Radiative forcing and temperature response to changes in urban albedos and associated CO_2 offsets

Surabi Menon[1], Hashem Akbari[1], Sarith Mahanama[2], Igor Sednev[1] and Ronnen Levinson[1]

[1]Lawrence Berkeley National Laboratory, Berkeley, CA, USA

[2] Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Abstract

The two main forcings that can counteract to some extent the positive forcings from greenhouse gases from pre-industrial times to present-day are the aerosol and related aerosol-cloud forcings, and the radiative response to changes in surface albedo. Here, we quantify the change in radiative forcing and surface temperature that may be obtained by increasing the albedos of roofs and pavements in urban areas in temperate and tropical regions of the globe. Using the catchment land surface model (the land model coupled to the GEOS-5 Atmospheric General Circulation Model), we quantify the response of the total outgoing (outgoing shortwave+longwave) radiation to urban albedo changes. Globally, the total outgoing radiation increased by 0.5 Wm^{-2}, and temperature decreased by ~0.008 K for an average 0.003 increase in albedo. For the U.S. the total outgoing total radiation increased by 2.3 Wm^{-2}, and temperature decreased by ~0.03 K for an average 0.01 increase in albedo. These values are for the boreal summer (June-July-August). Based on these forcings, the expected emitted CO_2 offset for a plausible 0.25 and 0.15 increase in albedos of roofs and pavements, respectively, for all global urban areas, was found to be ~ 57 Gt CO_2. A more meaningful evaluation of the impacts of urban albedo increases on climate and the expected CO_2 offsets would require simulations which better characterizes urban surfaces and represents the full annual cycle.

Key words: Radiative forcing, urban albedo, CO_2 offsets

Submitted to: Environmental Research Letters

1. Introduction

The radiative forcing associated with land use and land cover change from pre-industrial times to present-day due to land albedo modifications is about -0.2 ±0.2 Wm^{-2} (Forrester *et al* 2007). This value is small but of opposite sign compared to the 1.6 Wm^{-2} forcing from CO_2. Regionally, changes to radiative forcing from surface albedo changes can be much larger. For an increase in surface albedo of 0.09, due to an expansion of greenhouse horticulture in southeastern Spain, Campra *et al* (2008) show a strong negative forcing of an average of -19.8 Wm^{-2}. Alpert *et al* (2007) suggest that urban areas receive about 8% less annual surface solar irradiance (~ 12 Wm^{-2}) than rural areas due to increased aerosol emissions in urban areas. Similar to the urban heat island effect, where urban areas are generally warmer than surrounding rural locations due to urban development (Oke 1982) and indicate a quantifiable increase in surface temperatures (Jones *et al* 1990), radiation budgets in urban areas may be quite different from those in rural locations. These may be due to a variety of factors that include emissions (both GHGs and aerosols), lack of vegetation, urban development and surface albedos.

Here, we examine how surface albedos over urban areas affect radiative forcing. Over 60% of typical U.S. urban surfaces are pavements and roofs (Akbari *et al* 2003) and Rose *et al* (2003) estimate that roofs and paved surfaces constitute about 20-25 % to 29-44%, respectively of most metropolitan U.S. urban surfaces. Thus the potential modification to albedos of urban surfaces can have a strong effect on radiative forcing and it becomes useful to quantify this effect since it can to some extent mitigate or delay some of the consequences of warming from CO_2 emissions.

Using existing data, Akbari *et al* (2003) suggest that the albedos of roofs and pavements can be increased by at least 0.25 and 0.15, respectively, resulting in an increase of 0.1 in the albedo of urban areas. In order to estimate the benefits that may be obtained from changing urban albedo in terms of CO_2 emission offsets, Akbari *et al* (2009) (hereafter AK09) derived an equivalency relationship between the radiative forcing of CO_2 versus the radiative forcing obtained if the albedos of all urban land areas were increased by 0.1. To obtain the equivalency relationship, the radiative forcing of CO_2 was approximated as 0.91 kW/tonne of emitted CO_2 based on four different modeling studies. For a 0.01 mean increase in global albedo the average global radiative forcing was calculated as -1.27 W m^{-2} based on (a) observations, (b) a modeling study and (c) estimated changes in the radiation budget for the Earth-atmosphere system. AK09 found that increasing the reflectance of a roof by 0.25 could offset 64 kg CO_2 per m^2 of roof area (i.e., 16 m^2 of cool roof area to offset 1 tonne of emitted CO_2). (Note that for an albedo change of 0.4, a white roof replacing a dark roof, the CO_2 offset can be 100 kg m^{-2}.) For cool pavements with a proposed albedo increase of 0.15, the emitted CO_2 offset was equal to 38 kg CO_2 per m^2 of pavement area (i.e., 26 m^2 of cool paved area to offset 1 tonne of emitted CO_2). The estimate of the global emitted CO_2 offset potentials for cool roofs and cool pavements is calculated to be about 24 Gt of CO_2 and 20 Gt of CO_2, respectively, giving a total global emitted CO_2 offset potential range of 44 Gt of CO_2.

Assuming a plausible growth rate of 1.5% in the world's CO_2-equivalent emission rate, the 44 Gt CO_2-equivalent offset potential for cool roofs and cool pavements would counteract the effect of the growth in CO_2-equivalent emission rates for 11 years. The offset provided by cooling urban surfaces affords a significant delay in climate change during which further measures to improve energy efficiency and sustainability can be achieved. Here, we extend the study of AK09 by using the land surface component of a global model to quantitatively estimate the effect of urban albedo change on radiative forcing and temperature globally. We compare the changes obtained with those based on approximate calculations in AK09.

2. Methodology

We use the Catchment Land Surface Model (CLSM, Koster *et al* (2000)), the land surface model coupled to the NASA Goddard Earth Observing System Model, Version 5 Atmospheric General Circulation Model (GEOS-5 AGCM, Renecker *et al* (2008)), to quantify the effects of an increase in urban albedo on radiative forcing and temperature in the offline mode (not coupled to GEOS-5 AGCM). The CLSM computes surface fluxes and surface variables through a comprehensive surface water and energy budget analysis at the land surface. The CLSM uses topographically defined hydrologic catchments as computational elements at the land surface and the model accounts for horizontal heterogeneity of soil moisture within the computational catchment. This approach better characterizes surface properties.

In general, characteristic urban surface albedos are in the range between 0.09 to 0.27 with a mean of ~ 0.14 for urban centers (Oke 1988). The "urban extents mask" of Columbia University's Global Rural-Urban Mapping Project (GRUMP) classifies land as either urban, rural, or neither (e.g., ice-covered) based on a population density and presence of nighttime lights (GRUMPv1). Its 0.5° ×0.5° resolution raster was used to identify all urban areas, which comprise about 2.5% of global land area and 0.7% of global surface area.

The CLSM uses a surface albedo parameterization scheme that incorporates climatologies of visual and near-infrared surface reflectance of the Moderate Resolution Imaging Spectroradiometer (MODIS) observations, leaf area index, greenness, sun angle and a snow albedo scheme. To characterize the change in reflectance over urban surface areas, the climatological values of MODIS observations were modified. Monthly climatological values of global snow-free surface reflectance in two broad spectra (UV to visible, 0.3 - 0.7 μm; near-infrared, 0.7 - 5.0 μm) at a resolution of 2.5'x2.5' used in GEOS-5 was available. A hypothetical surface reflectance data set in which the UV to VIS and NIR reflectances of urban areas were each increased by 0.1 to represent the effect of whitening urban surfaces was then created. An example of the original and the modified surface UV to VIS reflectance data set is shown in figure 1 for June.

For the simulations used in this work, the CLSM was forced using bias-corrected surface meteorological forcings. The meteorological forcing was obtained from GSWP-2 (second global soil wetness project (Dirmeyer *et al* 2006)). The surface meteorological forcings consists of 3-hourly, 1° x 1° global values for shortwave (downward) (0.15-5 μm), longwave (downward) (5-120 μm), 2m air temperature, 2m specific humidity, total rainfall, snowfall, convective rainfall, wind, and surface pressure. The CLSM was forced with GSWP-2 forcings and the resulting output is a complete set of surface energy and water balance variables. These include surface hydrological variables, evaporation, surface albedo, surface temperatures, surface water and energy budgets, amongst other variables. By design, in the offline mode, the feedback of the sensitivity of the modifications to the atmosphere is removed. This may allow for the surface terms to be evaluated alone, though any land-atmosphere feedback effects would be missing. Nevertheless, the offline simulations provide a useful insight on how the changes in surface albedo due to urban build up could affect land surface variables and fluxes. Full coupling between the CLSM and the AGCM was not performed in this study due to the extensive simulation time and computational efforts required.

3. Results

As a first step, the CLSM was forced in the offline mode using bias-corrected GSWP-2 surface meteorological forcings for the period 1984-1995 (i.e. forced with reanalysis data) to evaluate the response of radiative forcing and surface temperature to the change in imposed surface reflectance. Four sets of simulations were performed and are described in table 1. These include a control simulation labeled as Control (which used the surface reflectances in its original form), a simulation with the modified surface albedos to mimic urban build up, labeled as Case A. Both Control and Case A simulations were performed on the catchment formulation of the 2^{o}x2.5^{o} resolution GEOS-5 AGCM. Additionally, two high-resolution (0.5^{o}x0.5^{o}) simulations similar to Control and Case A were also performed, labeled as Control H and Case AH, respectively. The high-resolution simulations require more intense computing efforts and thus the domain was restricted to the continental U.S. alone. All simulations were performed for three months (June to August) for 12 years. We choose the boreal summer period so that the expected climate response to changes in surface reflectance may be strong due to the larger number of urban areas in the NH and greater probability of occurrence of snow-free conditions.

Figure 2 shows the differences in surface albedo, surface temperature and outgoing shortwave radiation, between the Case A and Control, obtained from the average values over the simulation period (comprising 36 boreal summer months). The surface albedo is obtained from the ratio of total outgoing shortwave radiation (computed separately for each spectral band and snow and then aggregated) to incoming shortwave (downward) radiation. As can be seen in figure 2, in general, areas where the surface albedos have increased (top panel) indicate a decrease in surface temperature (middle panel) and an increase in outgoing shortwave radiation (OSR) (bottom panel) as expected. Changes to the total outgoing (outgoing shortwave + longwave) radiation (shown in figure 3) are dominated by the changes in the OSR field. Regionally, surface temperatures were reduced by a maximum of ~ 0.1 K (with an average reduction of 0.008 K) over domains that had an increase in albedo of up to 0.05 (with an average increase of ~ 0.003). The maximum increase in OSR was ~ 2.5 Wm^{-2}.

Several other fields, including the transpiration rate, surface energy fluxes (sensible heat flux, latent heat flux, ground heat flux), were also examined and differences were found to be small. Statistical significance of the differences (between Case A and the Control) was calculated for all fields to examine variables that may exhibit a significant difference. The significance, based on a Student's t-test, indicates high values (between 0.01 and 0.05) were mainly obtained for the radiation field (OSR) in regions with the surface albedo increases as expected. Differences for most other variables were not found to be significant at the 95% confidence interval level and are not discussed.

Figure 4 shows the absolute value of the standard deviation (based on differences between Case A and Control for the 36 months considered) for the variables listed in figure 2. Although the standard deviation for the change in surface albedo and OSR are smaller than the mean value, the standard deviation for temperature change is much larger and is close to the mean value. This is expected since changes to radiative forcing are a direct response to albedo changes, whereas temperature changes may be affected by more than one variable. When the surface albedo increases, net radiation at the surface decreases resulting in a decrease in latent heat fluxes (not shown) and surface temperatures. However, in the absence of land-atmosphere feedbacks in the offline mode, the resulting effect on surface temperature is relatively small because the 2m-air temperature from the boundary forcings tends to adjust the effects on surface temperature changes stemming from modified albedo.

In a recent study, Synnefa *et al* (2008) examined temperature changes from urban albedo changes over Athens, Greece. They found a decrease in the 2m noon temperature of 0.5 to 1.5 °C for an albedo change from 0.18 to 0.63 in climate simulations using MM5 (the fifth-Generation NCAR / Penn State mesoscale model). The horizontal resolution for the innermost nested domain resolved the city of Athens at the sub-km scale (0.67 km x 0.67 km). Their ~1 °C change in temperature was for a factor of 3.5 increase in albedo. In a different study, Campra *et al* (2008) examined temperature response to modified albedos due to greenhouse horticulture in Spain for the 1983-2006 time period. They obtain a surface temperature decrease of -0.29±0.12 ºC per decade for locations with greenhouse horticulture that had surface albedos of 0.28±0.05. The pasture surfaces had lower albedos of 0.19± 0.02 and a surface temperature increase of 0.40± 0.13 ºC per decade, giving a surface temperature decrease of 0.69 ºC per decade or ~0.069 ºC annual change for an albedo increase of 0.09.

For the results shown in figure 2, for a global average surface albedo increase of 0.003 a decrease in surface temperature of 0.008 K was obtained. The surface temperature response is higher than that of Campra *et al* (2008) (which may be expected since we only consider the boreal summer months). However, surface temperature differences from urban albedo changes quantified in this work cannot directly be compared to the results from Synnefa *et al* (2008) due to domain sizes and time period considered and since Synnefa *et al* consider the 2m air temperature response to changes in albedo. Jin *et al* (2005) have suggested that skin temperatures measured by satellite offer a better estimate of urban influences than do surface temperatures due to the weaker coupling between skin temperatures and the overlying atmosphere. The small change in surface temperature obtained here may be due to the overlying atmospheric column influence and the fact that the simulated changes were not resolving urban areas explicitly. To obtain an accurate surface temperature response from changes in urban albedo the strength of the signal must also be higher than the model variability. Since our simulations included only a small change in urban albedo we obtain a stronger response from the radiation fields as expected, compared to, for example, temperature. And as expected, changes in the radiative fluxes (OSR) obtained were significant and the standard deviations also smaller.

We further examined the signal to noise ratio of the various fields by evaluating the ratio of the mean difference between the fields (difference between modified albedo (Case A) and the control run) to the standard deviation of the control run. In general, year-to-year variability for the various fields examined appears to be small and thus increasing the sample frequency (runs that are of longer duration) would not modify the results. Thus, the response obtained is probably related to 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, especially for the surface temperature fields, since urban areas were not explicitly resolved.

We next examine differences in simulations for similar cases but at a finer resolution (0.5° x 0.5°). Resolutions finer than this were not feasible in the present study. Mean values of differences between Case AH and Control H for surface albedo, surface temperature and total outgoing radiation are shown in figure 5 and may be compared to the mean differences shown in figure's 2 and 3 for the coarse resolution runs. To quantitatively understand differences in the two sets of simulations based on resolution changes, average values and differences (modified albedo versus control) between simulations for a few variables are listed in tables 2 to 5 for a few locations (California, Florida and Texas) and the U.S. The choice of locations was based on areas where sufficient data points exist to provide a meaningful sample for the coarse and fine resolutions.

As shown in the tables 2 to 5, an expected decrease in temperature accompanied by an increase in total outgoing radiation is evident with an increase in albedo for all locations. The three locations (California, Florida and Texas) and the U.S. do indicate higher total outgoing radiation values for larger increase in urban albedo but results obtained appear to be resolution independent. A larger decrease in temperature for the higher albedo case was not necessarily evident. In general, it appears that increasing horizontal resolution from 2°x2.5° to 0.5°x0.5° did not significantly affect results in most locations since the fine resolution run was still not explicitly resolving urban surfaces. As illustrated in Synnefa *et al* (2008), resulting climate impacts may need to be examined at the sub-km scale to obtain the full response to the imposed albedo change. Based on the simulations performed at the two resolutions, we suggest that the radiative flux response to urban albedo changes is stronger (compared to the temperature or other fields), as expected, regardless of resolution. However, to obtain a meaningful temperature response, the domain should resolve urban areas and include full feedbacks between the land and atmosphere.

4. Discussion

We now compare results obtained with the CLSM with those based on approximate calculations in AK09. This comparison is only approximate as the AK09 results are based on annual changes, whereas results shown here are for the boreal summer months. AK09 found a decrease in the top-of-the-atmosphere (TOA) radiative forcing of 1.27 Wm^{-2} for a 0.01 increase in solar reflectance of the surface. We use RF01A to define the radiative forcing for a 0.01 change in albedo. This RF01A estimate of -1.27 Wm^{-2} is based on the annual average global insolation and cloud cover. With the CLSM, as shown in table 5, for an average increase of 0.012 in urban albedo an increase in total outgoing radiation of 2.15 Wm^{-2} was obtained for the U.S. This results in a RF01A value of 1.8 Wm^{-2} for the continental U.S. For the global scale, for an average increase in surface albedo of 0.003, the total outgoing radiation increased by ~ 0.5 Wm^{-2} (shown in figure 3). The RF01A values for the global scale (based on changes in radiative forcing to surface albedo for Case A versus Control) are shown in figure 6. The average RF01A value obtained globally is 1.63 Wm^{-2} (about 10% smaller than the value for the U.S.).

The simulated response (based on the CLSM), in terms of the radiative flux changes to an increase in urban albedo, is higher compared to that indicated in AK09. Some differences may be expected based on regional changes in cloud cover and insolation and seasonal changes since only values for the boreal summer months are included for the simulations with the CLSM (that may have a stronger response based on seasonality changes as also indicated by Campra *et al* (2008)). However, both studies indicate a reduction in radiative forcing or an increase in total outgoing radiation for an increase in urban albedo.

In order to compare the CO_2 emission offsets obtained for changing the roofs and pavements of all urban surfaces with that calculated in AK09, for the radiative forcing change of 1.63 Wm^{-2} obtained from the CLSM we show corresponding values in table 6. As shown in table 6, we obtain a total offset of 57 Gt of emitted CO_2 if albedos of urban roofs and pavements were to be increased by 0.25 and 0.15, respectively. AK09 obtained an offset of 44 Gt of CO_2. Our values are about 30% higher since here we consider only the boreal summer months, whereas AK09 based their values for annual changes. For annual changes, we expect a lower number, since winter savings could be lower in some locations. However, these calculations do indicate that the values in AK09 are comparable to those that are obtained with the CLSM.

5. Conclusions

To understand and quantify the effects of changes to radiative forcing and temperature if the albedos of urban areas were increased for cool roof and cool pavements, we performed several sets of simulations with the land component (CLSM) of the NASA GESO-5 climate model. The simulations were designed to understand the effect of an increase in urban albedo of 0.1 on radiative forcing and temperature. It was found that the temperature decreased by ~ 0.01 K globally for an average increase of 0.003 in surface albedo. Other climate variables such as surface energy fluxes (latent and sensible heat), evaporation, etc. indicated smaller changes that were not significant. Only changes to the radiation budget were significant, and an average increase in total outgoing radiation of ~ 0.5 Wm^{-2} was obtained. The RF01A value obtained (based on the radiative forcing for a 0.01 increase in the surface albedo) is ~ 1.63 Wm^{-2}. These values are based on the Northern Hemisphere summer averages. The radiative forcing obtained for a 0.01 increase in urban albedo based on the results from AK09 was slightly lower (RF01A

$=1.27\ Wm^{-2}$) than that estimated from our detailed modeling study, since the values in AK09 were based on annual values for mean global cloud cover and insolation and are thus not seasonal. Based on the radiative forcings from AK09 and this work, the potential emitted CO_2 offset for a 0.25 and 0.15 increase in roofs and pavements, respectively, in urban areas are about 44 and 57 Gt of CO_2, respectively. If the annual cycle was considered in this work, the offset may be lower and more comparable to that from AK09. Both studies indicate a qualitatively similar response of a reduction in radiative forcing or an increase in total outgoing radiation for an increase in urban albedo.

Although it would be ideal to couple the CLSM with GEOS-5 in an interactive manner to understand how land-atmosphere feedbacks may impact the results we obtain, the first task was to understand if differences obtained between the modified albedo simulation and the control were significant for the variables examined (surface temperature, evaporation, radiation budgets, etc.) and if the model resolution would make a difference. Examining coupled simulations (CLSM coupled to GEOS-5) at a fine resolution requires extensive simulation time and computational efforts that were not feasible for this study especially since the small perturbations in albedo resulted in small differences that were mainly significant for the radiation fields. Future work will include simulations with a fully coupled climate model at a high resolution (to explicitly resolve urban surfaces) and would include seasonality so that local climate impacts and expected CO_2 offsets may be evaluated more meaningfully.

Acknowledgments

This work was supported by the California Energy Commission (CEC) through its Public Interest Energy Research Program (PIER), and by the Assistant Secretary for Energy Efficiency and Renewable Energy at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231. The authors wish to acknowledge the support and guidance from staff of the California Energy Commission Project manager, Guido Franco; and PIER Energy-Related Environmental Research manager, Linda Spiegel. Commissioner Arthur Rosenfeld of California Energy Commissioned helped with problem formulation and analysis. We especially acknowledge support from Randy Koster of NASA GSFC, for advice and help with the simulations performed in this work.

References

Akbari, H., S. Menon, and A. Rosenfeld. 2009. "Global Cooling: Increasing World-wide Urban Albedos to Offset CO_2," *Climatic Change*, 94, 3-4, 275-286, doi 10.1007/s10584-008-9515-9.

Akbari, H., L. S. Rose, and H. Taha. 2003. "Analyzing the land cover of an urban environment using high-resolution orthophotos," Landscape and Urban Planning, 63: 1-14.

Alpert, P. and P. Kishcha, 2007: Quantification of the effect of urbanization on solar dimming. *Geophys. Res. Lettr*., 35, doi:10.1029/GL033012.

CRMD. 2007. Cool Roof Material Database. http://eetd.lbl.gov/CoolRoofs/.

Campra, P., M. Garcia, Y. Canton, A. Palacios-Orueta, 2008: Surface temperature cooling trends and negative radiative forcing due to land use change toward greenhouse farming in southeastern Spain. *J. Geophys. Res*., 113, doi:10.1029/2008JD009912.

Dirmeyer, P.A., M. Zhao, Z. Guo, T. Oki and N. Hanasaki, 2006: GSWP-2: Multimodel analysis and implications for our perception of the land surface. *Bull. Amer. Meteor. Soc*., 87, 1381-1397.

Forster, P., et al., Radiative forcing of climate change, in Climate Change 2007: The Physical Science Basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, pp. 129–234, Cambridge Univ. Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

GRUMPv1: Center for International Earth Science Information Network (CIESIN), Columbia University; International Food Policy Research Institute (IFPRI), the World Bank; and Centro Internacional de Agricultura Tropical (CIAT), 2004. Global Rural-Urban Mapping Project (GRUMP): Palisades, NY: CIESIN, Columbia University. Available at http://sedac.ciesin.columbia.edu/gpw.

Jin, M. R. E. Dickinson, D-L Zhang, 2005: The Footprint of Urban Areas on Global Climate as Characterized by MODIS, *J. Climate*, 18, 1551-1565.

Jones, P.D., P.Y. Groisman, M. Coughlan, N. Plummer, W.-C. Wang, T.R. Karl, 1990:. Assessment of urbanization effects in time series of surface air temperature over land, *Nature*, 347, 169–172.

Koster, R. D., M. J. Suarez, A. Ducharne, M. Stieglitz, and P. Kumar. 2000. A catchment-based approach to modeling land surface processes in a GCM, Part 1, Model Structure, *J. Geophys. Res.*, 105, 24809-24822.

Oke, T.R. 1988: The urban energy balance, *Progress in Physical Geography*, 12, 471-508.

Oke, T.R. 1982: The energetic basis of the urban heat island, *Quart. J. Roy. Meteor. Soc.*, 108, 1–24.

Rienecker, M.M, M.J. Suarez, R. Todling, J. Bacmeister, L. Takacs, H.-C. Liu, W. Gu, M. Sienkiewicz, R.D. Koster, R. Gelaro, I. Stajner, and E. Nielsen, 2008: *The GEOS-5 Data Assimilation System - Documentation of Versions 5.0.1, 5.1.0, and 5.2.0.* NASA/TM-2007-104606, Vol. 27.

Rose, L. S, H. Akbari, and H. Taha. 2003. “Characterizing the Fabric of the Urban Environment: A Case Study of Greater Houston, Texas,” *Lawrence Berkeley National Laboratory Report LBNL-51448*, Berkeley, CA.

Synnefa, A., A. Dandou, M. Santamouris and M. Tombrou, 2008: On the use of cool materials as a heat island mitigation strategy, *J. Appl. Meteorol. Clim.*, 47:2846–2856.

Table 1. Description of the GEOS-5 AGCM simulations

Simulation	Resolution	Surface Albedo	Domain
Control	2°x2.5°	Original	Global
Case A	2°x2.5°	Modified urban areas	Global
Control H	0.5°x0.5°	Original	Continental U.S.
Case AH	0.5°x0.5°	Modified urban areas	Continental U.S.

Table 2. California Results. Mean values and differences between simulations (modified albedo and control) for the coarse (2ºx2.5º horizontal resolution) and fine (0.5ºx0.5º horizontal resolution) model for surface temperature (K), surface albedo, total outgoing radiation (Wm^{-2}), outgoing longwave radiation (OLR) (Wm^{-2}), and outgoing shortwave radiation (OSR) (Wm^{-2}). Results are based on average values for 12 years of simulations for June to August. The spatial domain chosen was for **California** (36.25º to 42.25º N and 115.25º to 124.25º W).

Variables	Control H	Control	Case AH	Case A	Case AH- Control H	Case A – Control
Surface temperature	295.08	293.64	295.02	293.59	-0.06	-0.05
Surface albedo	0.195	0.179	0.205	0.194	0.01	0.015
Total outgoing radiation	479.3	465.1	481.3	468.2	2.0	3.1
OLR	431.9	423.2	431.6	422.9	-0.3	-0.3
OSR	47.4	41.9	49.7	45.3	2.3	3.4

Table 3. Florida Results. Similar to Table 2 but for **Florida** (24.25º to 31.25º N and 87.25º to 79.25º W)

Variables	Control H	Control	Case AH	Case A	Case AH- Control H	Case A – Control
Surface temperature	300.67	300.74	300.61	300.69	-0.06	-0.05
Surface albedo	0.171	0.169	0.195	0.198	0.024	0.029
Total outgoing radiation	495.9	495.9	500.1	501.2	4.2	5.3
OLR	463.7	464.1	463.3	463.7	-0.4	-0.4
OSR	32.2	31.8	36.8	37.5	4.6	5.7

Table 4. Texas Results. Similar to Table 2 but for **Texas** (25.25º to 36.75º N and 93.25º to 106.75º W)

Variables	Control H	Control	Case AH	Case A	Case AH- Control H	Case A – Control
Surface temperature	299.91	299.72	299.86	299.69	-0.05	-0.03
Surface albedo	0.214	0.215	0.224	0.223	0.01	0.008
Total outgoing radiation	505.7	504.9	507.4	506.3	1.7	1.4
OLR	459.8	458.8	459.5	458.6	-0.3	-0.2
OSR	45.9	46.1	47.9	47.7	2.0	1.6

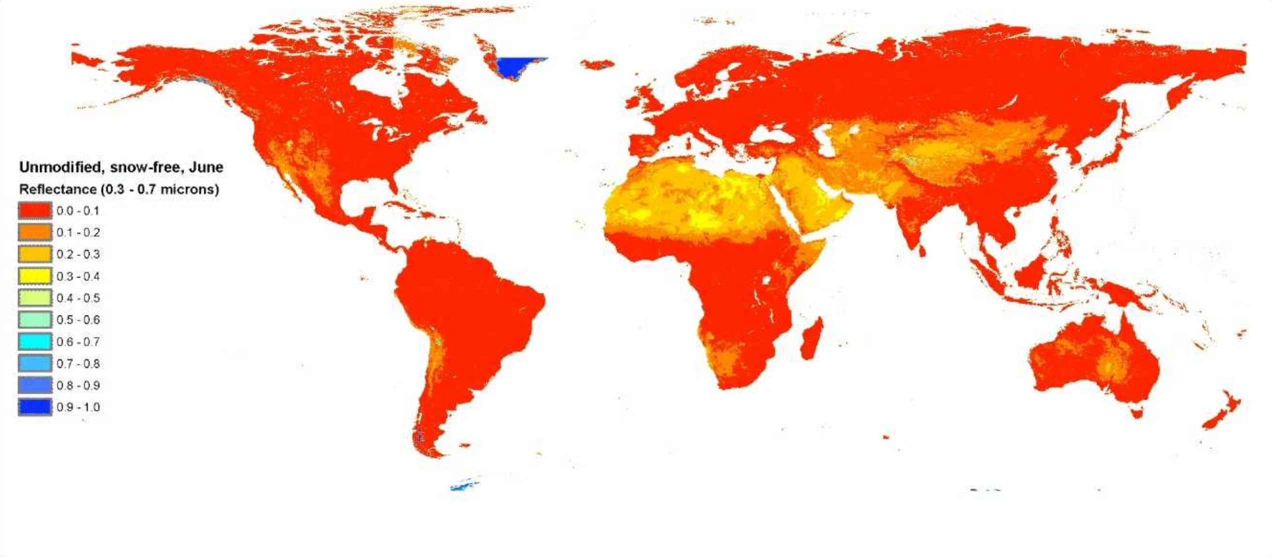
Table 5. U.S. Results. Similar to Table 2 but for the **U.S.** (25.25º to 48.75º N and 67.75º to 124.75º W). Also included are the values for the radiative forcing obtained for a 0.01 change in urban albedo (RF01A).

Variables	Control H	Control	Case AH	Case A	Case AH- Control H	Case A – Control
Surface temperature	295.17	295.15	295.14	295.12	-0.03	-0.03
Surface albedo	0.196	0.191	0.207	0.204	0.011	0.013
Total outgoing radiation	472.6	471.0	474.6	473.3	2.0	2.3
RF01A					1.8	1.8
OLR	431.8	431.7	431.6	431.5	-0.2	-0.2
OSR	40.8	39.3	43.0	41.8	2.2	2.5

Table 6: Equivalent CO_2 offsets based on the radiative forcings obtained for an increase in urban albedos

Item	Value from this work	Value from AK09
Radiative forcing for a 0.01 albedo increase	1.63 Wm^{-2}	1.27 Wm^{-2}
Atmospheric CO_2 equivalent for 0.01 urban albedo increase	−1.79 kg CO_2/m^2 urban area	−1.40 kg CO_2/m^2 urban area
Emitted CO_2 equivalent offset for 0.01 increase in urban albedo	−3.26 kg CO_2/m^2 urban area	−2.55 kg CO_2/m^2 urban area
Emitted CO_2 offset for increasing roof albedo by 0.25	−82 kg CO_2/m^2 roof area	−64 kg CO_2/m^2 roof area
Emitted CO_2 offset for increasing roof albedo by 0.40 (white roof)	−130 kg CO_2/m^2 roof area	−100 kg CO_2/m^2 roof area
Emitted CO_2 offset for increasing pavement albedo by 0.15	−49 kg CO_2/m^2 roof area	−38 kg CO_2/m^2 roof area
Potential emitted CO_2 offset for cool roofs	31 Gt CO_2	24 Gt CO_2
Potential emitted CO_2 offset for cool pavements	26 Gt CO_2	20 Gt CO_2

Base Case Surface reflectance



Increase in surface reflectance

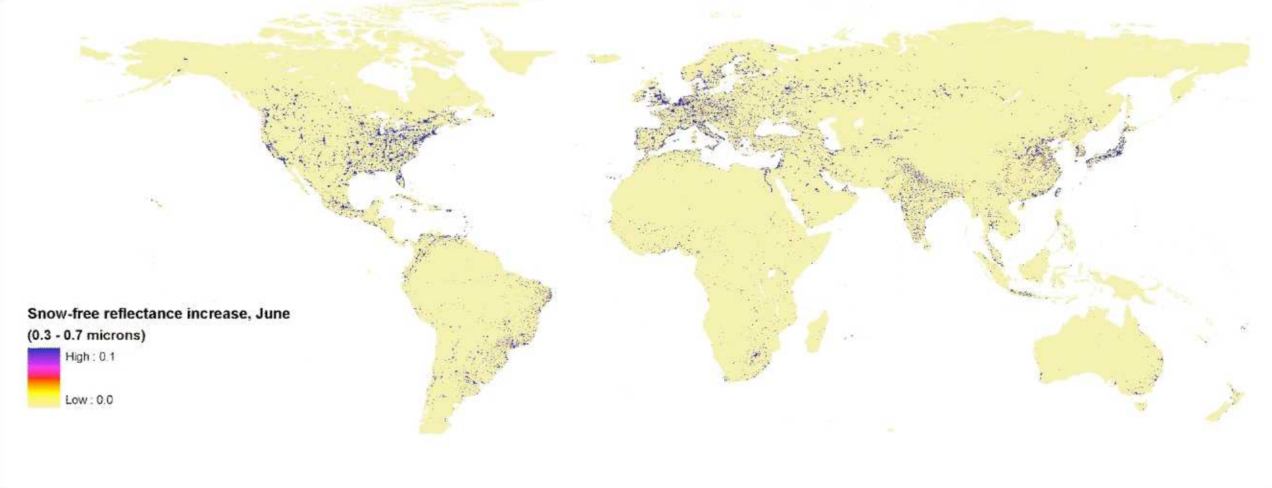
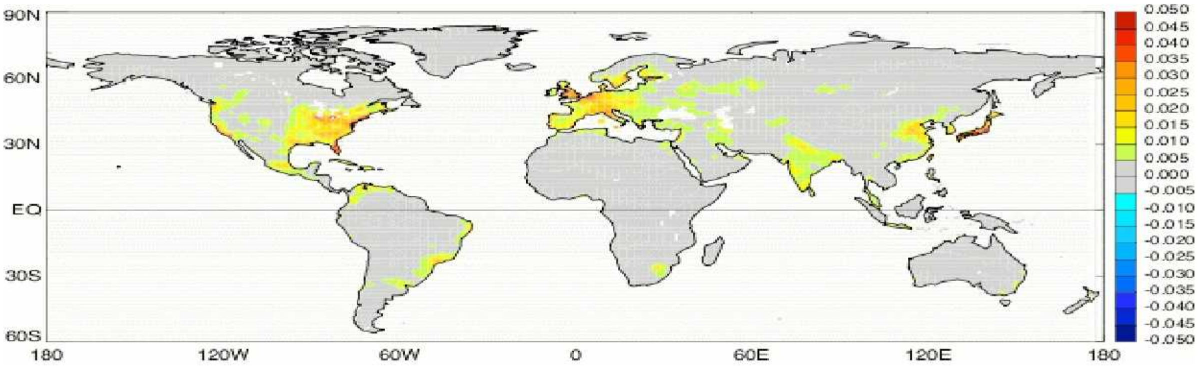
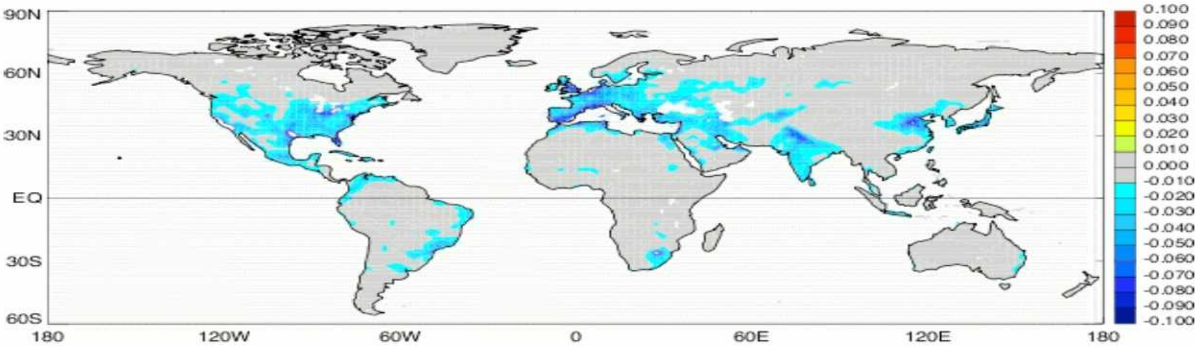


Figure 1. Initial values of surface reflectance (UV to visible) and corresponding increase for the selected urban locations for the month of June.

Surface albedo



Surface temperature



Outgoing shortwave radiation

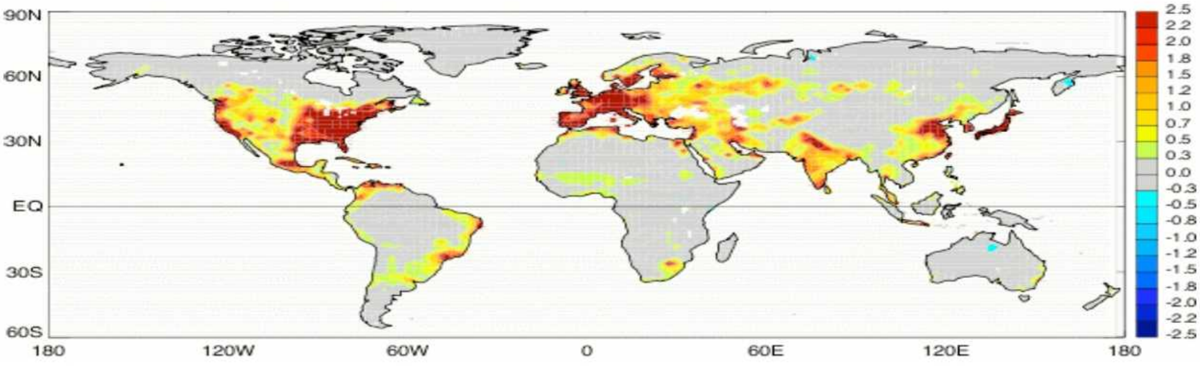


Figure 2: Differences between mean values of surface albedo, surface temperature (in K) and outgoing shortwave radiation (in Wm^{-2}) for Case A versus Control.

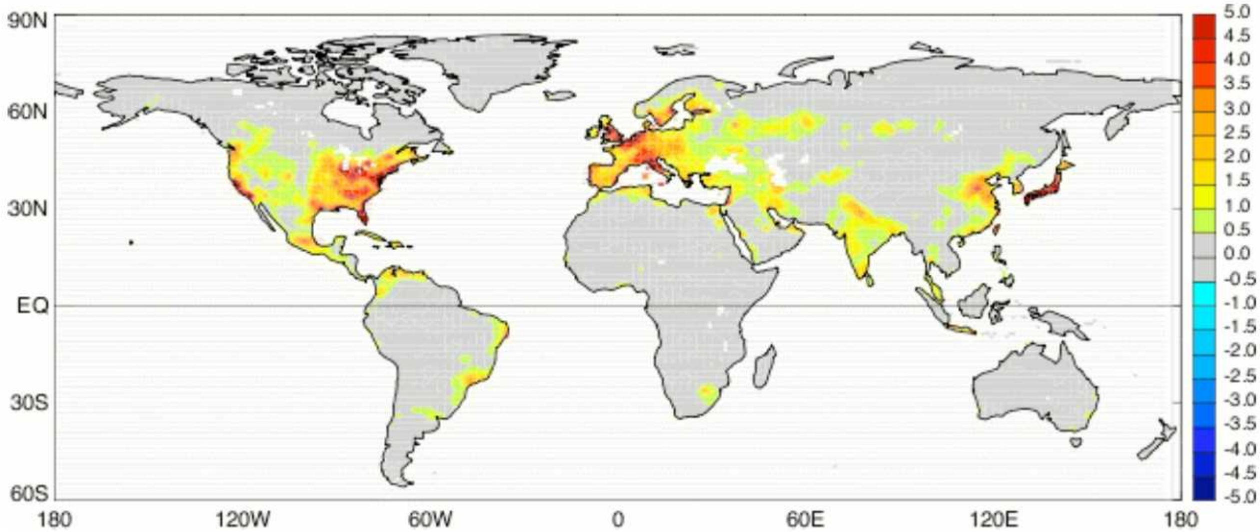
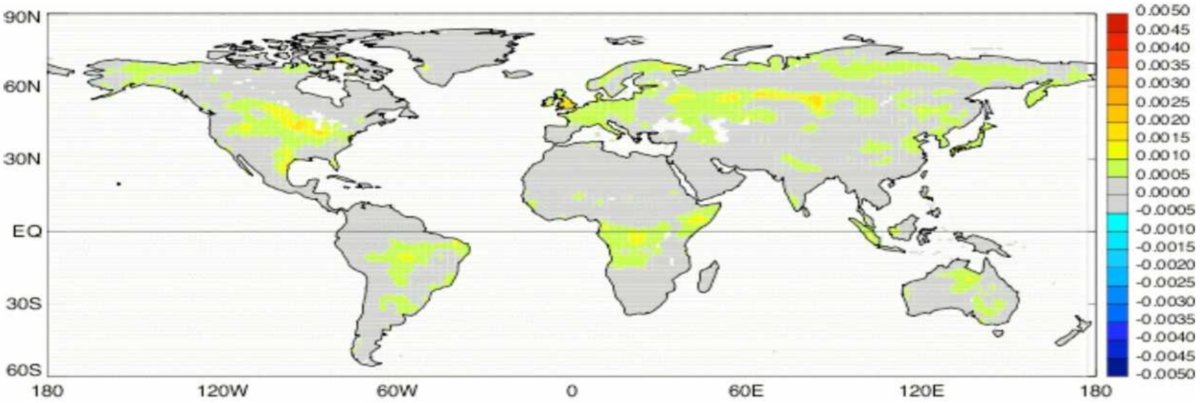
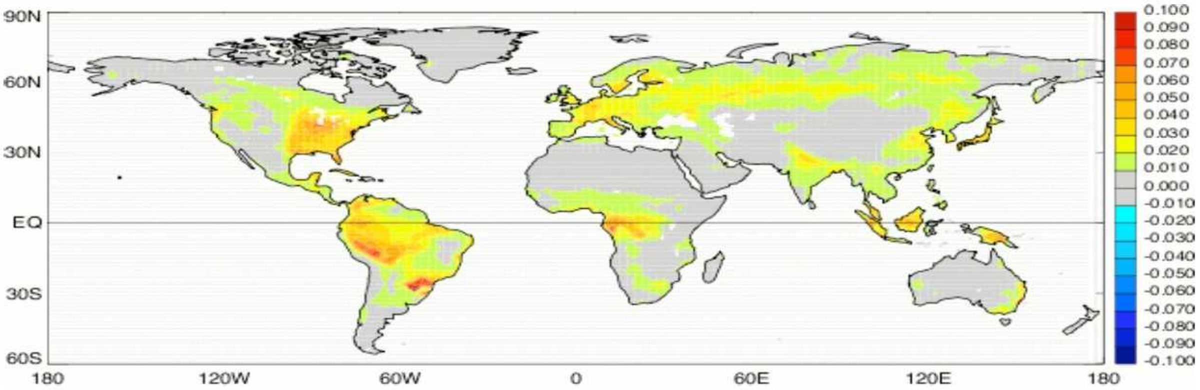


Figure 3: Similar to Figure 2 but for the total outgoing radiation (in Wm^{-2}).

Surface albedo



Surface temperature



Outgoing shortwave radiation

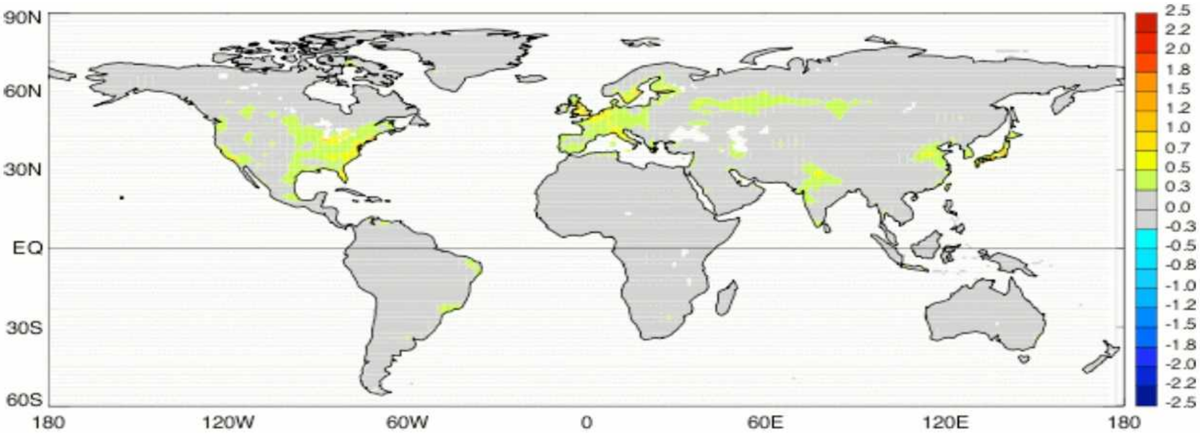
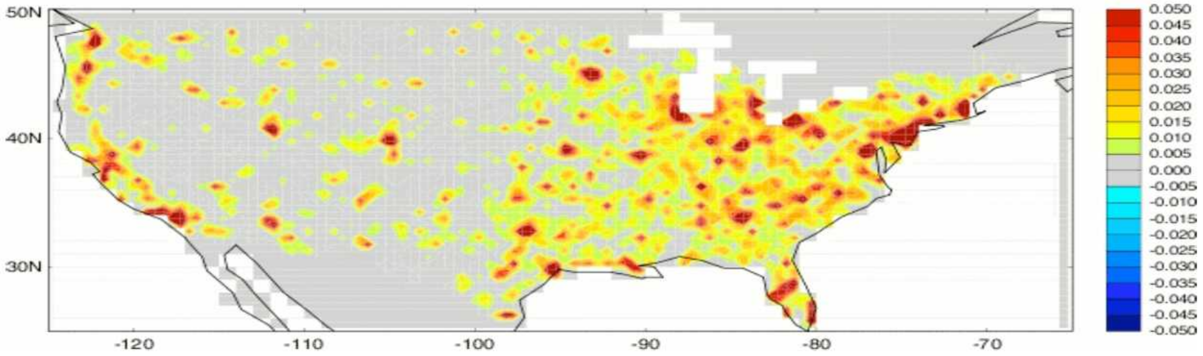
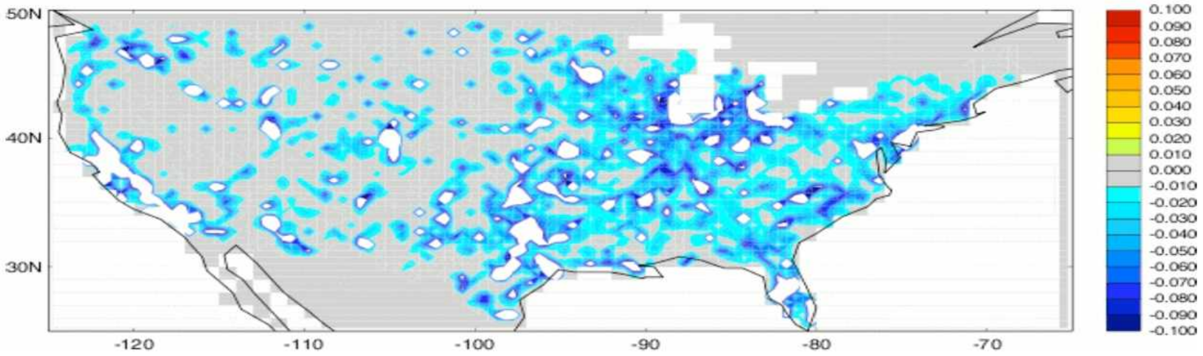


Figure 4: Similar to figure 2 but for the standard deviation of the mean differences.

Surface albedo



Surface temperature



Total outgoing radiation

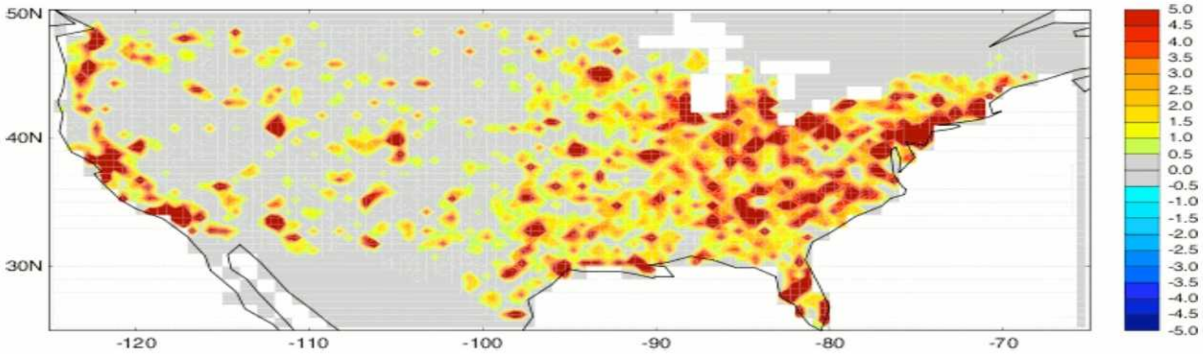


Figure 5: Differences between mean values of surface albedo, surface temperature (in K) and total outgoing radiation (in Wm^{-2}) for Case AH versus Control H.

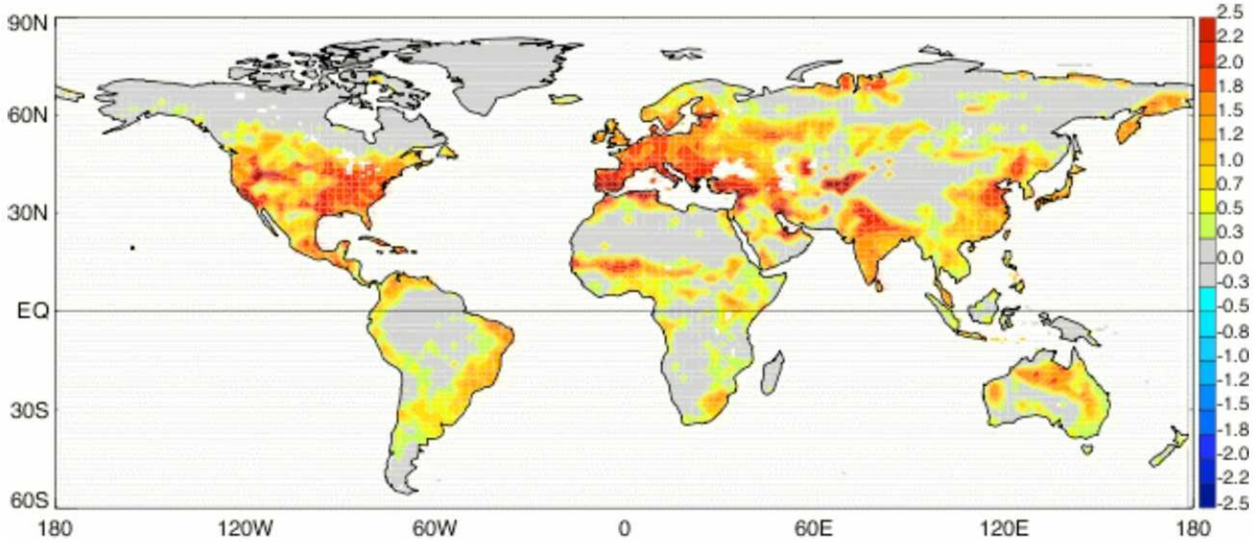


Figure 6: Similar to figure 2 but for the radiative forcing per 0.01 increase in albedo. Only values with significant differences in surface albedo were included.

“Radiative forcing and temperature response to changes in urban albedos and associated CO_2 offsets”

Authors:

Surabi Menon, smenon@lbl.gov
Hashem Akbari, HAkbari@ENCS.Concordia.CA
Sarith Mahanama, Sarith.P.Mahanama@nasa.gov
Igor Sednev, isednev@lbl.gov
Ronnen Levinson RML27@cornell.edu

Submitted to: Environmental Research Letters on 7/16/2009

POPULAR SUMMARY

Dark materials absorb more heat from the sun--as anyone who has worn a black t-shirt on a sunny day knows. Black surfaces in the sun can become much hotter than the most reflective white surfaces. Thus, staying comfortable in under a dark shingle roof often requires more air conditioning, yielding high energy bills. Alternatively, increasing reflectivity of incident solar radiation (surface albedo) on roofing materials by using whiter roofing materials could be an energy efficient solution to the rising energy cost. Given over 60% of typical U.S. urban surfaces are pavements and roofs, the potential modification to albedos of urban surfaces may have implications on radiative forcing, surface temperature and other surface variables.

A series of modeling experiments were performed to quantify the impact of changes to surface albedo on surface meteorological variables. Using the catchment land surface model (the land model coupled to the GEOS-5 Atmospheric General Circulation Model), we quantify the response of the total outgoing (outgoing shortwave+longwave) radiation to urban albedo changes. Globally, the total outgoing radiation increased by 0.5 Wm-2, and temperature decreased by ~0.008 K for an average 0.003 increase in albedo. For the U.S. the total outgoing total radiation increased by 2.3 Wm-2, and temperature decreased by ~0.03 K for an average 0.01 increase in albedo. These values are for the boreal summer (June-July-August).

Based on these forcings, the expected emitted CO_2 offset for a plausible 0.25 and 0.15 increase in albedos of roofs and pavements, respectively, for all global urban areas, was found to be ~ 57 Gt CO_2. A more meaningful evaluation of the impacts of urban albedo increases on climate and the expected CO_2 offsets would require simulations which better characterizes urban surfaces and represents the full annual cycle.

ABSTRACT

The two main forcings that can counteract to some extent the positive forcings from greenhouse gases from pre-industrial times to present-day are the aerosol and related aerosol-cloud forcings, and the radiative response to changes in surface albedo. Here, we

quantify the change in radiative forcing and surface temperature that may be obtained by increasing the albedos of roofs and pavements in urban areas in temperate and tropical regions of the globe. Using the catchment land surface model (the land model coupled to the GEOS-5 Atmospheric General Circulation Model), we quantify the response of the total outgoing (outgoing shortwave+longwave) radiation to urban albedo changes. Globally, the total outgoing radiation increased by 0.5 Wm-2, and temperature decreased by ~0.008 K for an average 0.003 increase in albedo. For the U.S. the total outgoing total radiation increased by 2.3 Wm-2, and temperature decreased by ~0.03 K for an average 0.01 increase in albedo. These values are for the boreal summer (June-July-August). Based on these forcings, the expected emitted CO_2 offset for a plausible 0.25 and 0.15 increase in albedos of roofs and pavements, respectively, for all global urban areas, was found to be ~ 57Gt CO_2. A more meaningful evaluation of the impacts of urban albedo increases on climate and the expected CO2 offsets would require simulations which better characterizes urban surfaces and represents the full annual cycle.