THE IMPACTS OF SURFACE ALBEDO ON CLIMATE AND BUILDING ENERGY CONSUMPTION: REVIEW AND COMPARATIVE ANALYSIS

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ABSTRACT

Rapid urbanization has changed land use and surface properties, which has an effect on regional and even global climate. One of the mitigation strategies proposed to combat urban heat island (UHI) and global warming as a result of urban expansion is to increase the solar reflectance (or albedo) of the urban surfaces (mainly roofs and roads). Despite the observed local cooling effect in many studies, the regional and global climate impacts induced by land surface change are still not well understood, especially the indirect and larger-scale effects of changes in urban albedo on temperature and radiation budget. Research has been growing on understanding the climate impact of changing albedo, while results still demonstrate great uncertainties and variations.

This paper presents a state-of-the-art review of the existing research on the climate impacts of albedo. Different analytical approaches and modeling works are synthesized and discussed. A comparative analysis of results from different studies shows that the radiative forcing (RF) for a 0.01 increase in albedo ranges from -2.9 to -1.3, and the air temperature reduces by 0.1 ℃ on average, indicating a cooling effect. The annual GWP savings can be up to 7 kg CO_2 per square meter of urban area or cool surfaces. The uncertainties in the results and limitations in the existing studies are discussed. This analysis will serve as a foundation for comparing the climate impacts of urban albedo.

Keywords: albedo, urbanization, global warming, green pavements

1. 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), a result of population growth and economic development, is considered as one of the principal human activities influencing land surface characterization and land-atmosphere interaction. As humans alter the natural landscape, energy exchanges through the surface and atmosphere are affected, thus influencing the local, regional, and even the global climate.

One of the land surface properties that has been changed due to urbanization is albedo, which 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 *(1)*, 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) *(2)*. Changes in the surface albedo can have direct and indirect impacts on the radiative energy balance of the earth and the local, regional and even global climate. Surface albedo change can affect the amount of solar radiation going back to the space, thus altering the radiative balance at the top-of-atmosphere (TOA), known as radiative forcing (which will be explained in the following section). Indirectly, changes to the urban surface albedo also contribute to a phenomenon known as an "urban heat island" (UHI) *(3)*, due in part to the lower albedo of urban surfaces compared to their rural surroundings. The higher temperature in urban areas increases the demand for cooling energy in buildings in order to maintain comfort levels, and thus leads to increased emissions of greenhouse gases. In addition to albedo, changes to other surface properties, such as heat capacity, thermal conductivity, permeability, etc., have also influenced the urban energy balance and climate. For example, impermeable surfaces like conventional roofs and pavements tend to suppress evaporative cooling. As a result, absorbed solar radiation is transferred to sensible heat more than to latent heat, contributing to the development of the UHI.

One strategy proposed for mitigating UHI and climate change 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, but could potentially contribute to the GHG reduction because of the larger percentage of urban surfaces covered by pavements.

While many efforts have been made to assess the climate impacts of changing albedo, comparative analyses of different modeling approaches and results from existing studies are limited. Yang et al. is the only one that did a comprehensive review of potential environmental impacts (including temperatures, building energy, hydroclimates, thermal comfort and air quality) of reflective materials at a variety of scales *(4)*. In addition, significant uncertainties exist in estimating the climate impacts of albedo though numerical modeling and analytical approximation. Therefore, this study aims to provide a summary of the state-of-art in research on quantifying the impacts of albedo change on radiative energy balance and climate change using different modeling approaches. Results from different studies are compared in terms of changes in temperature, radiative budget and energy consumption due to albedo changes.

2. IMPACTS OF ALBEDO CHANGE

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 *(5)*. 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 IPCC Assessment Report 5 (IPCC AR5) *(6)*, 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. However, there is great uncertainty and spatial variability associated with this estimate due to the characterization of land cover, exclusion of feedbacks, and the climate model used to simulate the RFs. Therefore, the uncertainty range associated with this estimate is large and the level of scientific understanding is medium-low as reported in IPCC AR5.

Climate Feedbacks

While RF is a simple and useful measure of climate impacts because it’s easily calculable and comparable, it does not attempt to represent the all the climate responses other than radiative balance. In fact, RF induced by changes in albedo can have a series of climate feedbacks, including temperature, moisture, latent heat and sensible heat fluxes. These climate responses and feedbacks, in particular through the hydrologic cycle, have the potential to offset the radiative impact of albedo changes, and they are more uncertain and difficult to quantify. As a result, there is low agreement on the sign of the net change in global mean temperature change induced by land use change *(6)*. For instance, Bala et al. showed that the net temperature change can be either positive or negative depending on the latitude *(7)*; Findell et al. also found a negligible impact of land use change on the global mean temperature through climate simulations, although there are some significant regional changes *(8)*.

Building Energy Demand

Changes in surface albedo due to urbanization have led to higher air temperature in the urban areas than their rural surroundings, known as the “urban heat island effect”. Elevated temperature in the summertime results in an increase in cooling demand for buildings and excess GHG emissions from producing the energy required to fulfill the needs. Akbari et al. reported that for the major metropolitan areas in the U.S., peak electricity load would increase by 1.5–2% for every 1°F increase in ambient temperature *(9)*.

There has been growing interest in mitigating the UHI effect by using reflective materials for roofs and pavements. Reflective materials can reduce cooling loads of buildings in summer, but increase heating loads in winter. The latter is known as the “heating penalty” of high albedo. The relative magnitudes of cooling saving and heating penalties depend on a combination of multiple factors, including location, climate conditions, building types, the source of energy used for heating and cooling, etc. Akbari et al. found the largest net savings in the hottest and sunniest cities and that the savings decreased as the climate got cooler *(10)*. Net savings were positive even in colder climates for most building types. Levinson and Akbari (2009) predicted that reflective roofs almost always reduced the annual cooling load more than it increased the annual heating load per-conditioned roof area, with the greatest savings in Hawaii and the least in Alaska *(11)*. However, in a case study, Akbari and Konopacki (2005) conversely found that the use of reflective roofs would lead to larger heating penalties than cooling savings in electric heating residential buildings under cold climate conditions *(12)*.

The impact of reflective pavements on building energy consumption is more complicated as it is affected by the interaction between pavements and buildings, as well as the energy exchanges in surface-atmosphere interactions. Yaghoobian et al. (2010) found a cooling load saving of 17% in buildings due to a reduction in shortwave radiation transfer from the ground to nearby buildings by using low-albedo ground surfaces, rather than reflective pavements *(13)*. In a later study, they found that increasing pavement albedo from 0.1 to 0.5 near a four-story office building in Phoenix would increase annual cooling loads up to 11% (33.1 kWh/m^2), while annual heating load was not sensitive to such a modification *(14)*. These results indicate the potential of increasing cooling loads in adjacent buildings by absorbing more radiation from reflective pavements.

3. MODELS AND METRICS FOR COMPARISON

Analytical Models

Radiative forcing calculation

RF, by definition, is calculated as the change in net (down minus up) irradiance (solar plus long-wave; in W/m^2) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium *(6)*. For shortwave forcing agents such as albedo change, the instantaneous RF at TOA is commonly used instead of stratospherically adjusted RF*(15)*, which is calculated as:

$$RF_{TOA} = -R_{TOA} \cdot f_a \cdot \Delta\alpha_s \text{ or } RF_{TOA} = -R_s \cdot T_a \cdot \Delta\alpha_s \tag{1}$$

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; 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 derivation of the equation could be found in *(16,17)*. Following the definition, several studies have calculated the RF due to albedo changes *(18–21)*. This model implicitly accounts for the effect of multiple scattering and absorption of radiation within the atmosphere. Regional impact of changing albedo could be calculated if location-specific incident shortwave solar radiation and cloud cover obtained from satellite measurements were used instead of global average value.

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 communicate 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) *(15)*. Using the Equation (1) for RF_{TOA}, the GWP of changing surface albedo can be calculated as:

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

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 local area affected by the area of Earth's surface. Based on this derivation, several studies analytically estimate the GWP of land surface albedo changes for different types of land use changes. Muñoz et al. *(17)* applied this method on greenhouse agriculture study and calculated the RF and CO_2-eq. offsets due to the use of reflective plastic cover, using an expression adapted from Equation (2):

$$CO_{2-eq} = \frac{A \cdot R_s \cdot T_a \cdot \Delta\alpha_s}{RF_{CO_2} \cdot AF} \quad (3)$$

where RF_{CO_2} represents the marginal RF of CO_2 emissions at the current atmospheric concentration, and AF is the average CO2 airborne fraction. Bright et al. *(22)* additionally considered the temporal dynamics of albedo and factored it into the calculation to quantify the GWP of land surface changes in a bioenergy system:

$$GWP_{alb} = \frac{\int_0^{TH} RF_{alb}(t)dt}{\int_0^{TH} RF_{CO_2}(t)dt} = \frac{\int_0^{TH} -A/A_{earth} \cdot R_{TOA} \cdot f_a \cdot \Delta\alpha_s \cdot y_\alpha(t)dt}{\int_0^{TH} RF_{CO_2}(t)dt} \quad (4)$$

where $y_\alpha(t)$ describes the time evolution of the initial albedo change.

Numerical Models

Numerical modeling is used extensively as a tool for weather forecasting and climate research. Regional and global meteorological models coupled with land surface models have been widely used to investigate the impacts of surface modifications on climate as well as on building energy efficiency. Table 1 lists a host of studies using different numerical models with varying complexities and resolutions to estimate the impacts of changing surface albedo. Unlike analytical models, which are simple but limited to estimating only a few parameters, numerical models are capable of simulating various energy exchanges and climate indicators at multiple scales. They can provide local to global, short-term to long-term climate feedbacks on radiative budget, temperature, heat flux, precipitation, etc. Due to the computational cost, most climate modeling works have to balance between resolution and time/spatial scale. Global and regional climate models capturing long-term effects tend to have very coarse resolutions *(23–27)*, while models with detailed urban parameterizations are capable of simulating short-term local-scale climate changes *(28–32)*. As a result, simulation results exhibit great variations, which limit the comparisons among different studies.

TABLE 1 Numerical models for simulating climate impacts/responses due to surface albedo change

Model	Resolution	Time scale	Spatial scale	Reference
CSUMM	5 by 5 km	1 day	Local	Sailor, 1994 *(28)*
HadAM3	3.75 °by 2.5 °	20 years	Global	Betts, 2001 *(23)*
MM5	2 by 2 km	3-4 days	Regional	Sailor, 2003 *(33)*
uMM5	1 by 1 km	5-7 days	Regional	Taha, 2008 *(34)*
MM5- MRF	0.67 by 0.67 km	1 day	Local	Synnefa et al., 2008 *(29)*
Noah LSM	1.3 by 1.3 km	7 days	Local	Lynn et al., 2009 *(30)*
WRF-Noah	2 by 2 km	1 day	Local	Zhou & Shepherd, 2009 *(31)*
CLSM	2 °by 2.5 ° 0.5 °by 0.5 °	12 years 12 years	Global Continental US	Menon et al, 2010 *(24)*
CLMU-CAM3.5	1.9 °by 2.5 °	59 years	Global	Oleson et al. 2010 *(25)*
TEB-OSU-CAPS	N/A (1-D)	3 days	Local	Krayenhoff & Voogt, 2010
GATOR-GCMOM	4 °by 5 °	20 years	Global	Jacobson & Hoeve, 2011 *(26)*
WRF 3.2.1	25 by 25 km	12 years	Continental US	Millstein & Menon, 2011 *(27)*
WRF	4 by 4 km	1 year	Regional	Campra & Millstein, 2013 *(35)*
WRF-Noah	250 by 250 m	3 days	Local	Giannaros et al, 2014 *(32)*
SLUCM-SCM	N/A (1-D)	6 days	Local	Song & Wang, 2014 *(36)*
WRF-PUCM	1 by 1 km	5 days	Regional	Li et al, 2014 *(37)*

Table 2 summarizes previous studies applying various numerical models for estimating building energy consumptions resulting from urban surface modifications. Most of the studies focus on the effectiveness of installing reflective roofs on overall energy efficiency, while a few also investigate other paved surfaces. These models, such as DOE, EnergyPlus and TRNSYS, are designed to simulate building-scale energy consumption. City to global scale energy simulation is more challenging due to the influence of surface heterogeneity and land-atmosphere interactions. Therefore, urban-scale energy savings are mostly estimated by a simple upscaling, which cannot capture the feedbacks from urban microclimate.

TABLE 2 Numerical models for simulating building energy loads due to surface albedo change

Model	Scale	Albedo change scenarios	Reference
DOE2	11 metropolitan areas	0.3 – 0.45 increase on roofs	Akbari et al, 1999 *(10)*
DOE2.1E	240 US cities	0.3 increase on roofs	Akbari & Konopacki, 2005 *(12)*
MM-CM-BEM	A district of Tokyo	0.2 increase on the ground, roofs, and walls	Kikegawa et al., 2006 *(38)*
TRNSYS	27 cities worldwide	Cool roof coatings	Synnefa et al., 2007 *(39)*
EnergyPlus	Phoenix, AZ	Cool roofs	Jo et al., 2009 *(40)*
DOE2.1E	236 US cities	White roofs	Levinson & Akbari, 2009 *(11)*
CLMU-CAM3.5	Global	White roofs	Oleson et al., 2010 *(25)*
TEB-OSU-CAPS	Chicago	0.59 increase on roofs	Krayenhoff & Voogt, 2010 *(41)*
TUF-IOBES	Phoenix, AZ	Ground surface albedo increase	Yaghoobian & Kleissl, 2012 *(42)*
EnergyPlus	Mediterranean region	0.55 increase on roofs	Zinzi & Agnoli, 2012 *(43)*
TRNSYS	A building in Athens	0.69 increase on roof	Synnefa et al., 2012 *(44)*
WRF	U.S. cities	Green roofs, cool roofs, reflective green roofs	Georgescu et al, 2014 *(45)*

4. COMPARATIVE ANALYSES

In this section, we first summarize the results from various analytical or modeling studies on RFs, changes in temperature, GWP and building energy due to changes in surface albedo. We then normalize these impacts (RF, ΔT, GWP and ΔE) to a unit change in albedo $\Delta\alpha$, and compare the normalized metrics across all available studies that report these quantities at the same spatial scale. These normalized metrics reflect the sensitivities of the climate- or energy- related impacts to changes in surface albedo, which provide useful information on the potential impacts of albedo and could be used to guide future mitigation strategies.

Comparison of Results on Radiative Budget

The direct impact of changing surface albedo on the global radiative energy budget can be calculated with analytical models or monitored through numerical simulations, as mentioned in the previous section. Figure 1 shows the comparison of the 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 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 *(46)*.

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 *(27)*.

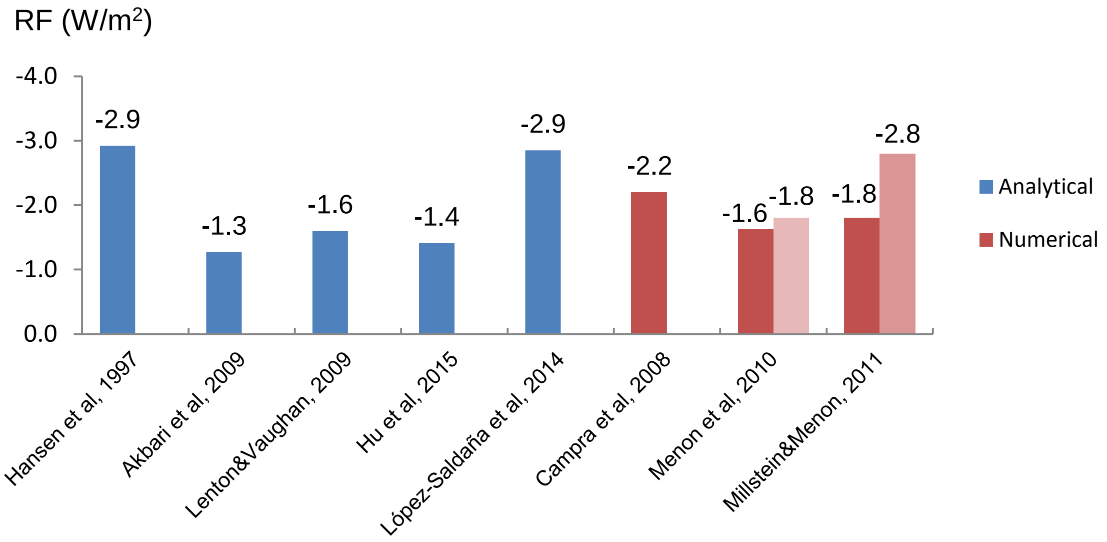

Figure 1 Comparison of normalized RFs due to 0.01 increase in albedo from analytical and numerical models (The blue ones are studies that used analytical models to calculate RF*(16,18–21)*, and the red ones on the right are studies using numerical models *(24,27,47)*. In particular, in *Menon et al, 2010*, dark red is for global land areas and light red is for the US 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 for an increase in surface albedo. The RF values indicate an approximate range in GWP or CO_2 offset that may be expected if urban albedos were increased. As shown in Table 3, the estimated annual GWP savings from an increase in urban surface albedo, normalized to a 0.01 albedo increase, could be up to 8.33 kg CO_2 per square meter of urban area or cool surfaces.

TABLE 3 GWP savings or CO_2 offsets from urban surface modifications in existing studies

Albedo increase ($\Delta\alpha$)	**Annual GWP savings (kg CO_2/m^2)**	**Normalized savings**	**Reference**
0.01	2.55	2.55	Akbari et al, 2009 *(19)*
0.01	3.26	3.26	Menon et al, 2010 *(24)*
0.25 on roofs	175	7	Millstein & Menon, 2011 *(27)*
0.15 on pavement	125	8.33	Millstein & Menon, 2011 *(27)*
0.01	7	7	Akbari et al, 2012 *(2)*
0.01	1.6	1.6	Rossi & Cotana, 2013 *(48)*

Comparison of Results on Climate Feedbacks

The most commonly used metric for assessing the climate feedbacks from radiative forcing is temperature, as there exists a linear relationship between the global mean forcing and the global mean equilibrium temperature response (i.e., $\Delta T = \lambda RF$, where λ is the climate sensitivity parameter) which is similar for all different types of forcing agents *(5)*. Table 4 summarizes the reductions in air temperature (summer day maximum and annual average) and surface temperature due to increases in surface albedo. Normalized to a 0.01 albedo increase at the same spatial scale, a comparison of ΔT (air and surface) from these studies is shown in Figure 2.

From the figure, it is obvious that the reduction in normalized reduction in surface temperature is greater than the reduction in air temperature. An average reduction of 0.1 ℃ in air temperature due to a 0.01 increase in surface albedo is observed across all studies included here. Most of these studies were run for a few days in the summer over a particular city or region, as opposed to a full-year global simulation. There is not a direct linear relationship between albedo increase and temperature reduction across locations, as local variables can influence this relationship *(35)*. Despite the variations, and although some of these studies are not directly comparable, they still demonstrate the potential cooling effect that can be achieved by increasing the albedo of urban surfaces.

Other climate feedbacks from albedo changes, such as surface heat fluxes, humidity and precipitation, were monitored by only a few simulations at global scale with very coarse resolutions *(26,27)*. Dominant effects were found on air temperature and radiation fields, with insignificant impact on other meteorological parameters. The magnitude of the feedbacks depends on model resolution and treatment, so future work is needed to study these impacts.

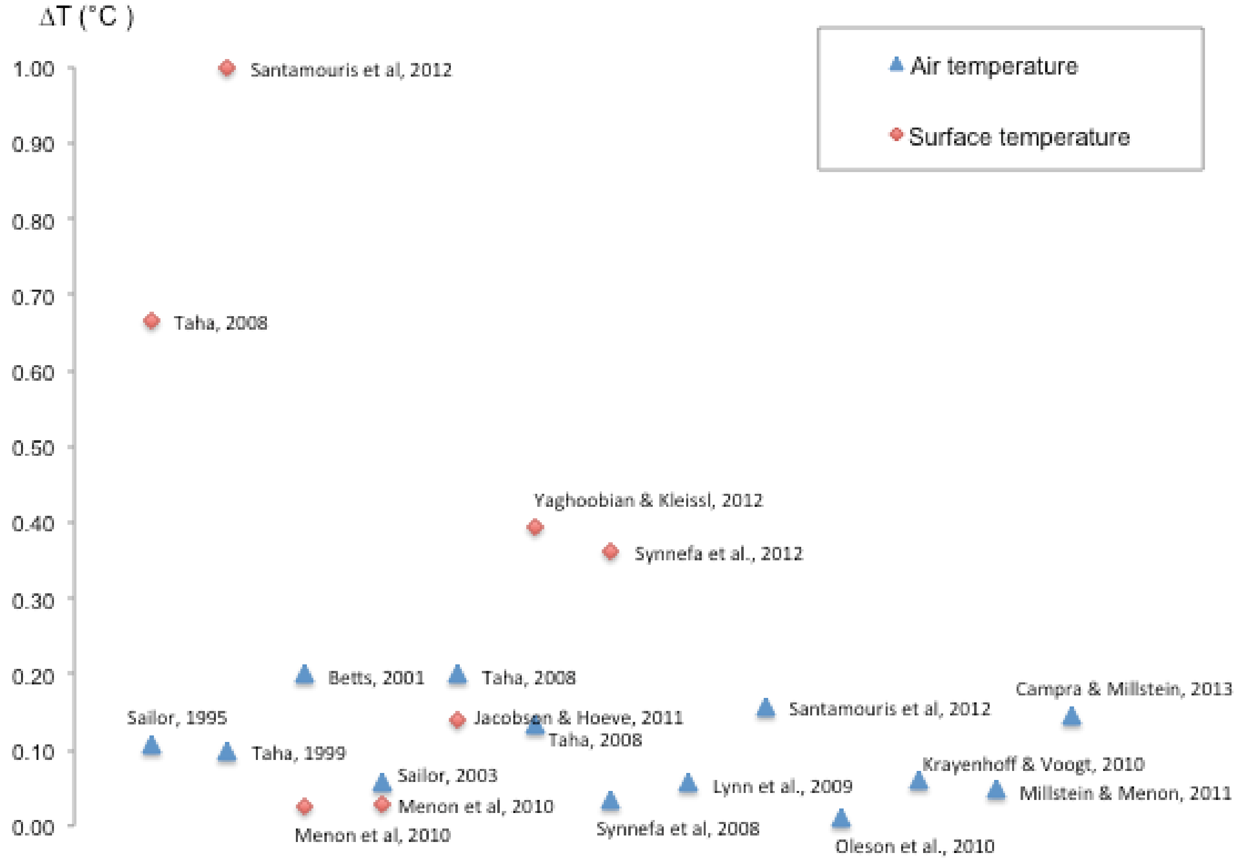

Figure 2 Comparison of normalized temperature changes due to 0.01 increase in albedo from existing studies

TABLE 4 Summary of albedo induced temperature changes (surface and air)

Albedo increase ($\Delta\alpha$)	$\Delta\alpha$ at pixel*	Summer daily max T_{air} reduction (°C)	Annual average T_{air} reduction (°C)	Average $T_{surface}$ reduction (°C)	Reference
0.08 in LA basin	0.14	1.5	N/A	N/A	Sailor, 1995 *(28)*
0.04 over 10 regions	0.15	0.5 – 1.5	N/A	N/A	Taha, 1999 *(49)*
0.1 due to deforestation	N/A	N/A	1 – 2	N/A	Betts, 2001 *(23)*
0.1 in urban albedo	0.1	0.14 – 0.58	N/A	N/A	Sailor, 2003 *(33)*
0.1 on roofs 0.25 on walls 0.08 on pavements	N/A	3	N/A	10	Taha, 2008 *(34)*
0.15 in urban albedo	0.15	2	N/A	N/A	Taha, 2008 *(50)*
0.45 on roofs	N/A	N/A	0.5 – 1.5	N/A	Synnefa et al, 2008 *(29)*
0.35 on impervious surface	0.35	1 – 2	N/A	N/A	Lynn et al., 2009 *(30)*
0.58 on roofs	0.58	N/A	0.56	N/A	Oleson et al., 2010 *(25)*
0.1 in urban albedo	0.003 globally 0.01 for US	N/A	N/A	0.008 globally 0.03 over US	Menon et al, 2010 *(24)*
0.59 on roofs	N/A	3.6	0.5 – 1.6	N/A	Krayenhoff & Voogt, 2010 *(41)*
0.02 – 0.11 in urban albedo	0.0 – 0.115	0.11 – 0.53	N/A	0.005 over U.S	Millstein & Menon, 2011 *(27)*
0.53 on roofs	– 0.0018	0.02	– 0.07	– 0.025	Jacobson & Hoeve, 2011 *(26)*
0.69 on roof	0.69	1.5 – 2	N/A	25	Synnefa et al., 2012 *(44)*
0.12 in an urban park	N/A	1.9	N/A	12	Santamouris et al, 2012 *(51)*
0.4 on ground	0.4	0.4	N/A	15.8	Yaghoobian & Kleissl, 2012 *(42)*
Greenhouse farming	0.09	1.3	0.25	N/A	Campra & Millstein, 2013 *(35)*

* pixel is the smallest spatial grid cell in the numerical simulation

Comparison of Results on Building Energy Consumption

The impact of changing urban surface albedos, particularly roof albedo modifications, on building energy consumption has been extensively studied and monitored for decades. A comparison of the resulting energy savings from some studies is presented in Table 5. Both cooling savings and heating penalties are reported for a square meter area of installed cool surface. In most cases, the heating penalties are smaller than savings from cooling energy, indicating a net energy savings from increasing the reflectivity of building surfaces. However, a few studies estimated a greater heating load than cooling demand in some regions with long winters, which offset the potential benefits of reflective roofs*(25)*. The energy savings from increased albedo on building energy exhibit great variation, depending on the building type, insulation, climate condition, and the specific cooling strategy.

TABLE 5 Summary of annual cooling savings and heating penalties due to increase in albedo

Albedo increase ($\Delta\alpha$)	Cooling savings (kWh/m^2)	Heating penalties (kWh/m^2)	Reference
0.46	8.4	N/A	Akbari (2003)
0.65	9 – 48	0.2–17	Synnefa et al., 2007 *(39)*
0.42	23.9	N/A	Jo et al., 2009 *(40)*
0.01	0.07 TW globally	0.69 TW globally	Oleson et al., 2010 *(25)*
0.69	1 – 3	0.7 – 2.6	Synnefa et al., 2012 *(44)*
0.40	33.1	N/A	Yaghoobian & Kleissl, 2012 *(42)*

5. CONCLUSIONS

This paper presents a state-of-the-art review of the existing research on the impacts of albedo. Different analytical approaches and modeling work are synthesized and discussed. A comparative analysis of results from different studies is performed, demonstrating the impacts of changing urban surface albedo on temperature, radiative energy budget and urban energy consumption. This analysis will serve as a good reference for comparing the climate impacts of urban albedo.

Results from analytical models and numerical simulations reported here support the argument that increasing the surface albedo has a local cooling effect by increasing the total outgoing radiation. Although many studies focus on a specific case of albedo enhancement, they support the use of numerical meteorological modeling as a tool for monitoring the radiative budget and climate feedbacks. While most of the existing studies examined the effect of urban surface albedo, particularly roof albedo modifications (e.g. cool roofs), the impacts of pavement albedo have not been separated from that of roof albedo. Pavement albedo is much more complicated than roof albedo in that its impacts involve more interactions with adjacent buildings, urban geometry, vegetation, traffic, etc. Further research is needed to better understand the impacts of paved surfaces and compare with that of roof surfaces.

Limitations and recommendations

While the analytical models and numerical simulations presented in this analysis can quantify climatic feedback and building energy consumption due to changes in surface albedo, limitations exist regarding the inadequacy of model resolution, lack of consistency in temporal-spatial scales, natural variability, etc. These limitations led to different, sometimes even contradictory (e.g.

heating penalty of increasing albedo) results.

Model resolution

The representations of albedo applied to mesoscale models are currently not adequate for the complex radiative exchange within a real urban canopy. In many mesoscale models, albedos implemented are determined only roughly and variations in the urban surface albedo have not usually been considered. Most likely the results obtained depend on the strength of the signal and the resolution of the modeling domain that may not represent the true effect of an increase in urban albedo, since urban areas were not explicitly resolved. Thus, in order to improve the model performance, a better parameterization of urban configuration, geographical and surface properties, seems to be necessary.

Natural variability and larger-scale impacts

The climate system is very complicated, introducing additional uncertainties to modeling the albedo impacts. Due to natural variability and the potential reversed impacts observed in some regions, it is essential to understand and quantify the feedbacks between land-surface energy exchange and surface albedo change at multi-scale.

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