Final Report

METEOROLOGICAL AND AIR QUALITY MODELING TO FURTHER EXAMINE THE EFFECTS OF URBAN HEAT ISLAND MITIGATION MEASURES ON SEVERAL CITIES IN THE NORTHEASTERN U.S.

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1 INTRODUCTION

This report summarizes the results of a modeling study designed to examine the effects of implementing measures to reduce the magnitude of the urban heat island on ozone air quality in cities located throughout the northeastern U.S. Two measures that have been identified as part of the EPA Heat Island Reduction Initiative (HIRI) program to be potentially effective in reducing the high temperatures associated with an urban heat island are (1) use of reflective roof and paving material and (2) increased vegetation cover (e.g., tree planting).

The concept derives from the premise that increasing the albedo and the vegetation cover of an area will result in lower surface temperatures, decreased photochemical reaction rates, decreased emissions, and consequently, lower ozone concentrations. However, the complex interactions among the various meteorological, emissions, and air quality parameters participating in the formation and transport of ozone requires a careful analysis of the numerous direct and indirect effects before such strategies can be implemented. For example, by altering the surface energy budget, a higher albedo will also affect other meteorological parameters such as wind speed, effective mixing height, and specific humidity. Lower mixing heights resulting from the lower temperatures may offset air quality benefits derived from the reduced chemical reaction rates. Conversely, increased vegetation cover (shading) will also result in lower surface temperatures and increased roughness lengths associated with the vegetation may enhance the atmospheric mixing processes. Lower temperatures will reduce the production of biogenic hydrocarbon emissions from existing vegetation and enhance the deposition of ozone and other pollutant species, but the addition of vegetation may offset this effect. Lower surface temperatures may also reduce emissions from motor vehicles (in particular, evaporative emissions) and power plants (due to reduced energy demand for cooling).

By representing the complex interactions between land-use, meteorology, emissions, and ozone formation and transport processes, meteorological and air quality models can be used to estimate the effects of the HIRI measures on temperature and other meteorological parameters as well as ozone air quality. In modeling terms, use of reflective roofing and paving material is accomplished by changing the albedo of the land surface as input to the models. Increased vegetation cover is accomplished by changing the characteristics of the land use (e.g., from urban to forest) as input to the models.

The model-based sensitivity analyses described in this report expand on the previous analysis of the effects of implementing HIRI measures by Hudischewskyj and Douglas (2000). Three sensitivity simulations were performed to provide information on the relative effectiveness of modifications to albedo versus vegetation cover on simulated ozone concentrations and to examine the effects of different levels of albedo and vegetation cover modification. The methods and results of the sensitivity analysis are presented in this report. We begin, however, with a brief review of the previous modeling study.

OVERVIEW OF PREVIOUS MODELING STUDY

The previous study entailed the combined application of advanced meteorological and photochemical modeling tools including the Systems Applications International (SAI) Mesoscale Model (SAIMM), for the preparation of meteorological input fields; the Biogenic Emissions Inventory System (BEIS-2), for estimation of biogenic emissions; and the variable-grid Urban Airshed Model (UAM-V), for the calculation of ozone concentrations. The HIRI measures were represented in terms of changes in surface reflectivity (albedo) and vegetation cover, as input to the meteorological and air quality models.

The models were applied for a domain that encompasses the northeastern U.S. and for a multi-day simulation period that includes 9 through 15 July 1995. The results of the HIRI simulation (incorporating the HIRI measures) were compared with those for a base simulation (that did not include the HIRI measures). The base simulation was conducted as part of a companion air quality modeling study by Myers et al. (1999). The comparison of the HIRI and base simulation results focused on the meteorological inputs (with particular emphasis on temperature) and the simulated ozone concentrations. Differences between the HIRI and base simulation results for the SAIMM and the UAM-V were used to quantify the effects of the HIRI measures.

The modifications to albedo and vegetation cover were based on data and guidance provided by researchers at the Lawrence Berkeley National Laboratory (LBNL). The data provided by LBNL consist of estimated increases in albedo and vegetative cover for each urban land-use category included in the U.S. Geological Survey (USGS) database. These estimates were based on field measurements and laboratory studies.

The albedo and land-use inputs for all predominantly urban areas within the modeling domain were modified for the HIRI modeling exercise. A detailed analysis of the output was performed for Washington, D.C., Baltimore, Philadelphia, New York, and Boston.

From the SAIMM results, surface temperatures over the major urban areas were reduced by approximately 1 to more than 3°F. The reductions in temperature occurred mainly during the daytime hours. The differences were not confined to the surface, and lower temperatures were found for several vertical levels. The vertical extent of the differences varied with time of day and was greatest during the afternoon hours, due to vertical mixing. Wind speeds were generally lower for the HIRI simulation. The combined effects of changes in temperature and wind speed altered the vertical exchange coefficients. This generally resulted in lower effective mixing heights.

The biogenic and motor vehicle emission inputs to the UAM-V were adjusted to reflect the cooler temperatures. Biogenic hydrocarbons were reduced by less than one percent domainwide. Motor-vehicle hydrocarbon emissions were reduced by two percent.

Both increases and decreases in simulated ozone concentrations characterized the UAM-V simulation results. In general, the increases in the urban areas occurred for days with higher wind speeds (pollutant transport conditions) and the decreases occurred under conditions of low wind speed (stagnation conditions). Detailed examination of the simulation processes using the UAM-V process analysis technique indicated that lower wind speeds and their effect on model dynamics (advection and diffusion) was the primary reason for the higher ozone concentrations in the HIRI simulation.

The simulation results suggested that the HIRI measures may be beneficial for localized ozone events (under stagnant wind conditions) but less beneficial for regional transport episodes such as occurred during the latter part of the July 1995 simulation period.

The study concluded with the recommendation of additional sensitivity simulations involving the SAIMM and UAM-V to further investigate the sensitivity of the results to changes in the meteorological and emissions inputs. These included examination of the relative influence of the albedo versus vegetation-cover modifications. Since a trade off between the benefits of lower temperatures (on reaction rates and emissions) and the disbenefits due to lower wind speeds and reduced vertical mixing was indicated, a scenario involving less of an increase in albedo and vegetation cover was also recommended. Both of these were pursued in the follow-on analysis discussed in this report.

2 SENSITIVITY ANALYSIS METHODS AND RESULTS

In this follow-on analysis, three SAIMM/UAM-V sensitivity simulations were made in which the original HIRI albedo and land-use modifications supplied by LBNL were further modified. Hudischewskyj and Douglas (2000) describe the basis for the original HIRI modifications to albedo and vegetation. The first two sensitivity simulations were designed to provide information on the relative effectiveness of modifications to albedo and vegetation cover on (UAM-V) simulated ozone concentrations. For the first sensitivity simulation, the modifications were applied (at the level used in the previous study) to albedo only. For the second, the HIRI measures were applied to the land-use (vegetation-cover-only). In the third, the original HIRI modifications to both albedo and vegetation were reduced by 50 percent. This last sensitivity was intended to address whether lesser modification could avoid some of the disbenefits simulated as part of the previous study. A similar sensitivity simulation was performed as part of the original study, but only for the last two days of the episode. Hereafter each of these scenarios is referred to as the albedo-only, vegetation-cover-only, or half-HIRI scenarios, respectively.

As for the original HIRI modeling exercise, each sensitivity simulation was run for the episode period of 9-15 July, 1995.

For ease of reading, all figures follow the text of this section.

SAIMM RESULTS

Differences between maximum surface temperatures for the three sensitivity simulations and those for the base case are discussed here. Plots for 14 and 15 July are used to illustrate the findings. The maximum decreases between the “full” HIRI simulation and the base case are 1.2 K (2.2 °F) and 0.9 K (1.6 °F) for 14 and 15 July, respectively (Figure 2-1a and b). In general, the sensitivity simulation in which only the albedo was modified produces results very similar to those for the original full HIRI simulation. Decreases are 1.1K (2.0 °F) and 0.6 K (1.0 °F), respectively, (Figure 2-2a and b) for these days. The spatial patterns and the locations of the maximum differences are very similar. When only the vegetation cover is modified, maximum decreases are 0.4 K (0.7 °F) and 0.2 K (0.4 °F) for these two days (Figure 2-3a and b). When both albedo and vegetation-cover values are modified to represent partial (50 percent) implementation of the HIRI measures, the maximum decreases for these two days are 0.7 K (1.3 °F) and 0.4 K (0.7 °F) (Figure 2-4a and b). It is interesting to note that the differences for the 50 percent albedo and vegetation-cover scenario seem to be nearly directly between the vegetation-cover-only (on the low end) and the albedo-only (on the high end) scenarios.

UAM-V RESULTS

Using the SAIMM results for the sensitivity simulations for the albedo-only, vegetation-cover-only, and half-HIRI simulations, three UAM-V sensitivity simulations were run. These also used modified biogenic emissions that were computed using the new temperature fields produced by the SAIMM. The results of each of the sensitivity simulations are presented relative to the previous base-case simulation and discussed relative to the results of the previous HIRI UAM-V simulation in which the albedo and vegetation-cover characteristics were modified using the full values suggested by LBNL.

Review of the Base-Case and Full HIRI UAM-V Results

The base-case and HIRI UAM-V (hereafter referred to as the 'full HIRI') simulation results for the model period of July 9-15, 1995 are presented in Douglas and Hudischewskyj (2000). In brief, the base-case simulation shows ozone concentrations increasing over the modeling period, reaching their highest values on the 14 and 15 July. On these days, simulated ozone concentrations are well over 100 ppb throughout much of the modeling domain and exceed 150 ppb the vicinity of the most densely urbanized regions of New York, Baltimore, and Washington. Maximum ozone concentrations tend to parallel the coastline. Notable among the results are slight under and over-estimations of ozone in Baltimore and Washington respectively, and an offshore shift, relative to observations, in the maximum concentrations in the area of New York City.

The HIRI simulation results are significantly different from the base-case results. In general, the full HIRI measures and associated lower temperatures tend to increase ozone concentrations within the modeling domain. Some areas of the domain do experience decreases in ozone, but these tend to be smaller in extent and magnitude than the areas with increases. The increases in ozone concentration over the urban areas seem to occur for days with higher wind speeds (or pollutant transport conditions) while the decreases occur under conditions of low wind speeds (stagnation condition). A plausible explanation for the simulated increases in ozone is that lower temperatures may result in slower reaction rates, producing a temporal and subsequently spatial lag between where precursors are emitted and where ozone appears (increases occur downwind). Further, reduced temperatures and wind speed produced by the HIRI measures appear to result in a lower SAIMM turbulent-kinetic-energy-derived pollutant mixing height.

Results of Albedo-Only, Vegetation-Cover-Only, and Half-HIRI Sensitivity Simulations

As with the full HIRI UAM-V, the three modified HIRI UAM-V scenarios produce differences in the simulated ozone concentration that vary in magnitude and sign for different areas of the domain and among the simulation days. The results of the albedo-only, vegetation-cover-only, and half-HIRI sensitivities relative to the base case of Douglas and Hudischewskyj (2000) are presented in Figures 2-5 through 2-7. All plots depict the results for the high-resolution (nested) UAM-V grid (see Douglas and Hudischewskyj, 2000 for a discussion of the modeling domain characteristics).

For each sensitivity simulation, implementation of the modified HIRI measures tends to increase ozone within the domain. There are again considerable regions were ozone is decreased and there appear to be significant differences between the relative effectiveness of changes in albedo versus changes in vegetation cover. The UAM-V simulated ozone appears much more sensitive to changes in albedo and the results of the separated albedo and vegetation-cover effects do not appear to be fully additive when implemented in tandem.

Albedo-Only Sensitivity Simulation

Plots of the differences in maximum ozone concentration between the albedo-only sensitivity and base-case simulations are given for each simulation day in Figure 2-8. On the first day of the simulation, 9 July, differences in maximum ozone concentration between the sensitivity and base-case simulation across the domain are less than 4 ppb in magnitude, with both the maximum increase and decrease occurring off the New Jersey coast.

On 10 July, the effects on maximum ozone concentration become more noticeable with a maximum increase of 8 ppb near Washington and a decrease of 9 ppb in central New Jersey. The spatial pattern of the changes is consistent with the original "full" HIRI UAM-V simulations; that is, the changes occur downwind of the urban areas.

These spatial similarities between the original full HIRI results and those for the albedo-only simulation continue for the rest of the simulation period. The spatial ozone concentration pattern is the same, with decreases in the urban areas but larger magnitude increases further downwind. However the magnitude of the changes for the albedo only case are lower than for the full HIRI simulation (by about 10 to 20 percent) and the spatial extent is also less than with the full HIRI measures.

As for the full-HIRI modeling results, differences between the albedo-only and base-case simulations are greatest on the 14 and 15 July. On 14 July, there is a maximum increase of 31 ppb to the northeast of New York. For the full HIRI simulation (in which both albedo and vegetation cover were modified), there was an increase of 37 ppb in the same region. The maximum decreases for this date are within 1 ppb for both simulations. On 15 July, the albedo-only simulation shows a maximum increase of 39 ppb in the area north of Washington compared to a value of about 44 ppb in this area for the original HIRI results on this day.

Vegetation-Cover-Only Sensitivity Simulation

Plots of the differences in maximum ozone concentration between the vegetation-cover-only sensitivity and base-case simulations are given for each simulation day in Figure 2-9. For the vegetation-cover-only simulation, the differences in ozone concentration are much smaller in magnitude and spatial extent than those for the albedo-only and full-HIRI simulations. Both the simulated decreases as well as the simulated increases in maximum ozone concentration are smaller for the vegetation-cover-only simulation. For example, distinct increases in ozone concentration for some days in the vicinity of Philadelphia and New York for the albedo-only and full-HIRI simulations do not appear in the vegetation-cover-only results.

Differences for the vegetation-cover-only sensitivity simulation are again small for 9 and 10 July, and show a pattern similar to that for the albedo-only simulation. The magnitude of the differences is approximately half, however. On 11 and 12 July, the magnitude and extent of the ozone differences is again much less than for either the albedo-only or the full-HIRI simulation, but on both of these days there is a 6 ppb reduction in the vegetation-cover-only simulated ozone to the southwest of Washington that is not present in the other results.

The results for 13 July show some large differences between the vegetation-cover-only and albedo-only results. Both the full-HIRI and albedo-only results show significant increases and decreases straddling the New York/New Jersey border (to the northwest of New York City), while the vegetation-cover-only only simulation shows virtually no differences when compared with the base case in this area. Also the full-HIRI and albedo-only simulations show the maximum increase in the Baltimore/Washington, while the vegetation-cover-only run shows a minimal increase and a maximum decrease of 7 ppb in this region.

For 14 July, the difference plot shows only small changes relative to the base-case simulation. Again these are much smaller than those for the full-HIRI and albedo-only runs. There is a small region of increases with a maximum value of 7 ppb to the north of Long Island and a localized decrease of 5 ppb in Maryland. Both the full-HIRI and albedo-only simulations showed double digit increases and decreases on this day.

Finally, the results for 15 July show increases in the Washington area, but of only 16 ppb compared to 44 ppb and 39 ppb for the full-HIRI and albedo-only simulations, respectively. There is again much less sensitivity in the New York region for the vegetation-cover-only modification. A similar situation is seen near Boston, with differences that are visible in this area for both the full-HIRI and albedo-only runs that do not appear in the vegetation-cover-only simulation. A very localized maximum decrease of 10 ppb is seen near Philadelphia in a region that shows modest increases for the other runs.

Fifty Percent Vegetation and Albedo (Half-HIRI) Sensitivity Simulation

Plots of the differences in maximum ozone concentration between the half-HIRI sensitivity and base-case simulations are given for each simulation day in Figure 2-10. On all days of the modeling period, the concentration difference patterns are very similar to those for the full-HIRI simulation, but the magnitude of the changes is on the order of half as large and the areal extent of the changes is greatly reduced. There are however some are noticeable exceptions to this finding. On 14 July, the increase in simulated ozone in the region is about half as great as for the full-HIRI simulation, but simulated decreases are similar in magnitude (within about 2 ppb of the full-HIRI value). Similarly, on 15 July, the largest simulated increase in maximum ozone located near Washington is reduced in magnitude from 44 to 27 ppb, compared to the full-HIRI simulation. Conversely, near Philadelphia, the largest reduction in maximum ozone is 13 ppb for the full-HIRI simulation and 11 ppb for the half-HIRI simulation. Thus the decreases are similar in magnitude. This decrease for the half-HIRI simulation is shifted north to an area that showed modest increases with the full HIRI measures.

UAM-V Process Analysis

The UAM-V process analysis technique allows examination of the contribution of each of the various simulation processes (chemistry, horizontal advection and diffusion, vertical advection, vertical diffusion, and deposition) to the simulated ozone concentrations within a grid cell or subregion of the modeling domain. To gain insight into the reasons for differences among the sensitivity simulations, we examined and compared the process-level contributions to ozone for each of the five urban areas of interest.

Process analysis shows that on most days, the dominant source of the simulated surface layer ozone are horizontal advection (transport) and vertical diffusion (mixing). Chemistry is usually an ozone sink at the surface but accounts for the large majority of ozone production in the upper layers.

On days where surface ozone in the sensitivity simulation is greater than for the base case, (e.g., 14 and 15 July for the albedo-only simulation), process analysis shows reduced vertical transport out of the surface layer and increased vertical diffusion into the surface layer (a signature of reduced vertical mixing). These results are consistent with a conceptual model in which the lower surface temperatures (from the higher albedo and greater vegetation cover) result in lower mixing heights and less vertical mixing.

The process analysis results also support the hypothesis presented earlier to explain the general observed pattern of ozone decreasing in the urban areas as a result of the albedo and vegetation-cover changes but increasing further downwind. This hypothesis is that with lower reaction rates, ozone formation occurs more slowly and the higher ozone values are more likely to form downwind of the urban areas rather than in the vicinity of the (urban) emissions sources. Process analysis, conducted at sites within several urban areas, shows that chemistry is a sink for ozone (i.e., this term has a negative contribution) within the surface layer. This is because ozone is quickly scavenged by initial low level emission of NO_x within the urban areas. This reaction is less temperature dependent than the reactions that produce ozone and at lower temperatures, NO_x scavenging will tend to dominate in situ production. Larger negative values for the chemistry sources term in the sensitivities than for the base-case simulation indicate that less ozone production in the urban areas occurs during the sensitivity simulations.

At upper levels, where precursors are more mixed, ozone is not being scavenged by local emissions but is being produced from photochemical reactions involving NO_x and VOC. For the upper levels, process analysis shows chemistry to be the overwhelmingly dominant source. The ozone produced chemically at upper levels is then turbulently mixed to the surface. This shows up as the positive vertical diffusion term within the process analysis and is the source of the majority of surface ozone for all simulations. Cooler surface temperatures (in the urban areas for the sensitivity simulations) give less convective buoyancy and result in a lower boundary layer (or mixing) height. In this case, atmospheric pollutants have less of a volume to be mixed in, so there is a greater proportion that comes to the surface, i.e. ozone is mixed to the surface as opposed to being vented to higher altitudes within the boundary layer. Days with the highest surface ozone show the largest values of the vertical diffusion into the surface layer.

Similarly, with less buoyancy-generated turbulence, there is subsequently also a reduced characteristic upward vertical velocity within the lower atmosphere. Thus less ozone is advected or vented out of the surface layer. Process analysis shows that simulation days with greater ozone concentration display reduced vertical advection as a sink of surface ozone.

Lastly, the large horizontal advection terms are consistent with the spatial shift of ozone production that is visible in the difference plots. With simulated ozone being produced as it is transport downwind of urban area, where in situ chemical production will now dominate over local source NO_x scavenging, one would expect advection to be visible as a source term in the process analysis and it is shown to be a major source of ozone in both the surface and upper level process analysis results.

3 SUMMARY OF RESULTS

Three sensitivity simulations were conducted to investigate the relative influence of changes in albedo versus vegetation cover as well as the effects of different levels of implementation of HIRI measures (as originally prescribed by LBNL). This included application of the SAIMM meteorological model as well as the UAM-V photochemical model for a multi-day summertime simulation period. The objective of this modeling study was to characterize the changes in surface temperature and other meteorological parameters as well as ozone concentrations that are expected to occur within urban areas throughout the northeastern U.S. under similar meteorological conditions, as a result of implementing HIRI measures.

The results of the sensitivity simulations were examined by comparing (using spatial difference plots) the daily maximum simulated ozone concentrations in the urban areas and throughout the modeling domain. The UAM-V process analysis technique was also used to gain insight into the reasons for differences among the sensitivity simulations. Process analysis is used to examine and compare the contributions from each of the various UAM-V simulation processes that include chemistry, horizontal advection and diffusion (transport), vertical advection, vertical diffusion, and deposition.

For the first sensitivity simulation, the modifications were applied (at the level used in the previous study) to albedo only. For the second, the HIRI measures were applied to the land-use (vegetation-cover-only). In the third, the original HIRI modifications to both albedo and vegetation cover were reduced by 50 percent. The results of each of the sensitivity simulations were compared to the results of the previous HIRI UAM-V simulation in which the albedo and vegetation-cover characteristics were modified using the full values suggested by LBNL.

In general, decreases in surface temperatures for the sensitivity simulation for which albedo was modified by 50 percent of that used in the original HIRI simulation are almost directly between those for which vegetation cover only (on the low end) and the albedo only (on the high end) were modified. Also, results for the scenario for which only albedo was modified most closely resemble the results of the original HIRI scenario in which both albedo and vegetation cover were modified to their fullest as prescribed by LBNL.

With respect to simulated ozone concentrations, the overall trend is still toward higher simulated model ozone concentrations, with decreases in the urban areas but larger increases further downwind in each of the albedo-only, vegetation-cover-only, and half- HIRI sensitivities. However, the UAM-V simulated ozone concentration is much more sensitive to changes in albedo than changes in vegetation cover. The maximum differences in surface ozone concentration, relative to the base case, for the albedo-only case, are in the range of 80 to 90 percent of the magnitude of the differences observed for the full-HIRI UAM-V results. Conversely, the changes in simulated ozone for the vegetation-cover-only case are only 10 to 20 percent as large as for the full-HIRI simulation.

The spatial distribution of surface ozone indicates significant differences between scenarios, particularly between the albedo-only and vegetation-cover-only simulations, with large areas, notably in the vicinity of New York, that appeared to exhibit ozone concentrations that are rather sensitive to albedo changes but not to changes in vegetation cover.

Further, the albedo and vegetation-cover induced influence for the respective sensitivities do not appear to be fully additive. That is the ozone differences that result from the separated albedo-only and vegetation-cover-only simulations do not, when added together, equal the differences in ozone from the full-HIRI simulation. For example, on the area of maximum increase near Washington shows a value of +39 ppb for the albedo-only scenario and +16 ppb for the vegetation-cover-only scenario, but the full-HIRI scenario shows a value, +44ppb, that is less than the sum of the other two.

The differences in maximum simulated ozone produced by the half-HIRI simulation are approximately half as large as for the full-HIRI simulation in the areas where ozone is increased. However, the decreases are similar in magnitude, though the locations of the largest decreases were slightly shifted. This indicates that lesser implementation of the HIRI measures might overall be more effective in reducing ozone (similar benefits with fewer disbenefits). The reductions in ozone are achieved without the corresponding increases that occurred in the full-HIRI simulation. This indicates that there may exist optimal levels or approaches to implementing HIRI measures that would accentuate the benefits and avoid the disbenefits that we see in the simulations. These may be different for different urban areas, ozone concentration levels, and/or meteorological conditions.

It is interesting to note that, although the ozone differences from the separated albedo and vegetation-cover sensitivities do not appear to be additive with respect to the full HIRI measures, the results of the half HIRI simulation do appear to be consistent with an additive effect. That is, half of the maximum differences from the albedo-only simulation plus half those from the vegetation-cover-only simulation are approximately equal to the differences that result from the half HIRI measures. This perhaps suggest that there is a decreasing marginal effectiveness or sensitivity of the UAM-V simulated ozone with respect to increasing changes in albedo and vegetation.

Previous modeling of the full HIRI measures for this same domain and episode period indicated that the simulated increases in ozone concentrations tended to occur for days with higher wind speeds (pollutant transport conditions) and the decreases occur under conditions of low wind speed (stagnation conditions). The albedo-only, vegetation-cover-only, and half-HIRI sensitivity simulation results are similar in this regard.

It is interesting to note, and this was not discussed in detail in the previous report, that the days with high wind speeds (the possible transport days) also tend to exhibit higher ozone concentrations (both simulated and observed). Thus, increases in ozone concentrations on these days may tend to make already high ozone concentrations even higher. In contrast, the benefits occur on days such that moderate to high ozone concentrations are reduced.

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