Environmental Benefits of Heat Island Mitigation Measures

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ABSTRACT

The urban heat island effect contributes to increased energy use and pollution in cities across the United States. Reversing this phenomenon through the use of reflective roof and paving material and strategically-placed vegetative cover saves individuals, communities, and cities energy and money, and can reduce local and global air pollution. The Urban Heat Island Pilot Project (UHIPP) seeks to determine which heat island mitigation measures are most effective for various regions in the U.S., and quantify the benefits associated with the implementation of these measures.

Our new analyses show that Salt Lake City UT, Baton Rouge LA, and Sacramento CA could achieve average annual energy savings of up to $26 million from both the direct and indirect effects of heat island mitigation strategies. In addition, computer simulations indicate that adopting heat island reduction measures can result in average temperature reductions of 1.8 - 3.6ºF over modified areas as well as changes in other meteorological parameters. The corresponding ozone reductions range from 1.1 - 4.4 ppb/ºF.

In order to provide information to additional communities about the potential benefits of cost-effective heat island mitigation measures, this paper will discuss the results of the pilot project, as well as the approach that is currently underway to streamline the meteorological and air quality modeling effort and reduce the costs and data burden on communities that wish to access the information.

Introduction

Modeling and field studies suggest that heat island reduction strategies can have various meteorological implications, including surface and air temperatures reduction. The general impacts on air quality of relatively lower ambient temperatures include: 1) a reduction in temperature-dependent photochemical reaction rates; 2) a decrease in temperature-dependent biogenic hydrocarbon emissions; 3) a decrease in evaporative losses of organic compounds from mobile and stationary sources; and 4) a decreased need for cooling energy, generating capacity, and, ultimately, emissions from power plants. Thus, increasing urban surface reflectivity, or "albedo", and the amount of vegetation, has the potential to reduce ozone formation.

Recent field-measurements and modeling studies support these conclusions. For example, Gabersek and Taha (1996), Taha (1996,1997), and Sailor (1993) all show that implementing heat island reduction strategies may be an effective way of reducing urban air temperatures by up to 9º F in summer, reducing exceedance exposure to ozone by 10-20%. As with previous studies, the UHIPP attempts to quantify the impacts of heat island mitigation measures on energy use, meteorology, and air quality. In this study, improved modeling approaches were followed and more innovative surface characterization (aerial urban fabric analysis) was performed, than in previous studies.

In 1997, the U.S. Environmental Protection Agency (EPA) initiated the Urban Heat Island Pilot Project (UHIPP). The UHIPP is an effort to investigate the use of reflective roofs, reflective pavements, and urban vegetation to reduce cooling energy use in buildings and lower the summertime ambient air temperature in urban areas. The regions surrounding the cities of Sacramento CA, Salt Lake City UT, and Baton Rouge LA were selected for the UHIPP and are the subject of this paper.

Modeling Method

Several steps were taken to perform the meteorological and photochemical simulations for this study. First, the domains of the simulation were characterized in terms of surface properties, land use/land cover (LULC), topography, and water/land distributions. These data were obtained from the United States Geological Survey (USGS), remotely-sensed data, aerial photographs, and in-situ field campaigns, where applicable. In terms of surface characterization, several parameters were quantified. These were needed to specify the lower boundary (surface) in the meteorological and air quality models. Parameters needed by these models include, but are not limited to, surface density, specific heat, albedo, normalized difference vegetation index (NDVI), thermal inertia, thermal diffusivity, moisture content. These parameters were gridded at a resolution corresponding to that of the simulations for each region. In addition, all of these parameters were computed and re-specified for each modification scenario, e.g., changes in albedo and urban vegetation fraction. These changes were then re-mapped onto the domain's grid.

Next, the domain characterization in terms of meteorological initial and boundary conditions was undertaken. Initial conditions were based on observational data representing the times and episodes of interest. Following this step, emission input data were prepared for use in the photochemical model (e.g., UAM). In this study, the emission information and pollutant-concentration boundary conditions were obtained from the state air quality regulatory agencies in each region. These include emission rates for all relevant pollutants and chemical species from area, point, mobile, and biogenic sources.

The next step was the initiation of meteorological modeling of the selected domains for the specified episodes. The episodes correspond to those used by the states in their State Implementation Plan (SIP) attainment demonstration modeling. Typically, these are hot summer episodes of poor air quality such as late May to mid-August, although the modeling episodes may not always capture the worst air quality conditions in the regions. The meteorological simulations were performed for up to four days at a time for the base-case conditions as well as the modified scenarios. The meteorological simulations were performed off-line with respect to air quality models. Results from these simulations were used as direct boundary condition input to photochemical models as well as input to emission processors (indirectly) to adjust the emissions of various precursors and pollutants to changes in meteorological conditions. The changes in meteorology and emissions from all affected sources were then mapped onto the input to the UAM. This modified input was used to simulate the effects and impacts of increased-albedo/increased-vegetation strategies (IAIV) in each region, accordingly. To summarize, the following tasks were performed for this study:

- Obtain and derive meteorological, surface characteristics, and air quality data;
- Characterize urban surfaces through analysis of aerial photographs, remotely-sensed data, and information from cities and state agencies;
- Define base and modified scenarios for simulations;
- Perform meteorological simulations for base and modified scenarios;
- Perform air-quality simulations for base and modified scenarios; and
- Analyze the simulation results to quantify the potential role of heat island mitigation measures in reducing summertime air temperature and smog.

Summary of Modifications

Surface change scenarios (albedo and vegetative fraction increases) were developed by using USGS Land Use Land Cover (LULC) data and aerial photography to determine the degree to which heat island mitigation measures could be used to modify the existing makeup of the cities. For each surface type, a certain level of albedo increase was assumed based on laboratory research and measurements in the field (e.g., Berdahl and Bretz, 1997). The assumptions we made for increasing albedo per surface type include: increase in residential roof albedo by 0.3, commercial roof albedo by 0.4, roads by 0.25, sidewalks by 0.2, and parking lots by 0.25. This is a “final” number for each surface type, i.e., after accounting for weathering and soiling effects on initial increase in albedo. Pomerantz et al. (1999) discuss albedo measurements and values for a wide range of urban surface types. They also discuss the change in albedo over time, i.e., the effects of weathering and aging.

For vegetation cover modifications, the assumption is that each building unit in USGS LULC categories 11, 12, 15, 16, 17 (see Table 1) is given an additional four trees (in the scenarios simulated and reported here), and each unit in LULC category 13 is given an additional six trees. The USGS LULC category 14 (transportation) does not receive any additional trees. It is further assumed that each tree, upon maturity, will cover a top-view area of 50 m^2.

Table 1 summarizes the resulting level of changes. This scenario represents a feasible *upper bound* for potential modifications in each land use category and given region. The increases given in this table are on a 200-m grid-cell basis. These changes are then averaged to the meteorological model's grid size (between 2 and 4 km) a hundred times or more, depending on the grid interval selected for simulation. Thus, the final increases in albedo and vegetative fraction in the models' grids are generally smaller than given in Table 1. Tables 2 and 3 summarize the changes as they pertain to the meteorological modeling domains of each region.

Table 1. IAIV[1] Scenarios Assumptions for Modeling Sacramento, Baton Rouge, and Salt Lake City Regions

USGS LULC ID (Urban Land Use)	D albedo	D vegetation
Residential 11	+0.118	+18% of cell area
Commercial 12	+0.175	+18% of cell area
Industrial 13	+0.145	+8% of cell area
Transportation 14	+0.237	+4% of cell area
Industrial/Commercial. 15	+0.162	+12% of cell area
Mixed Urban 16	+0.136	+11% of cell area
Mixed/Built-up 17	+0.155	+11% of cell area

Table 2. Albedo Changes Statistics (in meteorological modeling domains)

Total cells in domain (including water)	Salt Lake City, UT 9657 (x4 km^2)	Baton Rouge, LA 4700 (x4 km^2)	Sacramento, CA 1118 (x16 km^2)
Number of modified cells (over **entire** domain)	868	1876	480
Largest albedo increase (in any one cell, anywhere in domain)	0.20	0.21	0.14
Representative albedo increase in core area	0.13	0.11	0.13

Table 3. Vegetative Cover Changes Statistics (in meteorological modeling domains)

Total cells in domain (including water)	Salt Lake City, UT 9657 (x4 km^2)	Baton Rouge, LA 4700 (x4 km^2)	Sacramento, CA 1118 (x16 km^2)
Number of modified cells (over **entire** domain)	868	1876	480
Largest fraction increase (in any one cell, anywhere in domain)	0.18	0.18	0.17
Representative cover increase in core area	0.16	0.14	0.14

1 Increased Albedo/Increased Vegetation.

Results

Meteorological simulations were performed for the base case (current conditions) and for several modified scenarios for each region. The output from meteorological models was used as input to photochemical models (directly) and to emission processors (indirectly). This allowed for adjustment in the emissions of various precursors, such as nitrogen oxides (NOx) and VOC (volatile organic compounds), to changes in meteorological conditions.

Table 4 is a summary of temperature changes resulting from heat island control measures in each of the three pilot cities for two selected hours. It shows the base case temperature, and the cooling resulting from heat island reduction. The temperature shown is representative of the urban area (e.g., city center) in each of the three cities simulated in this study and is for the last day of the respective episodes, to ensure that the effects of initial conditions in the model are minimal.

Table 4. Air temperatures and reductions at 6:00 a.m. and 4:00 p.m. local standard time (LST) for each of the three pilot cities

Region		ºF at 6:00 a.m.	ºF at 4:00 p.m.
Salt Lake City	Base case temperature	68.0	89.6
	Change in temperature from heat island reduction strategies	-1.8	-3.6
Baton Rouge	Base case temperature	68.0	93.2
	Change in temperature from heat island reduction strategies	0	-1.4
Sacramento	Base case temperature	80.6	100.4
	Change in temperature from heat island reduction strategies	-1.8	-2.2

From this table, it is clear that all of the cities enjoy greater reductions in air temperature in the afternoon than in the morning. Salt Lake City enjoys the largest reductions in air temperature as a result of heat island reduction strategies, followed by Sacramento, and then Baton Rouge. This is due to the fact that in Salt Lake City, the level of modification in albedo and vegetation, was slightly higher than in the other two cities.

Photochemical simulations in this study were performed using the Urban Airshed Model (UAM) to determine the impact of heat island mitigation strategies on ozone concentrations. The UAM is a three-dimensional, Eulerian, photochemical model that simulates the advection, diffusion, transformation, emission, and deposition of pollutants. The UAM accounts for emissions from area and point sources, elevated stacks, mobile and stationary sources, and vegetation (biogenic emissions). The model has been approved and recommended by the US EPA for ozone air quality studies of urban areas (EPA 1986). UAM-ready input data were provided by the appropriate environmental agencies in each participating state.

The results of the photochemical modeling indicate that all three cities experience improvements in air quality through reductions in ozone levels as a result of adopting heat island reduction measures. Of the three cities, Sacramento experiences significant reductions in peak ozone concentrations. This is primarily due to the fact that Sacramento covers a larger geographical area, thus allowing for larger cumulative impacts from heat island control strategies. Table 5 provides a summary of air quality modeling results.

Table 5. Some Air Quality Modeling Results

Region	Largest decrease in ozone concentrations[2] (at selected hours)	Change in peak ozone[3]
Salt Lake City	4 ppb (at 7 a.m.) 3 ppb (at 2 p.m.)	0%
Baton Rouge	5 ppb (at 9 a.m.) 4 ppb (at 12 p.m.)	- 0.8%
Sacramento	7 ppb (at 2 p.m.) 10 ppb (at 4 p.m.)	- 6.5%

Streamlining

While the methodology used in the UHIPP study of Salt Lake City, Baton Rouge, and Sacramento has provided significant insight into the potential benefits of implementing heat island mitigation measures in these cities, the modeling process itself is quite involved and resource-intensive. Clearly, the same approach cannot be followed for the vast array of cities that might benefit from heat island mitigation measures. Hence, there is a need to develop a streamlined approach that can be readily applied to any metropolitan area of interest. Such a streamlined process will necessarily sacrifice some accuracy, so care must be taken to ensure that the overall conclusions remain robust. As the streamlining process is currently envisioned it has three components.

First, there is potential to streamline the urban fabric analysis. After a number of cities have been carefully characterized with respect to existing fabric and potential for modification, it is envisioned that additional cities can be characterized with respect to their similarity to previously analyzed cities. The important issue to resolve is the number of cities that must form the basis for this analysis, and how these cities should be chosen. From our initial investigations it is clear that the required number of cities is greater than three. Additional cities for study should clearly span a range of population sizes, ages, geographical locations, and architectural composition.

There are also simplifications that can be implemented in the meteorological modeling that is required for both analysis of air quality impacts as well as analysis of the indirect effects on energy consumption. One possible simplification is to use a set of coincident episodes for multiple metropolitan study areas, all of which can be modeled within nested grids of a single meteorological simulation. It may be possible, for instance to have an outer grid that includes the states of Utah and Colorado with one nested grid focusing on Salt Lake City and a second nested grid focused on Denver. This philosophy could clearly reduce the required number of meteorological simulations by a factor of two or more. Another meteorological streamlining option that could extend the applicability of this work tremendously would be to model a subset of strategic metropolitan areas and episodes that are somehow representative of typical areas that may be of interest for future extrapolative analysis. The choice of metropolitan regions would be guided by some of the same principles discussed above for the urban fabric streamlining.

2 Anywhere in the domain.
3 At location and time of urban peak.

Potential streamlining options within the photochemical modeling arena are similar in nature to those suggested for meteorological modeling. It is important to realize, however, that two regions may be similar with respect to their meteorology, but not with respect to their photochemistry. Therefore, the approach for mapping a modest number of air quality studies to arbitrary metropolitan regions across the country is necessarily different from the meteorological mapping approach, and probably more difficult. Related to this issue is the need to ensure that a representative range of air quality episodes is chosen for the streamlined photochemical modeling.

To ensure minimal errors in implementing the streamlined process, extensive sensitivity analysis will be performed using the meteorological and air quality models. The purpose is to understand and quantify the response and sensitivity of meteorological and air quality parameters to certain perturbations and changes in initial conditions of the surface, meteorology, and pollutant concentration fields.

Conclusions

Each of the three cities discussed in this report can benefit from implementing heat island mitigation measures. Clearly, the extent to which urban areas can effectively improve local air quality through heat island mitigation measures depends on numerous factors. These include meteorology and climate, geography, scale, topography, basin morphology, proximity to water bodies, land-use patterns, precursor emission rates and mix, baseline albedo and vegetative fraction distributions, and potential for modification (increasing albedo and vegetative fraction). These factors help to explain why Sacramento enjoys relatively larger improvements in air quality compared to Salt Lake City or Baton Rouge. They also explain why the least amount of cooling is achieved in Baton Rouge, where mostly albedo increase has a measurable effect because of the higher moisture in the area.

The simulations suggest that Salt Lake City achieves reductions in ambient air temperatures of up to 3.6 ºF at 4:00 p.m. As a result, the city achieves reductions in ozone concentrations by up to 3 or 4 ppb, the equivalent of about 3.5% if it were compared to an urban peak of 95 ppb. Baton Rouge achieves reductions in ambient air temperatures of 1.4 ºF, and corresponding ozone reductions of up to 4 or 5 ppb, the equivalent of about 4% if compared to an urban peak of 113 ppb. Baton Rouge is unique in that the temperature effect results primarily from increases in albedo. This is due to the higher moisture in the area, which tends to limit evapotranspiration from increased vegetation. Finally, Sacramento enjoys reductions of 2.2 ºF as a result of heat island mitigation measures. Although these temperature reductions are not as large as those experienced in Salt Lake City, their impacts on ozone concentrations are relatively larger, with reductions of up to 10 ppb from peak ozone concentrations (about 7% of the peak of 139 ppb). Sacramento enjoys larger reductions in ozone as a result of its larger geographical area.

Based on these and earlier modeling efforts, we found that the larger the modified area, the larger the impacts on meteorology and air quality. This is important in large metropolitan areas with thousands of square kilometers of developed land. In such conditions, e.g., Los Angeles CA, it is possible to lower the peak ambient temperatures by as much as 9 ºF locally and by up to 5 ºF on average. The reduction in ozone concentrations, therefore, can be larger than what has been simulated in these three cities.

Future efforts focused on streamlining all aspects of the modeling method including the urban fabric analysis, the meteorological modeling and the photochemical modeling are currently underway. By streamlining the process for determining the benefits associated with heat island mitigation, it will be possible for a large variety of U.S. cities to determine the degree to which these mitigation strategies can serve as a cost effective and practical means to save energy and improve air quality in their areas.

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