

Assessment of the Potential of Cool Materials to Contribute to the Mitigation of the Heat Island Effect in Athens

A. Synnefa¹, A. Dandou¹, M. Santamouris¹, M. Tombrou¹, N. Soulakellis²

¹*National and Kapodistrian University of Athens, Department of Applied Physics, Physics Department, Build. Physics 5, 15784, Athens, GREECE*

²*Department of Geography, University of the Aegean, Mytilene, Greece*

Corresponding author (E-mail: asynnefa@phys.uoa.gr, Tel: +302107274092, Fax: +302107295282)

ABSTRACT

The mitigation of the heat island effect can be achieved by the use of cool materials that are characterized by high solar reflectance and infrared emittance values. Several types of cool coatings, both commercially available and prototype ones have been tested. Their spectral reflectance, infrared emittance and surface temperature measurements reveal that these materials can be classified as “cool” materials with the ability to maintain lower surface temperatures. Cool materials can be used on buildings (roofs and walls) and other surfaces of the urban environment. Based on these results, a modeling study has been undertaken to assess the Urban Heat Island effect over Athens, Greece, a dense populated city, trying to analyze the impacts of large-scale increases in surface albedo on ambient temperature. Numerical simulations were performed by the ‘urbanized’ version of the non-hydrostatic PSU/NCAR Mesoscale Model (MM5, version V3-6-1). Two scenarios of modified albedo were studied a moderate and a high increase in albedo scenario. It was found that large-scale increases in albedo could lower ambient air temperatures by 2°C. The results of this study can help to promote the adoption of high albedo measures in building energy codes and urban planning regulations.

KEYWORDS

Heat island mitigation, cool materials, albedo, mesoscale modeling, ambient temperature

INTRODUCTION

The heat island effect is becoming increasingly more intense in urban areas causing thermal discomfort, increased energy demand and accelerating the formation of harmful smog. (Akbari et al. 1992; Santamouris et al. 2001, Taha et al., 1994) Several techniques have been proposed for the mitigation of the heat island effect. Among them the use of cool materials has gained a lot of interest during the past few years. Cool materials are characterized by high solar reflectance and infrared emittance values. Increasing either reflectance and/or emittance lowers a surface’s temperature, which in turn decreases the heat penetrating into the building, if it is a surface of the building envelope, or contributes to decrease the temperature of the ambient air as heat convection intensity from a cooler surface is lower. City scale application of cool materials will increase surface albedo. This means that surface temperatures will be lower as well as near surface air temperatures. Field-measurements and modeling studies support these conclusions. Direct field observations verify the impact of high albedo surfaces on near surface air

temperatures. Experimental measurements were carried out at White Sands Monument in New Mexico, an area that has a high albedo (≈ 0.6) because its surface is composed of white gypsum and little vegetation, and also at the surrounding desert area, which has an albedo of 0.26. Results have shown that in the morning hours, the air over White Sands Monument was by 3°C cooler than the air over the surrounding dark surface. It was also found that the air remained cooler throughout daytime hours, but the amount of cooling was reduced later in the day because of increased upwelling (Fishman et al. 1994). Sailor (1995) showed by means of 3D meteorological simulations that increasing the albedo over downtown Los Angeles by an average 0.08 decreased summertime temperature by as much as 1.5°C . Numerical simulations undertaken by Taha (1997) found that increasing the albedo of the California's South Coast Air Basin by 0.13, simulated reductions of averagely 2°C . In another mesoscale modeling study Taha et al. (2000 and 2002) showed that cool-city strategies can reduce urban air temperatures by a typical 1-2K for the case of three US cities and by $0.5 - 1^{\circ}\text{C}$ for the case of Greater Toronto Area, Canada.

This study aims to report the experimental results regarding the performance of several commercial and innovative cool coatings and based on their performance to investigate the impacts of large-scale increases in surface albedo on ambient temperature trying to analyze the Urban Heat Island (UHI) effect over Athens, Greece, a dense populated city. Numerical simulations were performed by the 'urbanized' version of the non-hydrostatic PSU/NCAR Mesoscale Model (MM5, version V3-6-1). Two scenarios of moderate and high increased albedo have been studied.

EXPERIMENTAL ASSESSMENT OF COOL MATERIALS

Estimates of the potential for altering the urban albedo of Athens are based on a two-dimensional analysis and do not consider vertical surfaces like walls. Furthermore only the albedo of building structures (rooftops) will be changed in this study, therefore we will consider materials that can be used on building rooftops. There are a number of cool materials currently commercially available for building rooftops (e.g. cool surface coatings, reflective tiles, light colored marble and mosaic, concrete and conventional asphalt with white aggregate). Berdahl P. et al. (1997) has measured the solar reflectance of several cool roofing materials like paints, roof coatings and membranes and found that their solar reflectance ranges from 0.8 to 0.85. The emissivity of these materials was measured to be about 0.9. According to another study carried out at the University of Athens, the spectral reflectance and the emissivity of several commercially available roof coatings including white acrylic, elastomeric, ceramic and aluminum coatings were measured. It was found that their solar reflectance varies between 0.4 and 0.85 and their infrared emittance between 0.4 and 0.93. Surface temperature measurements demonstrated that a "cool" coating can reduce a concrete tile's surface temperature under hot summer conditions by 4°C and during the night by 2°C . (Synnefa et al. 2006). All the above mentioned products are white or light colored. However, there is a need for cool non-white products because in many cases the aesthetics of darker colors is preferred. Cool non-white coatings, absorb in the visible range, in order to appear having a specific colour, but they should be highly reflective in the near infrared part of the electromagnetic spectrum to maintain a high solar reflectance. This is very important considering the fact that about half of all solar power arrives as invisible near infrared radiation. Specialized, complex inorganic color pigments that are dark in color but

have the ability to reflect strongly the near infrared (NIR) portion of the solar spectrum have been created by pigment manufacturers and they are used in order to develop cool colored coatings with higher solar reflectance compared to conventionally pigmented coatings. In the framework of a study a palette of cool colored coatings was developed at the University of Athens using near infrared reflective color pigments. These coatings were tested in comparison to color-matched, conventionally pigmented coatings. The maximum difference between the solar reflectance of a cool and standard colored coating was found to be 0.22 with a corresponding temperature difference of 10.2°C, for summer conditions. Several engineering methods have been developed to apply cool coatings to roofing materials (clay tiles, concrete tiles, metal roofs and shingles). In general, the solar reflectance of commercially available roofing products has increased to 0.30-0.45 from 0.05 –0.25 for all materials except shingles whose solar reflectance exceeds 0.25 (Akbari et al. 2005). Using cool colored materials for large scale increases in albedo has also the benefit of avoiding the problem of glare.

DESCRIPTION OF THE MODELING METHOD

Numerical simulations were performed by the non-hydrostatic, mesoscale model developed by PSU/NCAR, known as MM5, version V3-6-1, (Grell et al., 1994) with the modified MRF-urban PBL scheme (Dandou et al., 2005). The MM5 numerical simulations were performed by applying the 25-category USGS land use classification scheme in order to provide the land-cover data for the model domains. The initial and lateral boundary conditions for the outermost domain were provided by a coarser numerical weather prediction model, the European Center for Medium range Weather Forecast (ECMWF). The numerical simulation was supplemented by information derived from satellite image analysis. In particular, one Landsat-5/TM image, acquired on the 13th May 2003 covering the greater Athens area, has been digitally processed and analysed in order to extract all urban elements which are greater than the size of the higher spatial resolution pixel (30 m). In this procedure, an updated and more realistic representation of the urban expansion was obtained. This detailed information was used in the MRF-urban scheme in order to construct new fields for various parameters such as the albedo, the roughness length and the semi-empirical coefficients for the heat storage flux within the urban limits of the city, by applying an aggregation procedure. This was achieved by providing to each 30 m pixel (from the higher resolution domain) literature values (e.g. Grimmond et al., 1991; Grimmond and Oke, 1999) for the various parameters, according to the above urban categories. Thereafter, these values were aggregated to each 4 km² and 0.45 km² grid cells in the MM5 modeling domains using an area-weighting scheme. Thus, the new values of the parameters, in the modified version, reflect the presence of all the areas with different specifications within each 4 km² and 0.45 km² grid cell and are not related to a fixed land use type.

The simulated domains covered the extended areas of Europe, Greece, Attica peninsula and the city of Athens respectively. The spatial resolution for the innermost nested domain (the city of Athens) was 0.67 x 0.67 Km² (Figure 1A). Simulations have been performed for a clear and warm summer day, the 15th August 2005.

Based on the experimental results reported in the previous paragraph the base case albedo for building structures was considered 0.18 (Figure 1B) and two scenarios of increased albedo were chosen for the simulations: a moderate and feasible increase

in the buildings structure albedo of 0.45 (albedo =0.63) and an extreme case were the albedo of building structures is considered 0.85 (Figure 1 C and D).

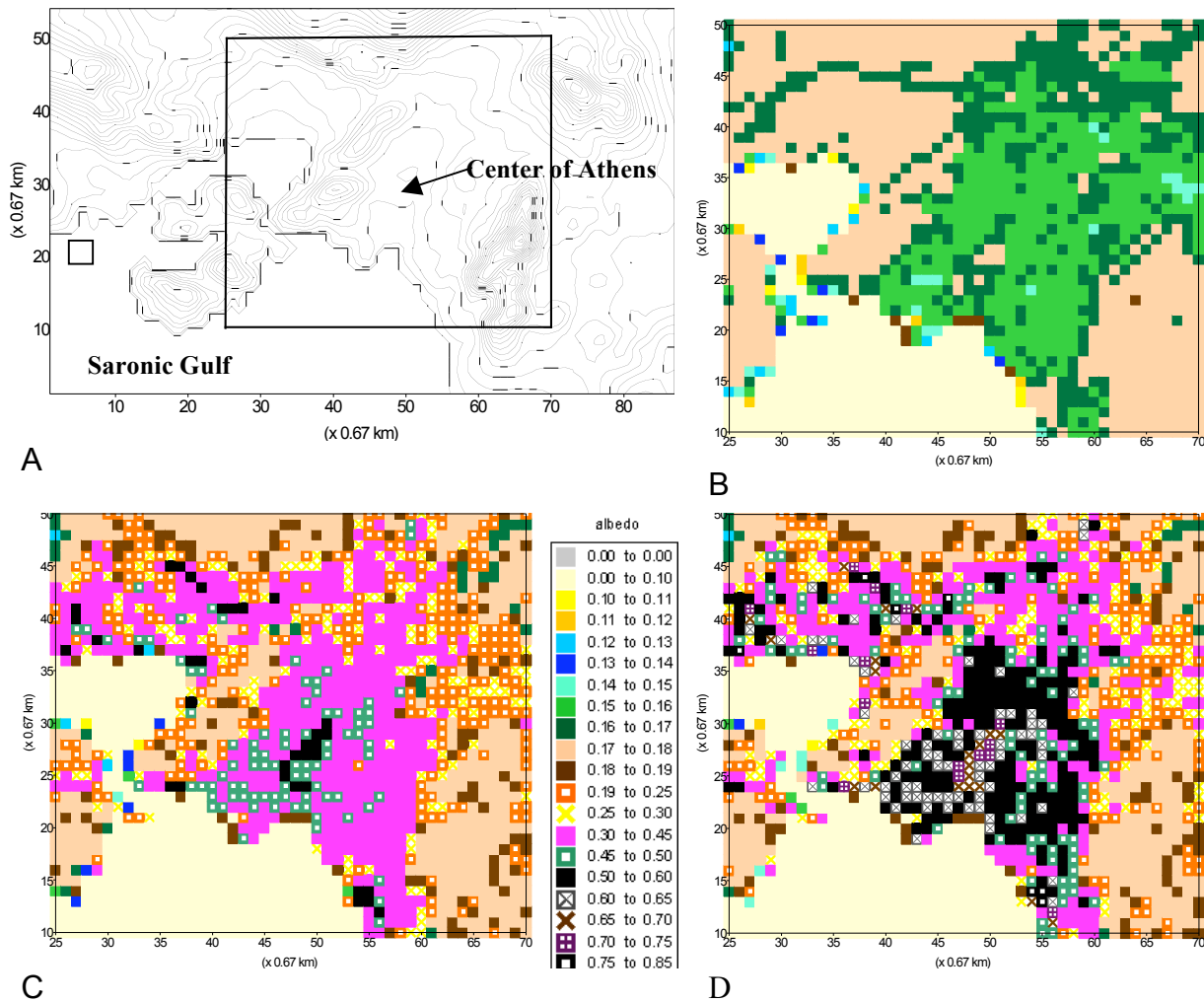


Figure 1: A) Topography contour lines at 50 m intervals of the fourth nested domain. B) the base case scenario (building structures albedo $a_{bs}=0.18$) C) the moderate increase in albedo scenario ($a_{bs}=0.63$) D) the high increase in albedo scenario ($a_{bs}=0.85$)

ANALYSIS OF THE SIMULATION RESULTS

While all the meteorological parameters are affected by changes in surface albedo, only the effect on temperature is being discussed in this paper. The impacts of high albedo primarily influence the regions that underwent the simulated increase in albedo. The simulations suggest that the urban areas (as well as other suburban and rural areas) are generally cooler than in the base case. The impact of albedo increase is higher at 12p.m. to 3p.m.

More specifically, for the moderate increase in albedo case, the temperature depression at 2m height at 12p.m. varies between 0.8 and 1.6°C (Figure 2A). If the albedo is further increased (extreme albedo case), then the temperature difference from the base case varies between 1 - 2 °C; with individual depressions as high as 2.2°C (Figure 2B). Most of the temperature depression occurs in the central and central east basin.

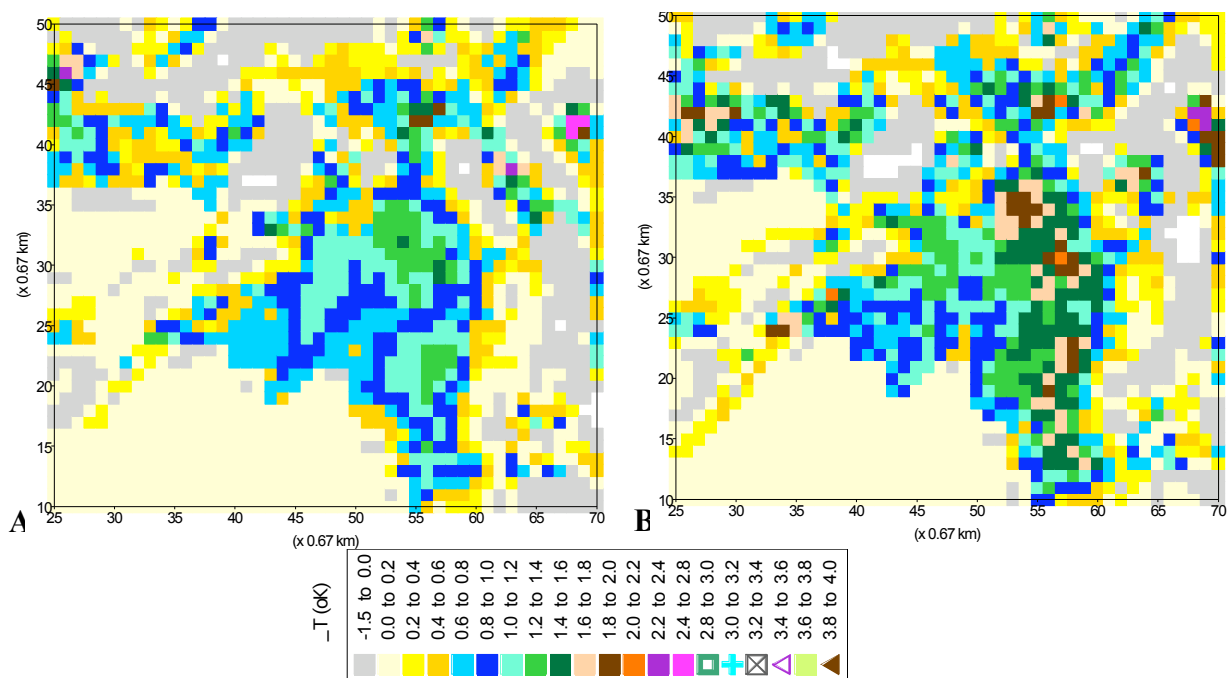


Figure 2: Air temperature differences (at 2 m) between the base case and A) the moderate case scenario and B) the extreme case scenario at 1200 LST on 15th August 2005

During the night, the temperature remains in general unchanged between the base case and the modified albedo scenarios.

In this study only the albedo of building structures has been increased. The impact of high albedo on air temperature would have been even greater if the albedo of roads and pavements had also been increased. Nevertheless, a decrease in air temperature of 2°C is quite significant considering the fact that for every degree °C the temperature rises, the demand for electric power rises by 3% and the probability for a smog incident by 3% (LBNL Heat Island Group).

CONCLUSIONS

This study arises from the need to put forward passive solutions, which can mitigate the negative effects of the heat island phenomenon. The possible impacts of large scale increases in surface albedo on heat island mitigation were investigated using the mesoscale model MM5 (V3-6-1). Two cases of increased albedo have been simulated: a moderate one where the albedo of building structures is considered to be 0.63 and an extreme case with building structures' albedo equal to 0.85. It was demonstrated that for the first case air temperature can decrease by 1.6°C. and for the second one by 2.2°C. The change in surface albedo can be achieved gradually if cool materials are chosen to replace dark existing ones during maintenance or in new structures. Cool materials offer an inexpensive solution to increasing thermal comfort, improving air quality and reducing energy demand.

References

Akbari, H., Davis, S., Dorsano, S., Huang, J., Winert, S., (1992). *Cooling our Communities—A Guidebook on Tree Planting and White Coloured Surfacing*. US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division.

Akbari H., Levinson R., Miller W., Berdahl P., 2005. Cool colored roofs to save energy and improve air quality. Proc. International Conference "Passive and Low Energy Cooling for the Built Environment", Santorini, Greece.

Berdahl, P., Bretz, S. E.. Preliminary survey of the solar reflectance of cool roofing materials. *Energy and Buildings* 25, (1997) 149-158

Dandou, A., Tombrou, M., Akylas, E., Soulakellis N., and Bossioli E.: 2005, 'Development and evaluation of an urban parameterization scheme in the Penn State/NCAR Mesoscale Model (MM5)', *J. Geophys. Res.* **110**, D10102, doi: 10.1029/2004JD005192

Grell, G. A., Dudhia, J., and Stauffer D.: 1994. 'A description of the fifth-generation Penn state/NCAR mesoscale model (MM5)', *NCAR technical note*, NCAR/TN-398 +STR, National Centre for Atmospheric Sciences, Boulder, CO, 138 pp.

Fishman B., Taha H. and Akbari H., (1994). Mesoscale cooling effects of high albedo surfaces: Analysis of meteorological data from White Sands National Monument and White Sands Missile Range. LBL Report 35056.

Grimmond, C. S. B., Cleugh, H. A., and Oke, T. R.: 1991, 'An objective urban heat storage model and its comparison with other schemes' *Atmos. Environ., Part B* **25**, 311-326.

Grimmond, C. S. B., and Oke, T. R.: 1999, 'Heat storage in urban areas: Local scale observations and evaluation of a simple model' *J. Appl. Meteorol.* **38**, 922-940.

LBL Heat Island Group: <http://eetd.lbl.gov/HeatIsland>

Sailor, D., 1993: Role of surface characteristics in urban meteorology and air quality. Lawrence Berkeley National Laboratory Report No. 34459, UC-Berkeley, Doctoral Thesis.

Santamouris, M.(Ed.) (2001). *Energy and climate in the urban built environment*. James and James Science Publishers, London.

Synnefa A., Santamouris M., Livada I., 2006. A study of the thermal performance and of reflective coatings for the urban environment. *Solar Energy*, **80**, 968-981.

Taha, H., 1994. Meteorological and photochemical simulations of the south coast air basin. In: Taha, H. (Ed.), *Analysis of Energy Efficiency of Air Quality in the South Coast Air Basin—Phase II*, Rep. No LBL-35728, Lawrence Berkeley Laboratory, Berkeley CA, pp. 161–218 (Chapter 6).

Taha H. (1997). Modeling the impacts of large-scale albedo changes on ozone air quality in the South Coast Air Basin. *Atmospheric Environment* 31, No. 11, pp. 1667-1676.

Taha H., Chang S., Akbari H. (2000). Meteorological and air impacts of heat island mitigations measures in three U.S. cities. LBNL report 44222.

Taha H., Hammer H., Akbari H. (2002). Meteorological and air impacts of increased urban surface albedo and vegetative cover in the Greater Toronto Area, Canada. LBNL report 49210.