Evaluation of the Albedo-induced Radiative Forcing and CO_2 Equivalence Savings: A Case Study on Reflective Pavements in Four Selected U.S. Urban Areas

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Abstract

There is a growing interest in developing cool pavement strategies to mitigate pavement's impact on the global warming in recent years. One of the mitigation strategies is by increasing the solar reflectance (or albedo) of the pavement surface, which directly contributes to global cooling by adjusting radiative forcing and potentially reduces the energy demand in the urban areas. In this paper, the radiative energy budgets in four urban areas are investigated based on the data derived from NASA satellite measurements. The radiative forcing (RF) due to the change of urban surface albedo as a result of reflective pavements is estimated using a simplified engineering model. The carbon dioxide (CO_2) equivalence savings are also calculated with reference to the 100-year global warming potential of CO_2. Results show that the implementation of reflective pavement has a great potential to reduce global warming. The CO_2 reduction is significant in the urban areas but also affects the surrounding regions to some extent. In the end, we recommend using a climate model incorporating site-specific information that enables the visualization of the outputs through spatial maps. The results from this work would be useful for guiding the implementation of the cool pavement strategies.

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Introduction

Anthropogenic modifications to land surface properties due to land use change have the potential to change the climate. Urbanization (conversion of large areas of natural surfaces to man-made impervious land), as a result of population growth and economic development, is considered as one of the principal human activities influencing land surface characterization and the climate system.

Albedo is a measure of surface reflectance defined as the ratio of solar radiation reflected by a body or surface to the amount incident upon it, ranging from 0 (complete absorption) to 1 (complete reflection). Roofs and pavements, which constitute about 20-25% and 29-44% respectively of typical US urban surfaces (Rose et al. 2003), generally have lower albedos than their surrounding areas. These urban surfaces have to be changed and maintained regularly (e.g. pavements are typically resurfaced once in a decade and new roofs are installed or resurfaced every 2–3 decades) (Akbari et al. 2012). Changes in the surface albedo directly affect the energy balance of the earth and its climate feedbacks, leading to global climate change. Radiative forcing, as a measure of the imbalance of the earth’s energy budget, is usually used to quantify such direct impacts and can be translated into global warming potential (GWP). In addition, energy absorbed by urban surfaces raises the air temperature (by 2 - 4 °C) in the urban area, causing a phenomenon known as an "urban heat island" (UHI) (Oke 1992). The higher temperature increases the demand for cooling energy in buildings in order to maintain comfort levels. Furthermore, increased electricity generation by power plants leads to higher emissions of greenhouse gases. These are the indirect impacts of changing surface albedo in the urban areas, which can also be measured in terms of GWP.

One strategy proposed for mitigating global warming and UHI has been to increase the solar reflectance of roofs and pavements in urban areas, commonly referred to as cool roof and cool pavement strategies. Cool roofs have been mandated in many states and cities over the past decades. Cool pavements, however, have not been widely adopted as standard practice. They have a longer life and hence a lower life cycle cost, which could potentially decrease greenhouse gas (GHG) emissions because of lower energy requirements for installation and maintenance (Pomerantz & Akbari 1998). Many studies have assessed the impacts of implementing cool roofs using analytical models or numerical tools (Jo et al. 2010; Jacobson & Hoeve 2012; Li et al. 2014). Only a few studies could be found that quantify the potential impacts of cool pavements (Yaghoobian & Kleissl 2012; Santamouris et al. 2012).

The goal of this study is to estimate the potential benefits of reflective pavements through a simplified engineering model, and demonstrate the dependency of the albedo impacts on some contextual factors. The paper first reviews the existing literatures on estimating the radiative forcing induced by changing surface albedo in general (regardless of roofs or pavements), and the estimated GWP savings associated with different cooling strategies. Next, an analytical method is developed to calculate the RFs and CO_2 equivalence saving due to surface albedo change. The method is then applied in a case study to investigate the impacts of reflective pavements in four selected urban areas in the U.S., using the context-specific data from NASA.

Literature Review

Reflective pavements. Albedo or solar reflectivity is an important thermal property of a pavement surface. As one of the cool pavement strategies to combat global warming and UHI, reflective pavements with high albedo can be achieved by using surfacing materials of light color (e.g. Pomerantz et al. 2000; Levinson & Akbari 2002;

Pomerantz et al. 2003), or applying light color coating on dark surfacing materials (e.g. Karlessi et al. 2011; Synnefa et al. 2011; Kolokotsa et al. 2012; Santamouris et al. 2012). Table 1 lists several techniques to increase the pavement surface reflectivity.

TABLE 1 Existing techniques to increase the albedo of concrete and asphalt pavements

Pavements	Techniques	Albedo	Reference
Concrete pavement	Conventional	0.35–0.40 (new) 0.20–0.30 (weathered)	(ACPA 2002)
	White concrete	0.70–0.80 (new) 0.40–0.60 (weathered)	(ACPA 2002)
	Adding slag	0.20-0.58	(Boriboonsomsin & Reza 2007)
		0.36-0.69	(Marceau & VanGeem 2008)
	White-topping	0.34-0.40	(Sultana 2015)
Asphalt pavements	Conventional	0.05–0.10 (new) 0.10–0.15 (weathered)	(ACPA 2002)
	Chip seal	0.08-0.20	(Bretz et al. 1992; Pomerantz et al. 2003)
	Light-colored aggregate	0.52	(Anak Guntor et al. 2014)
	Light-colored paint	0.40-0.60	(Wan & Hien 2012)

Concrete pavements can be highly reflective if white cementitious materials and light-colored aggregates are present in the concrete mix. The albedo of concrete is predominately determined by the solar reflectance of the cement (Marceau & Vangeem 2007). The albedo increases when the portland cement hydration produces calcium hydroxide, and the albedo stabilizes after the hydration completes (Levinson & Akbari 2002). Adding fly ash in the concrete mix can reduce the albedo (Boriboonsomsin & Reza 2007), possibly because fly ash is darker than portland cement. Adding slag, on the contrary, increases the albedo because slag has high reflectance than fly ash (Marceau & VanGeem 2008). White-topping is a technique to resurface the distressed pavements with concrete overlay. Roller-compacted concrete pavements are constructed by using vibratory rollers to place dry, stiff portland concrete mix as compacted surface layers. Both of them have relatively high albedos due to their cementitious mixture (Qin 2015).

Asphalt pavements typically have a lower albedo than concrete pavements due to the dark color of bitumen, but there are still ways to improve their reflectivities. The most commonly used techniques are chip seal and slurry seal with light-colored aggregates. In the construction of a sealed surface, the aggregates are partially exposed so the surface albedo is between the reflectance of the asphalt binder and of the aggregates. The albedo of these sealed pavements mainly depend on the color of the aggregates and the pavement's age (Pomerantz et al. 2003). Other techniques such as painting with light-colored coatings or microsurfacing with light-colored materials also increase the reflectance of asphalt pavements substantially (Tran et al. 2009).

The albedo of a pavement surface can be greatly affected by wetting, soiling, abrasion and weathering after exposure to traffic and pedestrian (Levinson & Akbari 2002). As a pavement ages, the albedo becomes more dependent on the reflectance of the aggregate and the sand paste (Marceau & VanGeem 2008). A newly constructed gray-cement pavement has an albedo of 0.35–0.40. As concrete ages, it becomes dark because of dirt and tire wear, so most aged concretes have an albedo of 0.20–0.30. Alchapar et al. (2013) found that the reflectance index of colored pedestrian pavements decreased about 20% after one-year exposure.

Albedo-induced radiative forcing. The term "radiative forcing" (RF) is defined as the change in net (down minus up) irradiance (solar plus long-wave; in W/m^2) at the tropopause or at the top of the atmosphere (TOA) due to an imposed change (Ramaswamy 2001). It describes any perturbation or imbalance in the radiative energy budget of the Earth-atmosphere system, which has the potential to lead to climate changes and thus results in a new equilibrium state of the climate system. A variety of forcing agents can cause such a perturbation including greenhouse gases, tropospheric aerosols, ozone, land-use change (surface albedo change), solar irradiance and aerosols from volcanic eruptions. RF is then used to estimate and compare the relative strength of different anthropogenic and natural forcing agents on climate change. Positive RFs represent global warming and negatives lead to global cooling. According to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR5) (Myhre et al. 2013), surface albedo change, primarily due to deforestation, have induced an overall increased surface albedo and an RF of –0.15 ± 0.10 W/m^2. The uncertainty range associated with this estimate is large and the level of scientific understanding is medium-low as reported in IPCC AR5. Besides, albedo-induced RF has also been estimated by analytical models or monitored through climate simulations. Figure 1 presents the calculated RFs normalized to every 0.01 (1%) increase in albedo from several existing studies.

As shown in the figure, RFs calculated from different analytical and numerical models are comparable, ranging from -2.9 to -1.3 for a 0.01 increase in albedo. The variation in results from theoretical calculations mainly comes from the assumptions and estimations used for solar insolation and atmospheric transmittance, both varying with location and cloud cover. Myhre and Myhre (2003) have demonstrated that RF is not linear with surface albedo changes. In general, tropical regions have a stronger forcing than at higher latitudes for the same vegetation change or surface albedo change.

Difference in the RFs simulated from numerical models is possibly a result of model resolutions and land surface characterizations. RFs simulated from using fully coupled climate models tend to be greater than those simulated using an uncoupled land-surface model, since atmospheric feedbacks from urban albedo changes can not only attenuate forcing changes but also amplify the changes in some regions (Millstein & Menon 2011).

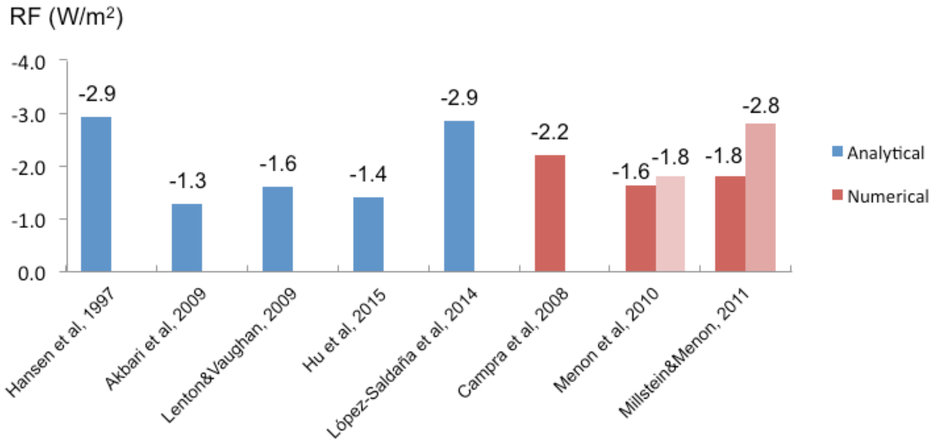

Figure 1 Comparison of normalized RFs due to 0.01 increase in albedo from analytical and numerical models (in *Menon et al* (2010), dark red is for global land areas and light red is for the U.S. only; in *Millstein & Menon* (2011), dark red is annual average and light red is summer average)

Most of the existing studies indicate a similar response of a reduction in RF or an increase in outgoing radiation due to an increase in surface albedo. The negative RF values can be further translated intp GWP or CO_2 offsets that may be expected if urban albedos were increased. As shown in Table 2, the estimated annual GWP savings from a 0.01 increase in urban surface albedo could be up to 7 kg CO_2 per square meter of urban area or cool surfaces.

TABLE 2 GWP savings or CO_2 offsets from urban surface modifications in existing studies

Albedo increase ($\Delta\alpha$)	GWP savings (kg CO_2/m^2)	Normalized savings	Reference
0.01	2.55	2.55	(Akbari et al. 2009)
0.01	3.26	3.26	(Menon et al. 2010)
0.25 on roofs	175	7	(Millstein & Menon 2011)
0.15 on pavement	125	8.33	(Millstein & Menon 2011)
0.01	7	7	(Akbari et al. 2012)
0.01	1.6	1.6	(Rossi et al. 2013)

There is great uncertainty and spatial variability associated with the above estimates due to the characterization of land cover, exclusion of feedbacks, and the climate model used to simulate the energy balance. The relationship between the contextual factors and the albedo-induced RF has not been well characterized by analytical models. In addition, most of the existing works focus on the estimations of RF due to large-scale land cover changes such as forestation/deforestation and greenhouse agriculture. Only a few studies have quantified the direct radiative impact as a result of the modifications to urban surfaces. Therefore, research is needed to fill the gaps in understanding the impacts of reflective pavements on the urban energy budget, and how it is affected by contextual factors.

Case Study

To estimate the magnitude of the albedo impact of reflective pavements on radiative balance, four major cities in the U.S are selected in this case study, representing different climate conditions. The location and climate information are summarized in

Table 3. The latitude of the urban area is related to the intensity of the incoming solar radiation, and the climate condition can affect the amount of radiation reflected by to the space. Such information is necessary when calculating the albedo-induced radiative forcing, which will be described in the following section.

TABLE 3 Location and climate information of the cities selected for the case study

City	Location (Latitude, Longitude)	Climate zone*
Los Angeles, CA	(34.05°N, 118.25°W)	3 (warm-dry)
Houston, TX	(29.76°N, 95.38°W)	2 (hot-humid)
Chicago, IL	(41.84°N, 87.68°W)	5 (cool-humid)
Boston, MA	(42.36°N, 71.06°W)	5 (cool-humid)

*Climate zone classified based on Briggs et al. (2002)

The albedo of conventional concrete pavements ranges from 0.25 to 0.4. As indicated in Table 1, white-cement concrete has an albedo between 0.4 and 0.6 when aged. In this analysis, we assume a hypothetical conversion of a conventional concrete pavement to a white-cement concrete pavement, which increases the albedo by 0.15 (the difference between albedos of average conventional concrete pavements and average aged reflective concrete pavement). Increased pavement albedo produces a climate "benefit" by creating a negative RF. We calculated both the RF and the CO_2-eq offset due to the 0.15 increase in pavement surface albedo ($\Delta\alpha_s$=0.15) over an analysis period of 50 years. The magnitude of this benefit for an urban area depends on the marginal increase in albedo, the intensity of the incoming solar insolation at the pavement surface, and the total area of pavement converted.

Data

Context-specific data on shortwave solar radiation are obtained from a NASA online database of satellite measurements (NASA 2015), for the four selected locations (Los Angeles, Houston, Chicago and Boston) according to their latitudes and longitudes. The NASA database consists of over 200 satellite-derived surface meteorology and solar energy parameters from 1983 to 2005. In specific, the parameters of our interest in this analysis are multiple years of daily averaged insolation on horizontal surface and the daily averaged top-of-atmosphere (TOA) insolation. The resolution of the dataset is 1-degree longitude by 1-degree latitude. The selected four cities are large enough to present in one or more grid cell. The functional unit is set as an overlay pavement section of 1 mile long and four lanes wide (two lanes in each direction). Each lane is 12 feet wide. Thus, the total pavement area is A = 1 mile * 5280 ft/mile * 4 lane * 12 ft/lane = 253440 ft^2 = 23545 m^2.

Method

Radiative forcing (RF) calculation. To estimate the RF of a conversion from a conventional concrete pavement to a white-cement concrete pavement, the first step is to compute the unit effects (W/m^2 net radiative forcing) for a standard albedo change. For comparison with the studies cited above, the calculations are based on a shortwave albedo increment of 0.01. Following the definition, the effective radiative forcing of the standard albedo change at the top of the atmosphere (TOA) in the unit of W/m^2 is expressed as:

$$RF_{alb} = -R_{TOA} \cdot f_a \cdot \Delta\alpha_s \ or \ RF_{TOA} = -R_s \cdot T_a \cdot \Delta\alpha_s \qquad (1)$$

where R_{TOA} is the downward solar radiation at TOA; f_a is a parameter accounting for the absorption and reflection of solar radiation throughout the atmosphere, which is associated with solar zenith angel, total precipitable water and cloud cover (Li & Garand 1994); R_s is the downward solar radiation at the Earth's surface; T_a is the atmospheric transmittance factor expressing the fraction of the radiation reflected from the surface that reaches the TOA; and $\Delta\alpha_s$ is the change in surface albedo. The negative sign indicates that increasing albedo if a negative radiative forcing. The derivation of the equation could be found in (Muñoz et al. 2010; Bright et al. 2012). This model implicitly accounts for the effect of multiple scattering and absorption of radiation within the atmosphere. Local impact of changing albedo on radiative budget could be calculated if incident shortwave solar radiation data are available and location-specific transmittance factor T_a is used.

For the purposes of this analysis, the daily average radiation flux at the surface R_s for the latitude of each selected city is used. This is obtained from 10 year (1995-2004) of daily mean surface insolation for each site from the NASA database. T_a reflects the energy transmitted by gases, particles, and clouds along the path from the ground to TOA. It can be computed using a detailed atmospheric radiation transfer model that can replicate weather, pollution, and their combined optical effects in three dimensions over the target location, or deriving it from routine in situ measurements. Since the output of interest is the long-term (multiple years) radiative forcing effect of a reflective pavement surface, it is computational expensive to run atmospheric simulation to assess T_a. Therefore, a global average T_a of 0.854 is used in the calculations (Muñoz et al. 2010).

The annual and monthly averaged RF_{alb} values are both computed by averaging the 10 years of daily RF_{alb} for each site. The resulting estimated forcing due to installing a reflective pavement (expected albedo increase of 0.15) was computed by scaling the unit effects for albedo increment of 0.01 to the case specific albedo increment (i.e. multiplying by 15).

Global warming potential (GWP) calculation. Besides direct measure of changes in radiative energy balance as a result of surface albedo change, emission metrics such as GWP are also widely used to quantify and compare the relative and absolute contributions to climate change of different forcing agents. GWP is defined as the cumulative radiative forcing effect of a forcing agent over a specified time horizon relative to a pulse emission of carbon dioxide (CO_2) (Forster et al. 2007). Using the Equation (1) for $\boldsymbol{RF_{alb}}$, the GWP of changing surface albedo can be calculated as:

$$GWP_{alb} = \frac{\int_0^{TH} RF_{alb}dt}{\int_0^{TH} RF_{CO_2}dt} = \frac{\int_0^{TH} -A/A_{earth} \cdot R_s \cdot T_a \cdot \Delta\alpha_s \, dt}{\int_0^{TH} RF_{CO_2}dt} \tag{2}$$

where A/A_{earth} converts the RF due to a local albedo change on a unit of area into a effective global forcing by dividing the functional area affected by the area of Earth's surface; RF_{CO_2} represents the marginal RF of CO_2 emissions at the current atmospheric concentration. There are two possible approaches to compute RF_{CO_2}: one based on CO_2 emissions (Akbari et al. 2009; Menon et al. 2010) and the other based on ambient CO_2 concentration (Hansen et al. 2005; Shindell et al. 2009) (see these papers for a full discussion of the calculations). The emission approach estimates a marginal RF value of 0.908 W/kg and the ambient concentration approach results in 1.08 W/kg. Neither is "more correct" than the other; rather, they present different viewpoints on the best way to compare radiation effects with GHGs (VanCuren

2011). In this analysis, we use 0.908 W/kg as the effective radiative forcing of CO_2 emissions. The integral of RF_{CO_2} over a given time horizon is also called the absolute GWP (AGWP) values for CO_2. The AGWP values for CO_2 for 20, 100, and 500 year time horizons from IPCC AR5 are 2.47×10^{-14}, 8.69×10^{-14}, and 28.6×10^{-14} $W \cdot m^{-2} \cdot yr \cdot (kg\ CO_2)^{-1}$, respectively (Myhre et al. 2013).

The installation of a reflective pavement induces a one-time step change in the radiation balance of the earth. To simplify the integration in Equation (2), we intentionally assume that the radiative effect imposed by albedo change remains constant given reasonable material durability and proper maintenance once initial aging reaches equilibrium under soiling, weathering, maintenance, etc., and ends when the pavement is demolished assuming 50-year of design life.

Results and discussion

Table 4 summarized the results of averaged RFs and CO_2 offsets due to changes in pavement surface albedo, following the method described above. Site-specific RF_{alb} for a 0.01 albedo increase varies from -1.93 to -1.33 W/m^2, which falls within the range of RF estimated by other studies (-2.9 ~ -1.3 W/m^2 from Figure 1). The difference between this analysis and the previously work may be due to the spatial scale of the radiation calculations and the approach used to convert the albedo change to CO_2 savings.

TABLE 4 Computed 10-year averaged RF_{alb} and equivalent CO_2 savings for a 0.01 albedo increase and for the installation of reflective pavement (0.15 albedo increase) for the four selected cities

City	Site specific unit RF_{alb} (W/m^2)	RF_{alb} for reflective pavement (W/m^2)	Equivalent CO_2 savings (kg/m^2)
Los Angeles, CA	-1.93	-28.95	33.27
Houston, TX	-1.60	-24.00	27.61
Chicago, IL	-1.36	-20.40	23.41
Boston, MA	-1.33	-19.95	22.96

The simplified analytical model explicitly treats the atmosphere as unchanged, ignoring the interactions between the atmosphere and the surface. Therefore, differences between this approach and other model-based estimates exist, which provides some insights into the problem of extrapolating or interpolating the results when predicting the radiative forcing effects of albedo changes.

Figure 2 shows the plot of monthly CO_2-eq savings from 1-mile of reflective pavement section with 0.15 increase in surface albedo at each of the four selected cities. The cumulative annual GWP savings are calculated for each city based on the area of 1-mile pavement section (~23545 m^2) and the 0.15 albedo increment for average reflective pavements, as shown in the legend. It is obvious that the GWP impact of changing surface albedo varies by time and location. As shown in Figure 2, this effect is more pronounced in the summer than in the winter. The calculated effect of albedo change on radiative forcing, and thus the magnitude of the GWP savings, varies widely from city to city, as climates and the strength of solar insolation vary across the U.S. While all four locations benefit due to a change in albedo, Los Angeles presents a greater opportunity for global warming mitigation through installations of reflective surface materials. The spatial and temporal variations suggest that full understanding of the climate effects of reflective pavements requires understanding the range of conditions at the urban level, and possibly even at the facility level.

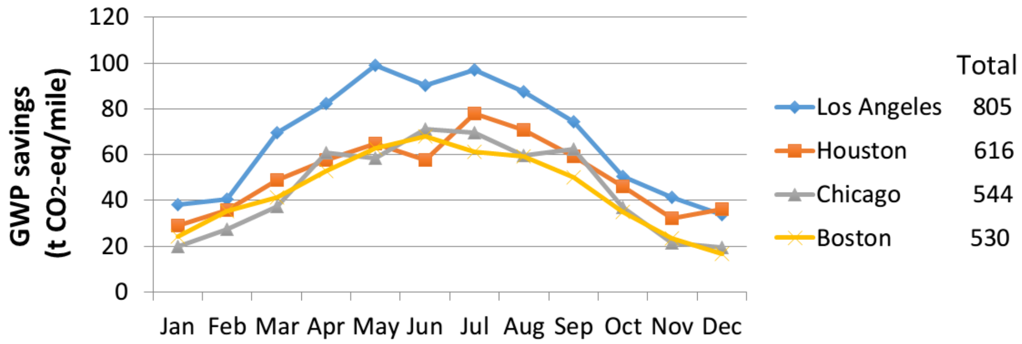

Figure 2 Monthly and cumulative GWP savings from 0.15 increase in albedo at four locations over 50 years

Conclusions

While the exact magnitude of albedo effects requires further validations, this analysis provides some insight into the local-scale variation of albedo-induced RF by allowing comparison across the U.S. and offering a computational approach that can be applied to any geographic area. The spatial variation also suggests that local variables may play an important role in promoting or hindering widespread adoption of reflective pavement as a climate mitigation strategy. Nonetheless, the site-specific evaluation presented here would provide guidance on valuing the reflective pavement strategy at the urban or the facility level.

The analytical model used in this study provides an easy way to approximate the impacts of changing surface albedo in terms of RF and GWP. It is a complement to the sophisticated climate model studies, with context-specific measurement-based calculations of the direct radiation balance impacts of increasing the reflectivity of pavements.

There are, however, challenges and limitations when applying this analytical model. First of all, location-specific data on T_a or f_a are not readily available. While incident shortwave solar radiation at TOA (R_{TOA}) and at the surface (R_s) can be obtained from historical satellite measurements or climate simulations, atmospheric transmittance factor T_a and f_a are not typical parameters tracked by satellite observations. Location-specific T_a and f_a depend on a number of contextual factors, including solar zenith angle, total precipitable water, and cloud cover. Local cooling effect of reflective pavements could be estimated more accurately if these location-specific data were used instead of global average value.

In addition, data on the evolution of surface albedo, particularly pavement albedo, is not available currently. Surface albedo varies from year to year. For example, as pavement ages, concrete surface tend to get darker so the albedo gets smaller, while asphalt surface gradually gets brighter so the albedo of asphalt becomes greater. Pavement albedo could also vary seasonally due to snow, rain and even the traffic on the pavement. Long-term measurements of albedo have been carried out by some researchers in order to better characterize the changes of albedo ($\Delta\alpha_s$).

Furthermore, the analytical model described above does not account for the shadings of trees and the multiple reflections by adjacent buildings. The effect of reflective pavements on building energy consumption at the urban-scale has not been quantified analytically by models.

Last but not least, the analytical model relies primarily on radiative and climate data, which come from measurements or numerical simulations. There are inevitably large measurement uncertainty or model uncertainty. The model must be validated and calibrated using different measured and simulated datasets.

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