling per 0.10 albedo increase) with few exceptions. The sensitivities in the current study are 18 for the residential area and 16 for the downtown area. These results represent maximum possible impacts for extremely stagnant atmospheric conditions; with lake breeze advection the sensitivity for the downtown scenario drops to 4. Indeed, the range of sensitivities of the studies in Krayenhoff and Voogt (2010) that include advection is approximately 3-11, or 0.3 °C to 1.1 °C of cooling per 0.10 albedo increase. Importantly, the sensitivity of any particular scenario will depend on a host of factors related to ambient meteorology, season, latitude, geographic setting, and the local character of the urban surface. This range of sensitivity is the result of a sample of modeling studies with variation in these factors as well as different levels of idealization and of spatial and temporal averaging.

If this range of sensitivities is assumed to hold, it suggests that a moderate density neighborhood with a roof fraction of 0.33 would require uniform α_r increases of ≈0.15-0.50 to reduce the air temperature by 0.5 °C on a typical clear-sky summer day. The relative merits of such an undertaking from health, comfort, economic, and ecological perspectives are beyond the scope here; furthermore, roof albedo increases have direct and indirect impacts beyond those considered here, such as air pollution mitigation and cooling of the top building floor(s), with attendant effects on health, indoor thermal comfort, and energy use.

Table 3: Summary of annual average cooling degree day (CDD) and heating degree day (HDD) changes for uniform implementation of 0.65 roof albedo in the residential area without advection. Model simulations are based on temperatures from Midway Airport. HDD with snow represents the impact of snow on roofs for the period: 21 Dec – 20 Feb (S) and 1 Dec – 31 Mar (L). Base 65°F is ≈18°C.

Method	CDD (Base 65°F)	HDD (Base 65°F)	HDD (Base 65°F) with snow	
			S	L
O'Hare Airport: Observed (1971-2000)	830	6498		
Midway Airport: Observed (1971-2000)	1001	6083		
Midway Airport: Observed (15 years)	1052	5908		
Residential Modeled (0.65 roof albedo)	750	6300	6246	6160
	CDD Reduction	HDD Increase	HDD Increase	
Residential Modeled (0.65 roof albedo)	302	392	338	252

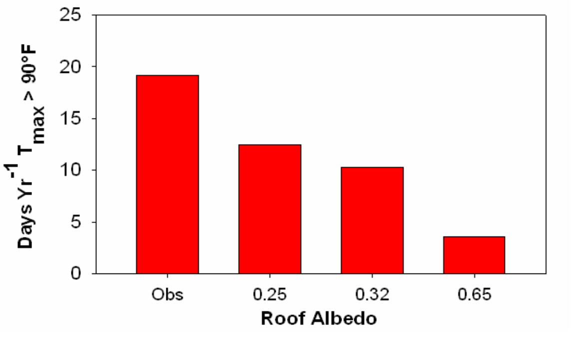
Taken together, the studies examined in Krayenhoff and Voogt (2010) indicate that $\Delta T/\Delta\alpha_N$ is probably no greater than 1.0 °C of cooling per 0.10 increase in α_N, except for extremely stagnant air masses when cooling might reach 1.5–2.0 °C (and when the benefits are likely most significant). This is supported by measurements at an idealized desert site that show 0.8–0.9 °C of cooling per 0.10 albedo increase (Rosenfeld et al. 1995); however, the absence at this site of a canopy, and of the associated reductions in efficiency with which high albedo surfaces cool the canopy-layer (e.g., the shading of high albedo ground surfaces, the mixing away of roof albedo cooling into the boundary-layer, and the shift of energy partitioning away from sensible heat due to enhanced urban storage), suggests that it may be a high estimate relative to real cities. A more typical clear-sky summertime sensitivity is probably closer to 0.5 °C of cooling per 0.10 increase in α_N. (Furthermore, seasonally averaged results for the Chicago residential neighborhood in Table 2 suggest that temperature sensitivity to albedo for summer, winter, and annual time scales is approximately 65%, 20%, and 45% of the clear-sky value, respectively, assuming no rooftop snow.)

5. CONCLUSIONS AND DISCUSSION

As applied scientists we seek to evaluate the probable effectiveness of various urban heat mitigation approaches rather than to promote any or all of these approaches. Local-scale in situ urban heat mitigation field experiments have not been undertaken because of cost and logistics, not to mention the difficulty in providing a "control" scenario. Hence, modeling approaches are used to quantify the thermal effects of urban surface modification. However, the empirical and theoretical bases for modeling the urban canopy and roughness sublayers remain limited, and our model estimates must be treated with care.

The present work combines several models to represent the most important processes affecting the urban canopy and boundary layer thermal environments. On an annual basis, the model simulations show that a change in α_r from 0.06 to 0.65 cools the near-surface air temperature of a Chicago residential neighborhood by about 1 °C on average when rooftop snow is included during the winter season. Impacts are largest in the summer and smallest in the winter. During a clear summer day the 0.06–0.65 α_r increase leads to a reduction of about 4 °C in the maximum daytime air temperature. Importantly, the size of the albedo increases considered here are well above the range of normally observed variation. Moreover, because of the neglect of advection, all of these temperature reductions are considered to be maximum possible impacts (i.e., typical impacts are expected to be significantly smaller). When an estimate of lake breeze advection is included, for example, the reduction of the maximum daytime air temperature in the downtown simulation on a clear summer day is reduced by more than half to little more than 1 °C. Reductions in diurnal maximum temperature are 2-3 times the corresponding decreases in minimum temperature.

Figure 2: Number of days per year with T_{max} > 90°F (≈32°C). Observed data are for the 15 year period 1988-2002 from Midway Airport. Simulations do not include advection.



In the residential area, annual CDD decrease by ≈300 and there are ≈15 fewer days with maximum air temperatures exceeding 90 °F (≈32 °C). Overall, however, impacts on HDD and CDD are similar for Chicago according to our analysis, and as such average annual energy use reductions deriving from roof albedo–induced local-scale air temperature reductions are not expected to be significant for this location (ignoring the cost/pollutant implications of different energy sources); net effects for individual buildings may differ. Effects on health and mortality, especially during summer heat waves, may be more significant. Our results suggest that α_r may be effective at reducing the frequency of days with stressful maximum temperatures, although this effect is likely overestimated because of the neglect of advection in the seasonal and CDD/HDD analyses.

Near-surface air temperature decreases resulting from α_r enhancement, as modeled in the present study, are consistent with previous work. For studies that include advection, maximum temperature reductions are below 1.2 °C per 0.10 increase in average albedo. The present results use a well-evaluated urban canopy parameterization and find sensitivities of ≈1.7 °C per 0.10 albedo increase without any advection, dropping to ≈0.4 °C with simple estimation of lake-breeze advection.

Our synthesis of results in the literature suggests that a 0.10 average increase in α_N will generate a peak daytime air temperature reduction on the order of 0.3-1.1 °C for typical clear-sky midlatitude summer conditions, while somewhat higher (lower) reductions are likely for more stagnant (advective) atmospheric conditions. The presence of clouds and/or seasonal declines in solar radiation will serve to diminish these impacts. Finally, these estimates of temperature sensitivity to albedo depend heavily on the fidelity of current urban surface-atmosphere exchange models.

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