Use of the UAM-V Modeling System as an Air Quality Planning Tool and for Examining Heat Island Reduction Strategies

Sharon G. Douglas, ICF Consulting/SAI
A. Belle Hudischewskyj, ICF Consulting/SAI
Virginia Gorsevski, U.S. EPA, Climate Protection Division

ABSTRACT

The variable-grid Urban Airshed Model (UAM-V) is a grid-based photochemical modeling system designed to evaluate the effects of emissions changes on ozone air quality. This paper describes an application of the UAM-V for the northeastern U.S. to examine and quantify the effects of Heat Island Reduction Initiative (HIRI) measures on ozone concentrations for five urban areas including Boston, New York, Philadelphia, Baltimore, and Washington, D.C. The effects of changes in (1) reflectivity of building/construction materials and (2) vegetation cover on meteorological conditions were simulated using a dynamic meteorological model. The predicted changes in temperature were used to adjust the emissions from motor-vehicle and biogenic sources. The changes in meteorology and emissions were then translated into changes in ozone concentration by the UAM-V air quality model. The changes in temperature can also be used to examine issues related to energy efficiency.

The UAM-V and other photochemical modeling tools are routinely used by state and local agencies for air quality planning. This paper provides an overview of the use of the UAM-V as an air quality planning tool and focuses on the heat island reduction study as an example of its relevance to energy related issues.

Introduction

Compared to other local control measures, lowering temperatures in urban areas may provide an alternative, cost-effective means of reducing ozone concentrations. The urban heat-island reduction measures involve increasing the reflectivity (albedo) and vegetation cover of an urban area through lightening roof and road surfaces and tree planting, respectively.

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. 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

\[ \text{Effective mixing height is the height at which pollutants emitted at the surface or within the mixed layer are expected to be well mixed.} \]
from the reduced chemical reaction rates. Lower temperatures will reduce the production of biogenic hydrocarbon emissions from existing vegetation, although the addition of vegetation may offset this effect. Lower surface temperatures may also reduce emissions from motor vehicles (in particular, evaporative hydrocarbon emissions) and power plants (due to reduced energy demand for cooling).

Meteorological and photochemical modeling tools enable the detailed examination of the effectiveness of HIRI measures by simulating the interactions among the meteorological parameters and integrating the complex and sometimes counterintuitive effects of changes in meteorology and emissions, respectively.

This paper summarizes the methods and results of a meteorological and air quality modeling analysis designed to examine and quantify the effects of HIRI measures on episodic ozone concentrations for urban areas in the northeastern U.S.

Technical Approach

A typical UAM-V modeling analysis involves application of the modeling system to the simulation of one or more historical multi-day (3-12 days) ozone episodes, projection of the emission inventory to a future year, evaluation of emission control measures through further modification of the emissions inventory, re-application of the modeling system, and comparison of the resulting ozone concentrations with those for the future-year baseline simulation. A model-based assessment of the effects of HIRI measures requires a slightly different approach in that the meteorological conditions as well as the emissions and land-use characteristics are modified.

The analysis described here 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 Biogenics 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 modeling domain includes an outer grid with a horizontal resolution of 16 km and an inner grid with 4-km resolution that covers the urban areas from Washington, D. C. to Boston.

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.

Results

Modification of the Albedo and Soil Moisture Parameters

Modification of the inputs for SAIMM was based on information obtained from LBNL (Aha et al. 1999). This included estimates of the change in albedo and percent change in vegetation cover (per each 200 square-meter area) that were derived from aerial photography data (from LBNL flights over Sacramento). For each surface type (e.g., roof, pavement, sidewalk, parking lot, etc.) a certain level of albedo increase is assumed, based on LBNL laboratory research and field measurements. For vegetation, the assumption is that each building unit in a certain USGS urban land-use category gets an additional pre-determined increase in low-emitting vegetative cover. This scenario represents somewhat of an upper-bound to what LBNL researchers expect can be achieved within an urban area as in the "real world" not every building would be vegetation-modified.

Based on this information, the albedo and soil moisture input values (two of the spatially varying surface characteristics considered by the SAIMM) were increased for urban areas within the modeling domain. For each SAIMM grid cell that was originally characterized as predominantly urban, the amount of increase was determined based on the percentage of the grid cell that is urban, weighted according to the percent change associated with each of seven urban subcategories. The increase in albedo is intended to represent the use of more reflective building, roofing, and paving materials. The change in soil moisture is intended to represent the increase in moisture due to increased vegetation cover (e.g., tree planting).

Change in albedo (Δα) for seven different urban land-use subcategories for the maximum HIRI scenario considered by LBNL is provided in Table 1. In order to relate these values to the input parameter used by the SAIMM, it is useful to first consider how albedo is defined and used by the model. Each SAIMM grid cell is assigned an albedo based on the land-use characteristics of the grid cell. The land-use category used to prescribe the surface characteristics represents the dominant land-use category for the grid cell. Thus, all urban grid cells in the SAIMM domain are predominantly urban. In the SAIMM, a single value of albedo is assigned to each land-use category. The value assigned to the urban category is 0.18.

The values provided by LBNL (Table 1) represent absolute changes in albedo. The values seem quite large compared to the current value for urban albedo, but this is because they are applicable to 200 x 200 square-meter grid cells, within which the characteristics correspond mostly, if not completely, to one urban subcategory. Data at this resolution are not easily incorporated into the SAIMM. It would not be appropriate to increase the urban

---

2 These include residential, commercial, industrial, transportation/communication, industrial and commercial, mixed urban/built-up, and other mixed or built-up.
albedo of 0.18 by 0.16 for a 4-km x 4-km grid cell.\textsuperscript{3} Thus, for this exercise, the increase was prorated according to the percent of the grid cell covered by urban area.

<table>
<thead>
<tr>
<th>Urban Land Use Category</th>
<th>Change in Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>0.118</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.175</td>
</tr>
<tr>
<td>Industrial</td>
<td>0.145</td>
</tr>
<tr>
<td>Transportation/Communication</td>
<td>0.237</td>
</tr>
<tr>
<td>Industrial &amp; Commercial</td>
<td>0.162</td>
</tr>
<tr>
<td>Mixed Urban/Built-up</td>
<td>0.136</td>
</tr>
<tr>
<td>Other Mixed or Built-up</td>
<td>0.155</td>
</tr>
</tbody>
</table>

To make use of the detailed information provided by LBNL, the land-use data for input into the SAIMM (as described earlier in this section) were reprocessed. In addition to the fraction of land use within each grid cell that is urban (the standard output), the fraction of urban corresponding to the seven urban subcategories was also calculated and saved.

Then, for each grid cell that is predominantly urban, a weighted average increase in urban albedo (weighting the change in albedo for each subcategory by the fraction of the urban area represented by the subcategory) was calculated. This average increase in urban albedo was then multiplied by the fraction of the grid cell that is urban. This value was added to the value as determined by the program that maps albedo to land use (e.g., assigns 0.18 to urban grid cells).

For example, consider a grid cell that is 65 percent urban. The portion of the grid cell that is urban is composed of seven urban land-use subcategories; their percent coverage is 20, 20, 20, 10, 10, 10, and 10, respectively. Using the values from Table 2-1, the weighted average increase in albedo for this grid cell is 0.1566. The change in albedo for the grid cell is then 0.65 x 0.1566 or 0.102. The modified albedo for input to the SAIMM is 0.18 + 0.102 or 0.282.

Percent change in vegetation cover for seven different urban land-use subcategories for the maximum HIRI scenario considered by LBNL is provided in Table 2. Soil moisture for the SAIMM was adjusted in a similar fashion to albedo in that the increases were prorated based on the percent of the grid cell covered by urban area, and the percent of the urban area assigned to each of the seven urban subcategories.

The maximum increase was assumed to be the difference between the soil moisture values for the deciduous forest and urban land-use types (in the SAIMM soil moisture is a unitless parameter; the value for deciduous forest is 0.25 while that for urban areas is 0.15). Thus if an urban area was converted to forest the soil moisture would increase by 0.1. The fractional increase in vegetation cover for the grid cell was calculated based on the distribution of area among the land-use categories and the information provided in Table 2. This value was then multiplied by 0.1 and the result added to the urban value for soil moisture (0.15).

\textsuperscript{3} Even if a cell is predominantly urban, it may not be entirely urban.
Table 2. Expected Percent Change in Vegetation Cover (per 200 sq. meter cell) for Seven Urban Land-use Subcategories for the Maximum HIRI Scenario

<table>
<thead>
<tr>
<th>Urban Land Use Category</th>
<th>Percent Change in Vegetation Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>18</td>
</tr>
<tr>
<td>Commercial</td>
<td>18</td>
</tr>
<tr>
<td>Industrial</td>
<td>8</td>
</tr>
<tr>
<td>Transportation/Communication</td>
<td>4</td>
</tr>
<tr>
<td>Industrial &amp; Commercial</td>
<td>12</td>
</tr>
<tr>
<td>Mixed Urban/Built-up</td>
<td>11</td>
</tr>
<tr>
<td>Other Mixed or Built-up</td>
<td>11</td>
</tr>
</tbody>
</table>

For example, consider again a grid cell that is 65 percent urban. The portion of the grid cell that is urban is composed of seven urban land-use subcategories; their percent coverage is 20, 20, 20, 10, 10, 10, and 10, respectively. Using the values from Table 2, the weighted average percent increase in vegetation cover for this grid cell is 12.6 percent. The change in vegetation cover for the grid cell is then 0.65 x 0.126 x 0.1 or equal to 0.008. The modified soil moisture for input to the SAIMM is 0.15 + 0.008 or equal to 0.158.

In summary, changes to the albedo and soil moisture input parameters for the SAIMM were calculated based on data provided by LBNL. All urban grid cells within the modeling domain were adjusted in accordance with the area of each grid cell covered by the seven different urban land-use subcategories. Twenty-two percent of the grid cells in the SAIMM modeling domain are characterized as urban. Among these grid cells the increase in albedo due to the HIRI strategies ranges from approximately 0 to 0.20. Thus, at the high end, the albedo is increased by approximately 111 percent. The range in increase in soil moisture is from approximately 0 to 0.018. The largest value represents an increase of twelve percent (from the value of 0.15 assigned to urban areas for the SAIMM).

**Meteorological Parameters**

The modified values for albedo and soil moisture were used in the SAIMM to prepare an alternative set of meteorological inputs for the UAM-V. Several of the meteorological parameters were affected including temperature, moisture, wind speed, wind direction, and mixing height.

Comparison of the base and HIRI-adjusted meteorological fields shows that surface temperatures over the major urban areas are reduced by approximately 0.5 to 2°C (or approximately 1 to more than 3°F). Differences in maximum temperature are illustrated for two of the simulation days (11 and 14 July) in Figure 1. The reductions in temperature occur mainly during the daytime hours. The differences are not confined to the surface, and lower temperatures are found for several vertical levels. The vertical extent of the differences varies with time of day and is greatest during the afternoon hours, due to greater vertical mixing during these hours. Wind speeds are generally lower for the HIRI simulation. The combined effects of changes in temperature and wind speed alter the vertical exchange coefficients and generally result in lower effective mixing heights. Thus, the changes in the meteorological inputs can be expected to alternately reduce (due to lower temperatures) and enhance (due to lower wind speeds and effective mixing heights) the production and build-up of ozone near the surface.
Ozone Concentrations

The UAM-V photochemical model was applied to the simulation of the 7-15 July 1995 ozone episode period for the northeastern U.S. modeling domain. Two simulations were performed. The first simulation used the base SAIMM meteorological and emissions inputs and will subsequently be referred to as the base UAM-V simulation. The second simulation used the HIRI-adjusted meteorological and emissions inputs. This sensitivity simulation will be subsequently referred to as the HIRI UAM-V simulation.

Because the biogenic and motor vehicle emissions were computed using the base-case temperature fields, for the HIRI simulation, these emission inputs to the UAM-V were adjusted to reflect the HIRI-modified temperature fields. Biogenic hydrocarbon emissions totals for the modeling domain are less than one percent lower for the HIRI simulation. Motor-vehicle hydrocarbon emissions are projected to be two percent lower. These small reductions in emissions are not expected to substantially lower ozone production.

When compared to the base simulation results, the HIRI UAM-V simulation results are characterized by both increases and decreases in simulated ozone concentrations. Increases and decreases as large as 20 ppb (or larger in some instances) are simulated. The location and magnitude of the increases and decreases varies from day to day. Through 13 July, the results are generally characterized by decreases over or near the urban areas and increases downwind of the urban areas. One possible explanation for this result is that the lower temperatures slow the reaction rates such that ozone is not formed in the urban areas (where the precursors are emitted) but is instead formed further downwind as the pollutants are carried away from the urban areas by the prevailing winds. The simulation results for 14 and 15 July show mostly increases in maximum ozone concentration. Differences in maximum ozone are illustrated for two of the simulation days (11 and 14 July) in Figure 2.

Based on a review of the meteorological conditions for the simulation days, it appears that in general, the increases in ozone concentration over the urban areas occur for days with higher wind speeds (pollutant transport conditions) while the decreases occur under conditions of low wind speed (stagnation conditions). Detailed examination of the simulation processes using the UAM-V process analysis technique indicates that lower wind speeds and their effect on model dynamics (advection and diffusion) is the primary reason for the higher ozone concentrations in the HIRI simulation. Thus, the simulation results suggest 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.

To further examine the reliability of the UAM-V simulation results, two sensitivity simulations were conducted. These were designed to examine the effects of assumptions in (1) the meteorological model application procedures and (2) the level of albedo and vegetation cover modification.

Effects of data assimilation. The first sensitivity simulation examined the effects of meteorological data assimilation on the HIRI-derived ozone concentration differences.4 For perspective, this value can be compared to the National Air Quality Standard (NAAQS) for ozone of 125 ppb. Data assimilation is a procedure by which observed data are incorporated into a meteorological model simulation. One or more of the time-dependent variables are related or “nudged” toward observed values during the course of the simulation. The objective is to ensure agreement between the model results and the

4 For perspective, this value can be compared to the National Air Quality Standard (NAAQS) for ozone of 125 ppb.
5 Data assimilation is a procedure by which observed data are incorporated into a meteorological model simulation. One or more of the time-dependent variables are related or “nudged” toward observed values during the course of the simulation. The objective is to ensure agreement between the model results and the
Observed data were incorporated into the base and HIRI meteorological inputs for the 9-15 July 1995 simulation period. To test whether use of this procedure affected the response of the model to changes in albedo and vegetation cover, two additional simulations without four-dimensional data assimilation (FDDA) were performed (one with and one without the albedo and vegetation cover modifications). These were performed for the last two days of the simulation period.

Without data assimilation, the SAIMM and UAM-V results are quite different from those for the corresponding simulations with data assimilation. In both cases, better results are obtained with data assimilation because this technique forces the meteorological model to agree better with the observed fields. The differences in temperature attributable to the incorporation of the HIRI measures, however, are similar in magnitude and location (both with and without data assimilation). This indicates that data assimilation does not affect the response of the meteorological model to changes in albedo and vegetation.

The differences in maximum ozone concentration are comparable in magnitude for the two sets of simulations but occur in different locations. This is expected, due to the large differences in the simulated meteorological conditions. Overall, for the two days simulated, the ozone-related benefits of the HIRI measures are greater without data assimilation. The differences in the spatial patterns apparent in the results suggest, however, that this is more likely attributable to the differences in the resulting meteorology rather than the effects of data assimilation.

**Effects of lesser albedo and vegetation cover modifications.** Since there is clearly 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, we also examined whether the benefits would outweigh the disbenefits for a scenario involving less of an increase in albedo and vegetation cover. The albedo and vegetation cover increases were reduced by 50 percent and the SAIMM and UAM-V were rerun for 14 and 15 July only.

The resulting differences in temperature and maximum ozone concentration are less than (approximately half) for the maximum change scenario. However, the characterization of the changes as increases or decreases is the same as for the maximum change scenario (the sign of the differences is unchanged). The results suggest that the level of albedo and vegetation cover change affects the magnitude of the resulting simulated ozone concentration differences. For the days and levels simulated, however, a smaller change in albedo and vegetation cover does not affect the distribution of increases and decreases. The day-to-day differences in the meteorological conditions appear to be a greater influence in this regard.

**Summary and Conclusions**

This paper summarizes the methods and results of a UAM-V modeling study designed to investigate the potential effects of incorporating HIRI measures on ozone air quality for the Northeast Corridor. It illustrates the use of meteorological and photochemical modeling techniques to simulate the meteorological processes and integrate the complex and sometimes counterintuitive effects of changes in land-use, meteorology, and emissions on ozone formation and transport within this area.

observed data and thus enable the preparation of day-specific meteorological inputs for photochemical modeling.
The UAM-V simulation results are characterized by both increases and decreases in simulated ozone concentrations. In general, the increases in ozone concentrations in urban areas occur for days with higher wind speeds (pollutant transport conditions) and the decreases occur under conditions of low wind speed (stagnation conditions). Detailed examination of the simulation processes using the UAM-V process analysis technique indicates that lower wind speeds and their effect on model dynamics (advection and diffusion) is the primary reason for the higher ozone concentrations in the HIRI simulation. The simulation results suggest 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.

Future research may include 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. Scenarios involving increases in albedo only and vegetation cover only would provide information on the relative effectiveness of these. Different scenarios may be appropriate for different areas and episodes.

The utility of the information provided by the modeling analysis is dependent in part on the representativeness of the modeling episode. Thus, an assessment of episode representativeness (based on the frequency of occurrence of similar meteorological and air quality conditions) should guide the use of the modeling results for future planning purposes. Analysis and simulation of other frequently occurring episode types may be needed for a complete assessment of the potential effects of implementing heat-island reduction measures.

This paper has provided an example of the use of meteorological and photochemical models in assessing the effects of HIRI measures on future air quality. The techniques illustrated here could be easily incorporated into modeling exercises for air quality planning for urban areas. Extension of such exercises (beyond identification of strategies aimed solely at reducing emissions from various sources) to include the effects of HIRI measures, could result in a more cost effective approach to improving air quality, conserving energy, and protecting human health.

References


Figure 1. Difference in Daily Maximum Surface Temperature (K) for (a) 11 July 1995 and (b) 14 July 1995. Values Represent Temperatures Created Employing HIRI Measures Minus those Created for Base-Case Simulations. Negative Values (and Dashed Lines) Denote Decreases in Temperature.
Figure 2. Difference in Daily Maximum Ozone Concentration (ppb) for (a) 11 July 1995 and (b) 14 July 1995. Values Represent Ozone Concentrations Created Employing HIRI Measures Minus those Created for Base-Case Simulations. Negative Values (and Dashed Lines) Denote Decreases in Ozone Concentration