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Research Article

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Quantifying the Albedo of the Montreal Island and its Potential for Increase

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Abstract

Urbanization has changed the Earth's surface, resulting in the urban heat island effect. There has been a recent focus on increasing urban albedo as a strategy to mitigate this phenomenon. Studies on Montreal's albedo have primarily looked at the impact of albedo manipulations upon the urban heat island effect. However, the current albedo of the island, broken down by land use type, has yet to be quantified. Therefore, previous studies often rely on generalized urban albedo and land use estimates that have not been proven to be generalizable to Montreal. This study attempted to quantify the current albedo of the Island of Montreal through urban land use categorization. The findings were then used to estimate albedo increase under different roof replacement scenarios. Data sets for building footprints, vegetation, and roadways were incomplete in Montreal, requiring the combination of several sources to obtain representative data for analysis. This study found the albedo of Montreal island to be 0.19 ± 0.057. Further, the hypothetical roof change scenarios then aligned with a 0.1 albedo increase , which is the albedo change used in current urban heat island effect mitigation literature. Using the albedo increase potential that resulted from the three scenarios tested here, future research should explore further estimation of the associated surface and air temperature decrease.

Introduction

Currently, 55% of the global population resides in urban areas, and the United Nations projects this proportion to increase to 68% by 2050[1]. There are many environmental benefits of increased urban population density. Sustainably planned cities can decrease energy consumption and greenhouse gas emissions per person through shared transport, living spaces, and food access[2]. However, there are clear threats that urban spaces pose to biodiversity, water and air quality, and the surrounding climate. Land use change due to urbanization produces the well-studied phenomena of the urban heat island (UHI) effect, where the temperature in an urban area will be on average 1-3°C warmer than the surrounding rural temperature[3]. The materials that make up city roadways and building roofs have a very low albedo and so absorb far more incident shortwave radiation than natural vegetation does. Further, these materials often have high heat capacities that cause the release of absorbed daytime thermal energy at night[4].

There has been focus on increasing urban albedo as a strategy for combatting the UHI effect. Albedo is the probability that a photon of solar irradiance is reflected on a surface, and can be assessed through the simple ratio of outgoing over incoming radiation[5]. Studies from across all urban regions relate albedo increases to reduced energy consumption, reduced electricity demand, improved air quality, reduced risk of heat-related discomfort and mortality, and changes to precipitation patterns (in non-snow cover regions/seasons)[6].

Generalized estimations find that rooftops and roads occupy 60% of urban spaces, with a 1.5 roof to road ratio[7]. The low albedo of these surfaces provides a potential for alteration of urban rooftops to produce changes to a city's climate. Greening of roofs is one strategy to increase albedo and offset heat through evapotranspiration. Whitening of urban surfaces has been studied as well[6]. Previous studies divide between focus on quantified albedo of urban materials, quantified albedo of total urban regions, and impacts of changes to urban albedo on the UHI effect.

Methods for quantifying albedo values vary. Prado and Ferreira[5] used an experimental spectrophotometer to find the albedos of rooftop types found in Sao Paulo, Brazil. Even with consideration for roughness and aging of materials, white surfaces consistently reported albedo values > 0.5. The Berkeley Lab Heat Island Group[8] found similar values using remote sensing techniques on satellite imagery of Californian cities.

Many studies explore the impacts of albedo increases on the UHI effect. To do so, they almost exclusively use the Weather Research and Forecasting-Urban Canopy model (WRF-UCM), a mesoscale numerical weather prediction model that simulates the urban area[6,9,10]. This WRF model uses a default albedo parameter of 0.2 that is applied to all urban area surfaces. In studies on Montreal and Toronto respectively, Jandaghian and Akbari[11] and Jandaghian and Berari[12] used this default albedo of 0.2, and tested the effects of increased albedo values of 0.65, 0.6, and 0.45. The 0.65 albedo value resulted in an average air temperature decrease of 0.6°C in Montreal and 1°C in Toronto. Another study on Montreal found an average air temperature decrease of 0.25°C due to a similar 0.45 increase in albedo from the baseline of 0.2[7].

Improvement to these models can be realized through more detailed estimations of the albedo in the urban areas of interest. Bretz, Akbari, and Rosenfeld[13] quantified the albedo increase potential of Sacramento through investigating the composition of the city and detailing albedo improvements for each surface type. They found a potential for an albedo improvement of 0.18 through maximizing the reflectivity of urban surfaces.

Although studies have been performed to manipulate the albedo of the Island of Montreal, there does not yet exist a similarly detailed estimate of its actual urban albedo. Cold cities have been largely ignored in urban albedo research due to the annual and prolonged period of snow cover. However, the average number of snow cover days in Montreal has decreased from 103 to 73 in the period since 1985[14]. Further, during intense summer heatwaves, Montreal experiences severe UHI effect. Over 400 deaths have been attributed to these heatwaves over the past 30 years[15].

Better policy must be formulated in order to combat the climate change driven increase in the aforementioned consequences of the UHI effect. Policies and pilot projects have already been implemented across the globe using the strategy of increased albedo to offset urban heat. Notably, New York City has painted 9.2 million square feet of roofs white since 2009[16], and Los Angeles is painting a portion of its roads white as a pilot mitigation effort[17]. A 2020 Government of Canada report on reducing UHIs strongly recommended policy that incentives green and cool roofs across Canadian cities[18].

The objective of this project is twofold. First, this research quantifies the current albedo of the Island of Montreal through consideration for the specific proportions of the land use categories of roofs, roads, vegetation, and impervious other. Second, using this baseline current day albedo, this study estimates the albedo increase possible through three roof replacement scenarios. The scenarios are designed to capture the Canadian trends in policy for UHI effect mitigation.

Methodology

Land Use Modification

Numerous data sources were combined to construct a land use map of Montreal*. Land use is divided into four types: [1] roofs; [2] roadways, not including roadside parking or shoulders; [3] vegetation; and [4] impervious other. Impervious other is defined as all land uses which do not fall into the first three categories. Although some porous surfaces, such as bare soil at construction areas, fall into this category, the majority of these miscellaneous surfaces are man-made features such as sidewalks and surface level parking lots, hence the characterization as impervious[13]. Since some urban areas of Montreal fall outside of the city's legal limits, the terrestrial limits of Montreal were used to delineate the city boundaries. All data sources were masked using a terrestrial limit vector file provided by the City of Montreal.

Roofs

We assumed that using building footprints was an adequate analogue for building roofs since walls are generally constructed at a 90% angle from the ground. Roofs were therefore classified using Microsoft Building Footprints, a dataset of computer-generated polygons. The polygon generator is highly accurate but has a recall of only 72.3%, indicating that not all building footprints are present. To address this systemic under-sampling, we assume that the area classified as rooftops by this dataset represents 72.3% of the total surface area of rooftops in Montreal. In order to assess the uncertainty associated with this estimate of roof area, we compared it with building data from OpenStreetMap (OSM), a large Volunteered Geographic Information dataset[19,20].

Roadways

Vector files from the Government of Canada's CanVec series were used for the identification of roadways. While the quality of these official data were uniform across the area of Montreal, certain features such as alleyways were noticeably absent. Therefore, the roadway data were supplemented with vector files from OpenStreetMap (OSM). In both the CanVec and OSM datasets, roadways are primarily represented in one dimension, whereas two dimensional representations are necessary to calculate surface area. Roadway vectors were converted to two dimensions using the attribute representing their number of lanes. 98.11% of roadways had a lane number associated with them.

In the case when the number of lanes was not specified, a value of one was assigned. Next, a standard lane width was derived by measuring 35 roadways across Montreal using the Google Maps "Measure Distance" tool. The average of these lane widths was applied as a buffer to the roadway lines, forming a collection of polygons. Next, the intersections between polygons were dissolved. The surface area of the resulting roadway shapes was then calculated.

Vegetation

Vector files from the Government of Canada's CanVec series were used in conjunction with vector files from OpenStreetMap (OSM). To account for roadways within parks, any vegetation area which intersected with roadways was removed from our vegetation dataset. In order to validate the categorization of vegetation, the vegetation polygons were overlaid on basemaps of Montreal. Three Planet basemaps, which are derived from satellite imagery, were used. To choose three dates for examination, historical climate data from Environment and Climate Change Canada[21] was used to find the maximum daily temperature from 2011-2021. Next, filters were imposed to ensure satellite images with less than 1% cloud cover and more than 98% of the Montreal Island was captured.

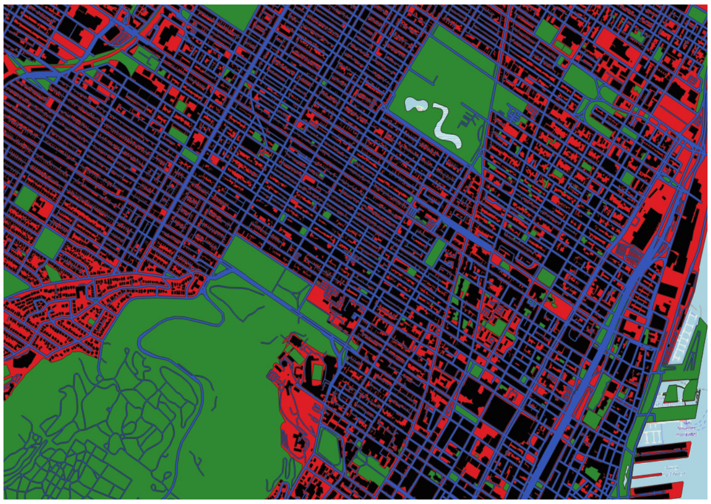

Figure 1. Land use map of Montreal's Plateau neighbourhood. The island area is shown in red. Roadways are overlaid in blue, roofs in black, and vegetation in green.

Upon visual inspection, it was clear that a significant number of vegetated areas shown on the basemaps were not present in the vegetation vector files. Automatic classification was used to address this gap. First, all pixels on the Montreal basemaps that were classified as roof, roadway, or vegetation were discarded. Within the remaining area, values were sampled from points in various vegetated areas across all three basemaps.

Image filters to detect vegetation were constructed using three different pixel value range sizes. The ranges of 50, 60, and 70 pixels were determined so that they captured a visual overestimation or underestimation of vegetation. This resulted in three filters: [1] band 1 values between 30-80, band 2 values between 40-90, and band 3 values between 40-90, [2] band 1 30-90, band 2 40-100, and band 3 40-100, and [3] band 1 30-100, band 2 40-110, and band 3 40-110. These filters were applied to each of the three selected basemaps in order to detect vegetation. The surface area of detected vegetation was calculated by averaging the surface area of the nine outputs. Next, the surface area of detected vegetation was added to the official vegetation surface area obtained from the CanVec and OSM datasets.

Shade Classification

Although roadways in Montreal tend to have dark surfaces, the albedo of roofing materials and other man-made surfaces can vary significantly[22]. To account for this diversity, we further divide the roof and impervious other land uses into white and dark categories.

As with our classification of vegetation, we used a simple threshold-based automatic classification method. The basemaps were first transformed into one-band satellite images of roofs. Then, a 3 by 3 numbered grid was overlaid on the basemaps and the brightest white roof from each grid cell was

*The code used to construct this map, as well as further technical details, is made available at https://github.com/sasgilmer/LandUseMap selected. This random sampling technique ensured that all portions of the study area are represented to account for local variances. The darkest value among the samples was used as a threshold value. All pixels whiter than this threshold were categorized as white roofs, and the remaining roofs were categorized as dark. The surface area of the two categories was then calculated and corrected for under-sampling in the same manner as the

Table 1: Literature derived surface albedo values for each land use category.

		Albedo Value
Roofs	White	0.5700 ± 0.1075
	Dark	0.1200 ± 0.0436
	White Paint	0.7100 ± 0.0584
	Toughkote	0.8500
	Simple Grass Green Roof	0.2560 ± 0.0247
Roads		0.1400 ± 0.0300
Vegetation		0.2600 ± 0.0133
Impervious Other	White	0.3375 ± 0.0520
	Dark	0.1680 ± 0.0585

Building Footprints dataset. The same threshold value was used to divide the impervious other area into white and dark categories.

Albedo Value Calculation

Standard measurements of the albedo of each category were sourced from numerous materialbased studies[4,5,8,13,22-34]. An average albedo value across studies was used to account for differences in methodology and date of data collection. Despite the range of land uses included in impervious other, average albedo values represent this category with relatively high certainty, as evidenced by Table 1.

The albedo of the island is calculated as follows:

$$A_{\mathrm{MTL}} = \frac{1}{SA_{\mathrm{MTL}}} \sum_{x \in \text{Land Uses}} A_x * SA_x \qquad (1)$$

A	Albedo
SA	Surface Area
MTL	Montreal (terrestrial limits)
Land Uses	The set of all land uses within Montreal

The current albedo of Montreal was then calculated by setting Land Uses= {Vegetation, Roadways, Dark Roofs, White Roofs, Dark Impervious Other, White Impervious Other}.

We also calculated albedo values for Montreal under different scenarios for land use change. First, we considered whitening roofs using an average white paint. This is reflected in Equation 1 by adding White Paint to the set of land uses while decreasing $SA_{\text{White Roof}}$ and/or $SA_{\text{Dark Roof}}$. However, the albedo of white paint can vary considerably depending on its material composition and the thickness of application[22]. Therefore, we wished to consider a scenario which represents only the highest albedo white paints on the market. To this end, we selected ToughKote as a representative of high albedo white paints since its albedo has been reported as some of the highest in two albedo datasets[22,29]. Similarly, we calculated the albedo of Montreal with increased green roofs.

Results

Current Day Albedo Value

Our analysis of surface albedo numbers in the literature revealed that the attribution of a standard albedo value for urban materials represents a significant source of uncertainty. Table 1 shows the literature derived albedo value for each of our land use categories, as well as the ToughKote and Simple Green Grass Roof albedos used for mitigation scenarios. Vegetation and White Roof values were relatively consistent across publications, while the values for White Paint and White Impervious Other vary. The land use categories, before correction for under-sampling, can be seen in Fig. 1. Note the under representation of roofs and vegetation.

Correcting for under-sampling and augmenting our data using threshold-based classification resulted in a more even breakdown (See Fig. 2). Vegetation occupies the largest proportion of the island with an area of 174.27 ± 34.16 km², impervious other has an area of 122.06 ± 52.91 km², roofs have an area of 105.88 ± 11.05 km². Of the four primary land use types, roadways represent the smallest category with a surface area of 96.43 ± 13.73 km².

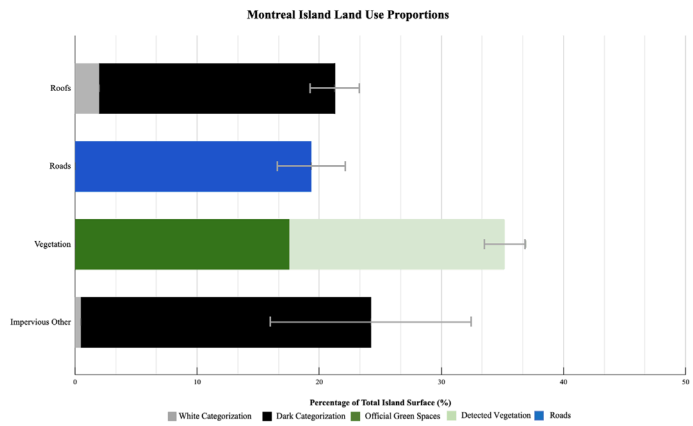

Figure 2. Montreal island land use proportions are reported as percentages of the total Montreal island area.

The roofs category includes 9.92 ± 1.04 km² of white roofs and 95.96 ± 10.02 km² of dark roofs. The impervious other category has a much smaller proportion of currently white surfaces, occupying 2.31 ± 1.00 km² of the island as compared to the 119.75 ± 51.92 km² of dark surfaces. The vegetation category is approximately equally made up of official green spaces (87.43 ± 17.08 km²) and detected vegetation from satellite imagery (88.10 ± 17.08 km²). The final current day albedo calculated is 0.19 ± 0.057, as indicated by Fig. 3.

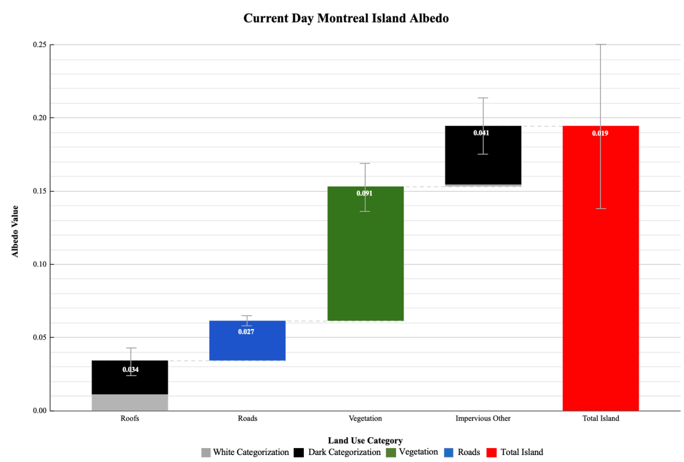

Figure 3. Breakdown of the final current day albedo of the Montreal island. Each land use category's albedo attribution is indicated by the white text.

As demonstrated by Table 2, the land use breakdown of Montreal includes nearly all other cited studies within its uncertainty bounds. However, vegetation occupies a greater proportion of the total area than other studies. This is likely due to the extent of the city incorporated in studies. The terrestrial limits of Montreal that we used as a mask include rural areas which fall outside of official city limits and are primarily agricultural land.

Table 2. Land use proportions of total city area reported across different cities [13, 35-39]

Study	City	Roofs		Pavement			Vegetation	
		White	Dark	Roads	Impervious Other		Official Green Spaces	Detected Vegetation
					White	Dark		
This Paper	Montreal	1.99 ± 0.21	19.24 ± 2.00	19.34 ± 2.75	0.46 ± 0.20	24.02 ± 10.41	17.53 ± 3.42	17.67 ± 3.42
Bretz et al. (1998)	Sacramento	8	20	16	4	10	42	
Akbari et al. (2008)	Global Average	20-25		30-35			40	
Rose et al. (1999)	Sacramento	19.7		44.5	15.4		20.3	
Rose et al. (2003)	Houston	21.3		29.2	12.4		37.1	
Rose et al. (2001b)	Chicago	24.8		37.1	11.4		26.7	
Rose et al. (2001a)	Salt Lake City	21		36.4	8.5		33.3	

Albedo Increase Potential

The potential effects on albedo of various UHI mitigation strategies are outlined in Figure 4. This figure illustrates scenarios where 100% of the current roofs are replaced by one of either average white paint, Toughkote, or simple grass. As the roof land use category has a white and dark component, consideration was later made to replace the roof category both proportionally and in parts.

As seen in Fig. 4, it may be more efficient to isolate certain shades of roofs in policy decisions. Due to the fact that white roofs are only 9.37% of the roof category (and 1.99% of the total island), painting only this proportion does not significantly change the current day albedo in any of the scenarios. In fact, it reduces the albedo in scenario 3 because grass has a lower albedo than the white surfaces. Painting only the dark roofs however nearly achieves the same final albedo increase as 100% of roofs in each scenario. Again, in scenario 3, because of the lower albedo of grass, replacing only dark roofs achieves a higher final albedo than replacing 100% of roofs.

Discussion

By confirming a value for the urban albedo of the Montreal island, we aimed to address the larger issue of the general use of 0.2 albedo for all urban surfaces within the literature. Here, we find that the albedo of the Montreal island is 0.19 +/- 0.057. This albedo value includes the 0.2 urban estimate within its range of uncertainty. Thus we satisfy our first hypothesis. This result implies that the urban albedo of 0.2 does generalize to Montreal. Through examining three roof replacement possibilities, we found a potential albedo increase that surpassed the desired 0.1 in 2 of the 3 scenarios. These increases fell short of the 0.18 potential increase observed by Bretz, Akbari, and Rosenfeld[13] in Sacramento, and thus satisfied our second hypothesis. Further, these results align with the 0.1 albedo increase frequently used in UHI effect literature. Therefore, we are able to assess the significance of the albedo increase scenarios by a comparison with previous studies, even within the Montreal context[35].

Our Montreal island urban fabric breakdown closely aligns to other studies. All previous studies captured in Table 2 demonstrate land use breakdowns near to or within our uncertainties, where differences are attributable to city-specific histories. This result suggests that the use of general urban land use breakdowns is justified in the case of Montreal. Therefore, the majority of the uncertainty in the current day albedo value derives from uncertainty in the albedo values applied to each land use category. Land surface albedo is reported in two categories: intrinsic values, specific to a material, and apparent values, observed to temporally change with solar radiation angle[40]. The smallest apparent albedo occurs at noon, and since intrinsic albedo is a measurement often taken in peak sunlight, there exists systematic misrepresentation in the literature[40]. Further, here we apply our intrinsic albedo values to surfaces based on colour, but surface roughness should also play a role.

Still, the potential for improvement of the Montreal albedo value resulted in values that align with other research[7,41] and allow for comparison between different replacement scenarios. The simple grass green roof scenario resulted in an extremely small albedo change of 0.02, while the two whitening scenarios resulted in values both causing an ultimate increase of albedo to 0.3+. To assess whether these increases are significant to the UHI effect, they must be related to temperature. The relationship between albedo, evapotranspiration and meteorological dynamics in urban spaces is still not well confined, but the abundance of literature allows for general conclusions[6].

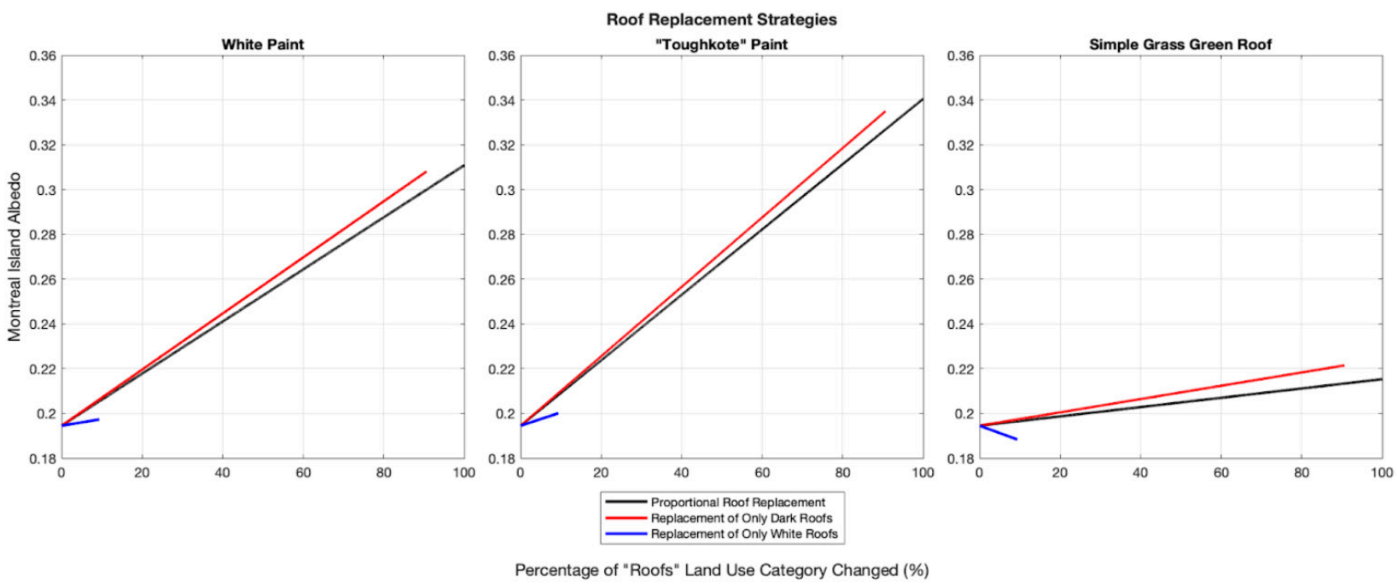

Figure 4. Resulting albedo increase due to each roof replacement scenario. Further, varied strategies for scenario implementation are displayed. Blue indicates replacement of only the white subcategory of the roofs currently present in Montreal. Red indicates replacement of only the dark subcategory of roofs currently present in Montreal. Black indicates 100% roof replacement.

First, we address the negligible effect to albedo caused by the simple grass roof implementation. Green roofs have gained popularity in recent years and covering roofs in short grasses has been widely shown to have a cooling effect[42]. However, these surfaces do not primarily mitigate the UHI effect through albedo. Instead, they primarily mitigate temperature by way of evapotranspiration. A study in Japan found that despite evapotranspiration, white roofs were cooler than simple grass green roofs[43]. This was corroborated by Mackey, Lee, and Smith[44], who found that grass roofs had a negligible effect on surface temperature because vegetation must be dense and varied to cause cooling.

The whitening scenarios may be related to the UHI effect by way of surface temperature, air temperature, and energy offsets. Mackey, Lee, and Smith[44] found a linear relationship between albedo increase and surface temperature change in Chicago by sampling satellite images over a 15-year span. Using their empirical linear relationship, our 0.1 increase to albedo would result in a 1°C reduction in daily average surface temperature. Yang, Wang, and Kaloush[6] find numerous studies that relate surface temperature to albedo changes. This can be a difficult relationship to compare across differing urban land use proportions. For example, a study on Sacramento by Taha[45] found an increase of roof albedo by far less than 0.1 to cause as much as a 10°C reduction in average monthly summer surface temperatures.

Using a Montreal specific model, Touchaei[7] found that an increase of 0.2 in albedo (within 2 standard deviations of both whitening scenarios) resulted in a 2.4°C decrease in surface temperature, and a 0.4°C decrease in air temperature (a function of the surface temperature and sensible heat flux). Relating air temperature to surface temperature is difficult due to turbulent mixing in the lower atmosphere causing an inconsistent relationship[6]. However, many studies still do so, such as Sailor, Kalkstein, and Wong[46] who found a 0.1 albedo increase in Philadelphia to produce a 0.3-0.5°C decrease in day time air temperatures.

Finally, global studies also argue for the significant impact that a 0.1 albedo increase may have. Use of the University of Victoria Earth System Climate Model[47] by Touchaei[7] finds a 0.01-0.07°C decrease through a global increase of 0.1 to only urban areas. Another global model found that a 0.1 albedo increase upon all latitudes within 45 degrees reduces long term global temperature by 2°C[41]. They produced a mathematical relationship where for each 0.01 increase of albedo to 1 m^2 of surface area, there results a long term global temperature decrease of approximately 3×10^{-5} K. A global study by Akbari, Menon, and Rosenfeld[35] related this albedo increase to the offset of 44 Gt of CO_2 by way of reduction of global cooling energy use.

Thus the literature shows that there is a linear relationship between temperature (both surface and air) and change in albedo, within which 0.1 albedo increase is significant both locally, within Montreal, and globally[41,44]. Our study shows that there are multiple routes to achieve this baseline increase of 0.1, by way of implementation of average white surfaces proportionally to all roofs, or by use of the maximal product Toughkote on only the roofs that are not yet light in colour.

However, there are limitations to this work. Although our work aimed at finding a well resolved albedo value for the island of Montreal, this value is not heterogeneous because it does not consider the geographical angles and solar interactions of the Montreal island. The scope of our work is limited to the summer months when the UHI effect is prevalent. Further work is needed to characterize the year-round albedo of Montreal, which involves considering the role of snow cover. As well, characterization of land use categories into vegetation and white/dark were completed through use of visible wavelengths and not the entire radiative spectrum. Improved practices seen in recent work by Mackey, Lee, and Smith[44] use remote sensing techniques to study interaction of all wavelengths with the Earth's surface, and this method would certainly improve the accuracy of the values found in this study. Large uncertainties on all results take these limitations into consideration.

Conclusion

The albedo value calculated for the Island of Montreal in this research substantiates the WRF-UCM model's default albedo value of 0.2. Therefore, general conclusions made in previous literature on the relationship between urban albedo and the UHI effect should continue to be understood as accurately representative. However, as proven in our study, this value will marginally vary between cities depending on their land use category proportions. Further, the uncertainty on the albedo value found here can be better confined through more accurate methods for identifying land use proportions. Thus, for cities considering rooftop changes to mitigate the effect of UHIs, calculating an initial albedo value will produce a more accurate understanding of the potential temperature decrease. Our research can provide a framework for this calculation for cities across the globe.

Secondly, the rooftop whitening scenarios by way of both average white paint and Toughkote paint align with the widely used 0.1 albedo increase present in urban albedo literature. While the simple grass green roof scenario showed a negligible albedo increase, there is opportunity for further Montreal specific research on the potential for green roofs to cool internal building temperatures as an additional UHI mitigation strategy. This research should focus instead on evapotranspiration potential of vegetation presence as opposed to albedo. Furthermore, using our data on the albedo increase potential of white roofs, future study should identify the associated surface and air temperature decrease. Focus should be placed both on Montreal regional temperatures and internal building temperatures as both are relevant to mitigating the UHI effect. These changes translate to improved energy use practices through summer months that present a number of other climate change related benefits. Finally, using a similar model to Jandaghian and Akbari[11], empirical linkages can also be made between changes in albedo and heat related mortalities in Montreal. Such research, made possible by building upon our study, will allow policymakers to weigh the economic, social, and environmental benefits of white roofs as an UHI mitigation strategy for the island of Montreal.

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