Mesoscale and Meso-Urban Meteorological and Photochemical Modeling of Heat Island Mitigation in California: Results and Regulatory Aspects

Haider Taha
Altostratus Inc.
Martinez, California, USA
haider@altostratus.com

ABSTRACT

Mesoscale and meso-urban meteorological models were updated and applied, using new techniques and parameterizations, in fine-resolution photochemical modeling of the effects of heat-island control in California. A meso-urban meteorological model, uMM5, based on Taha (2008a) and Dupont et al. (2004), improves the simulation of fine-resolution meteorological fields in the urban canopy layer. Compared to roughness-length-based mesoscale models, drag-force-based meso-urban modeling can capture phenomena of interest that are not typically detectable at the coarser scales. These include, for example, cool islands, heat islands, flow convergence associated with heat-island circulation, flow divergence at the leading edge of urban areas, and vertical variations in turbulent kinetic energy in response to changes in densities of buildings and vegetation canopies. Enhanced modeling of these meteorological fields is crucial for improved emissions and photochemical modeling of urban heat island mitigation.

From a regulatory perspective, photochemical air-quality modeling is an important tool in the planning and demonstration processes towards implementing strategies that target improvements in or maintenance of air quality. For State Implementation Plan (SIP) modeling purposes, urban heat island (UHI) mitigation has thus far been considered as an emerging control strategy that must be modeled and evaluated as a voluntary control measure, per USEPA requirements. Models developed for evaluating heat island reduction under funding from the California Energy Commission (Taha 2008b,c) are now being used in modeling the ozone air-quality benefits of urban forest in the greater Sacramento, California, region. This effort is part of an ongoing study performed for and led by the Sacramento Metropolitan Air Quality Management District (SMAQMD).

Mesoscale and meso-urban simulations to date suggest that implementation of heat-island control strategies, via increased urban albedo and forest cover, can be especially effective when large areas are modified whereas limited-area control, e.g., a geographical area smaller than ~100 km^2, may have both positive and negative effects, albeit at different times and locations. Limited-area UHI control can produce local improvements in air quality but sometimes mixed impacts downwind. The latter situation arises because of changes in mixing, boundary-layer height, wind speed (flushing of pollutants), and their interaction with topography, i.e., the blocking effect of the eastern mountain ranges in coastal California. Such findings can shed additional light on the "threshold" effect, previously identified in modeling California (Taha 2005, 2007), past which any further surface modifications result in smaller *net* ozone reductions. The results re-emphasize the need for region-specific planning and modeling to develop an optimal mix of surface modification strategies for UHI mitigation.

The improved modeling system can capture fine-resolution features of meteorological fields of interest to this application. For example, the vertical profiles of temperature within the

canopy layer reflect the effects of land-cover variations within an area. Vegetated areas in Sacramento can be up to 2ºC cooler than less-vegetated areas during the times of peak daily temperatures. The urban canopy-layer (UCL) simulations show Bowen ratios $\beta > 50$, $\beta \sim 3.5$, and $\beta \sim 1.3$ respectively for high-rise, resdiential, and forested areas in Sacramento. The model results also show that during nighttime hours, increased surface albedo and canopy cover have little or no effect, but that during the daytime, they have a significant impact on air temperature. The "cooler" air, i.e., temperature difference, can be transported downwind and thus can also impact areas beyond the modified urban regions (e.g., where surface albedo and/or canopy-cover were increased). In the Sacramento area, air temperature can be reduced by up to 3ºC in the high-albedo scenarios and up to ~2ºC in the increased urban forest scenario.

The fine-resolution photochemical simulations of the Sacramento region show peak ozone concentrations consistently downwind of the downtown area. The high ozone is displaced to the southeast on July 31st, to the east on August 1st, and to the northeast on August 2nd. The simulated peaks are respectively 96, 117, and 101 ppb on those three days. In terms of air quality impacts, and during these days of interest, concentrations can be decreased by up to 16-26 ppb in the high-albedo scenario and by up to 15-19 ppb in the increased-canopy scenario. Such large reductions occur at a few spots in the domain, typically impacting areas 1-2 km^2 or slightly larger and are thus non representative. The more relevant aspect of air-quality changes is the impact UHI control has on lowering the concentrations over the *larger* areas in the domain. Spatially-averaged concentrations decreases of 5-14 ppb in the high-albedo scenario and 5-10 ppb in the increased canopy scenario are more representative of the regional impacts in Sacramento. On one day of the episode, negative impacts also occurred upwind (to the west) of the areas that experience decreased concentrations. The increases can reach up to 11 ppb in the high-albedo scenario and up to 5 ppb in the increased-canopy scenario. However, the area impacted by increased concentrations is much smaller than that impacted by decreased concentrations and the increases are also short-lived.

Analysis of the 8-hour average ozone concentrations shows that except for one instance, the impacts of UHI control in Sacramento in all locations and days consist of a decrease in the 8-hour averages. The relative reduction factor (RRF) analysis shows that the daily maximum 8-hour average in the Sacramento area can be decreased by between 4 and 14% across the episode days.

Background

The study presented here developed models and data for California-specific applications and a framework for modeling and analyzing the potential air-quality impacts of surface modifications, i.e., UHI control. Two strategies of interest, increased urban albedo and canopy cover, were evaluated at the mesoscale (down to ~5km in resolution) and at finer resolutions using a new generation meso-urban meteorological model in conjunction with fine-resolution photochemical simulations (down to ~1km in resolution). The study used the MM5 and the uMM5 respectively for the mesoscale and meso-urban simulations. The MM5 is described in detail in various scientific papers (e.g., Dudhia 1993; Grell et al. 1994) and the uMM5 is an Altostratus Inc. version of the EPA's UCP MM5 (DuPont et al. 2004) and is discussed in Taha (2008a).

The purpose of this study to explore and evaluate the potential of surface modifications in improving ozone air quality in California *in addition to their energy savings*. As with many other control strategies, the modification of surface properties in urban areas can cause both net decreases and increases in ozone. The task, thus, is to develop strategies that are tailored specifically to locales of interest (region-specific) in that they would have overall beneficial impacts while minimizing negative effects. The optimal mix of such strategies (to maximize the net ozone reductions) will differ from one region to another and will depend on local emissions, meteorology, episodic conditions, topography, and flow regimes, etc. Thus ideally, the variability in all forcing mechanisms should be considered and specific modeling studies should be designed to quantify such local potential impacts and, by extension, the results are region-specific and non-transferable to other areas.

From a regulatory perspective, photochemical air-quality modeling is an important tool and a cornerstone component in the planning process to ultimately implement strategies that target ozone attainment status. The Clean Air Act requires that non-attainment areas, especially those designated as *serious* or higher (for ozone), use photochemical grid models to study the potential impacts of proposed control strategies and/or demonstrate attainment, using designated field-intensive periods or historical air-quality episodes, e.g., those with high observed ozone. Thus the modeling episodes selected in this study were chosen to be compatible with those used by regulatory agencies in California. The photochemical episode selected for presentation in this paper is July 29th through August 4th, 2000 for Central California (CCOS-2000). The corresponding meteorological modeling episode includes an additional two days of model spin-up prior to the start of the photochemical episode. In this paper, simulations of the Sacramento region are presented.

The Central California July-August 2000 episode, especially on the days considered here (31st of July through August 2nd), was characterized by strong inversions, as evidenced by a high 500-mb geopotential height and high 850-mb temperatures typical of subsidence motion. It was also typical of the conditions conducive to ozone build up, e.g., the Pacific high-pressure system and its extension over California preventing cyclonic systems from passing though the area. The result of such conditions is typically a stagnant air mass that is poorly mixed. In all days of the episode, high ozone was observed in Livermore and transport from the San Francisco Bay Area was strong; to the southeast (San Joaquin Valley) on some days and to the northeast (Sacramento) on others. On July 31st, flow through the Bay Area affected regions in Fresno and Bakersfield, but had no direct impact on Sacramento. The flow arriving Sacramento on that day passed further north of the Bay Area. On August 1st, the flow went through the Bay Area and thus the higher ozone in Sacramento. The peak observed ozone concentrations in Central California during that episode are summarized in **Table 1**.

Table 1. Observed peak ozone in central California

Date in 2000	Observed peak	General location of observed peak
July 31	126 ppb	Livermore
August 1	133 ppb	Sacramento
August 2	151 ppb	San Joaquin (Edison)

The ultimate goal of urban-surface modification strategies, such as proposed here, is to help lower ozone concentrations in California cities directly, by reducing cooling electricity use and emissions, and indirectly by affecting meteorology-dependent emissions and photochemistry. The anticipated effects from surface modifications, e.g., increased albedo and canopy cover, arise because of the relatively lower surface temperatures (slower rates of warming) of the modified surfaces. These in turn cause changes in air temperatures, area-emission rates of ozone precursors, cooling electricity use and related emission from power plants, and rates of photochemical production of ozone. The beneficial effects that are hoped for arise because lower air temperatures would reduce cooling electricity needs (and thus entail smaller power plant emissions), reduced meteorology-dependent emissions from anthropogenic (e.g., mobile source, off-road, evaporative and diurnal losses, and refueling operations, etc.) and biogenic (e.g., vegetation and soil) sources, and reduced rates of tropospheric and ground-level ozone formation and/or accumulation.

On the other hand, the adverse impacts of these strategies, i.e., potential increases in ozone, can arise from a combination of conditions that allows this pollutant to accumulate. Chemistry aside, these include reduced dilution and mixing caused by slower winds and decreased boundary-layer (PBL) heights. However, shallower polluted boundary layers in urban areas that are NOx-rich can sometimes have the opposite effect in this case (and as the NOx/VOC ratio changes in space and time). The atmospheric photochemical system producing ozone is non-linear which further complicates the identification of those conditions conducive to ozone formation and accumulation. Thus the proposed surface modification strategies can result in increased ozone depending on local conditions. For each region, the relative levels of benefits and adverse effects also change based on the level of surface modifications. For example, in coastal regions and/or areas with flow blocking (basins, mountain ranges), there seems to be a region-specific threshold or range for such modifications beyond which any further increases in surface modifications tend to produce smaller net benefits and possibly adverse effects as well. Because of such issues and the existence of competing non-linear effects, region-by-region and multi-episodic assessments and modeling may be needed to identify such regional thresholds and the optimal mix of surface modification strategies for each region.

Objectives and Approach

This study further improves the resolution of the simulations in computational domains of interest, e.g., the urban canopy layer (UCL). This goal is achieved by introducing and further developing new-generation fine-resolution meteorological (meso-urban) models and using them to drive fine-resolution photochemical simulations. While resolutions can be set as fine as needed, at least in theory, in this application the horizontal resolutions were 1km and in the vertical, they were in the order of 3m near the ground. **Figure 1** depicts the horizontal modeling domains; those shown with a black background are the mesoscale domains, whereas the small green rectangles delineate additional fine-resolution meso-urban modeling grids that were simulated with the uMM5 for California. In this paper, only results from the Sacramento grid simulations are discussed and analyzed. **Figure 2** shows a schematic representation of the fine-resolution vertical structure of the model within the UCL and compares it to the vertical structure used in typical mesoscale, e.g., regulatory, modeling.

From a UHI-mitigation perspective, the purpose of developing and using fine-resolution meso-urban and photochemical models is to evaluate in more detail the relevant dynamics, thermodynamics, physics, and photochemistry within the urban canopy layer. This layer is of interest, obviously, because this is where the bulk of the population is found, where most emissions are initially injected, and where initial chemical reactions producing smog occur. Thus, in theory at least, improving the modeling of the urban atmospheric environment within the canopy layer is critical for a better assessment of environmental and air pollution/health impacts as well as for more accurate regulatory air-quality planning purposes.

Figure 1. Modeling domains for Southern California, left, and Central California, right. Black background shows mesoscale meteorological modeling domains. The mesoscale photochemical modeling grids are shown as 5km and 4km grids, respectively. Green rectangles show meso-urban (uMM5) meteorological and fine-resolution photochemical (CAMx) modeling grids.

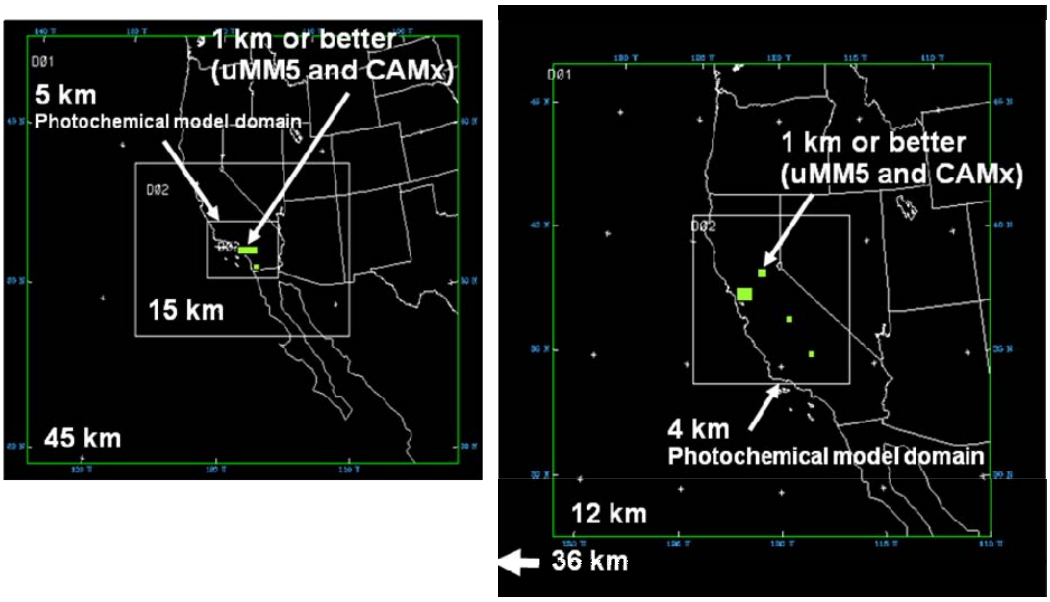
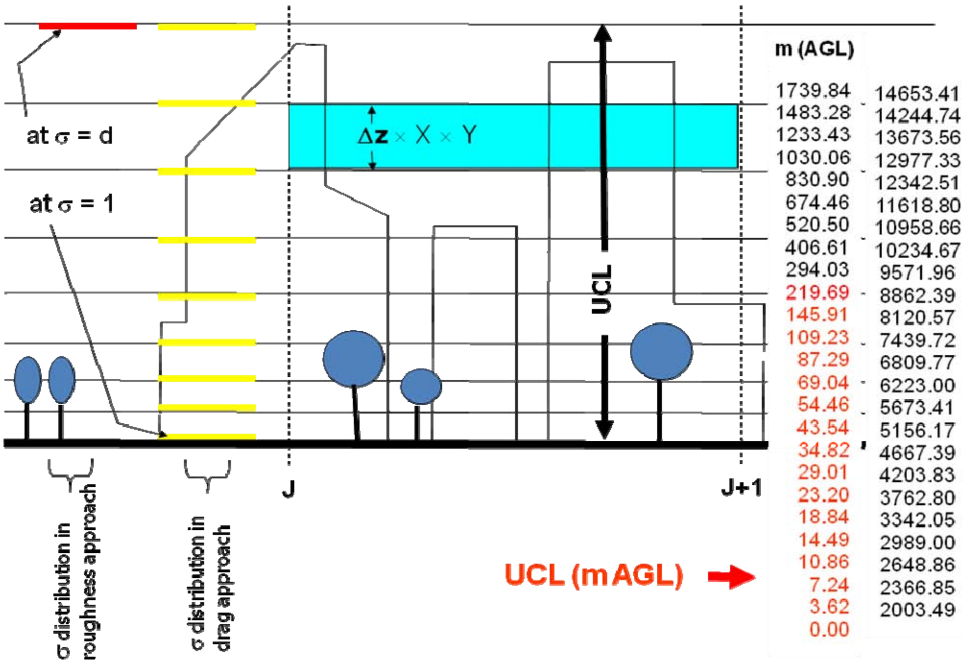


Figure 2. Schematic representation of fine-resolution meso-urban and mesoscale model vertical structures. The red line represents a typical first atmospheric level in roughness-based mesoscale models (e.g., at displacement height, d), whereas the yellow lines, starting at the actual surface, indicate several additional vertical layers in the uMM5 for the same interval. The numbers at right show the heights (m, AGL) used in this modeling study of Sacramento, with the red entries being within the canopy layer.



Thus, the general goals are: 1) to update and improve a meso-urban fine-resolution meteorological model (e.g., uMM5) for providing the driving meteorological fields to a fine-resolution photochemical model (e.g., CAMx/CMAQ), 2) to develop the corresponding region-specific fine-resolution input data and model parameters input that such new-generation models require, and 3) to apply the updated models, parameterization, and data to several regions in California to demonstrate the models' effectiveness and their diagnosis of the potential impacts of UHI control on meteorology and air quality. This is a first known application where *this* type of models is applied to studying the impacts of *surface perturbations* on meteorology and air quality in California.

The development and use of fine-resolution meso-urban meteorological and corresponding fine-resolution photochemical models is critical because, in theory at least, such fine-resolution modeling capabilities and data are useful not only in enabling fine-resolution photochemical air-quality modeling but also in developing fine-resolution 4-dimensional emission inventories that should ultimately improve the process of air-quality modeling and demonstration for a variety of strategies. Such modeling capabilities are also useful for actual planning and implementation purposes since it allows for detailed evaluation of meteorological and air-quality impacts at a neighborhood scale or on a block-by-block basis if needed.

The new models also require a new type of input data. For example, in addition to all meteorological, emissions, and surface initial and boundary conditions that are typically needed in mesoscale meteorological and photochemical modeling, meso-urban models, such as the uMM5 used here, require an additional set of specific input parameters, e.g., detailed 3-dimensional morphology. Those required by the uMM5 are listed in **Table 2**. These 2- and 3-dimensional arrays of parameters were developed in this study for the two domains discussed above using a combination of sources and an alternate, low-cost method (**Figure 3**) instead of the more typical sources of data, e.g., Lidar, that are very expensive. The alternate methods rely in part on using remote-sensed morphology data, such as from Google's Earth PRO facility. Thus a number of parameters were developed at 1-m (Δz) vertical intervals and for several wind approach directions, e.g., N, NNE, NE, ENE, E, etc., through the top of the canopy layer, i.e., about 140-160 m AGL in the regions of interest here, e.g., Sacramento, California. Once these parameters were developed (gridded over a domain of interest), an attempt was made to correlate them to region-specific LULC classification schemes, such as USGS Level-II (Anderson et al. 2001). The mapping was then used as an extrapolation template to generate morphology and related data in urban areas where no 3-dimensional morphological information exists.

Figure 4 shows an example of domain-wide morphological characterization of Sacramento resulting from the techniques developed in this study and in conjunction with land-use and land-cover information, as discussed above. The new delineation of the urban areas (boundaries seen in Figure 4) is more up-to-date than based on other, older, and less resolved data sources and shows the recent growth in Sacramento.

Table 2 and Figure 3. Fine-resolution 2- and 3-dimensional morphological parameters needed by the uMM5. The figure shows an analysis plane used in computing these parameters at each 1-m vertical interval.

Land-use fraction (e.g., 38-USGS, or own system)
Land-cover fraction (paved)
Land-cover fraction (roof)
Land-cover fraction (vegetation)
Land-cover fraction (water)
Building height-to-width ratio
Building wall-to-plan ratio
Connected impervious area
Mean orientation of streets
Mean building height
Vegetation mean height
Zo and Zd (grid level, surface-specific)
Building frontal area density (**multi-directional**) (**ΔZ**)
Building top (roof) area density (**ΔZ**)
Building plan area density (**ΔZ**)
Vegetation frontal area density (**multi-directional**) (**ΔZ**)
Vegetation plan area density (**ΔZ**)
Vegetation top area density (**ΔZ**)
Plan-area weighted mean building height
Sky-view factor (**ΔZ**)

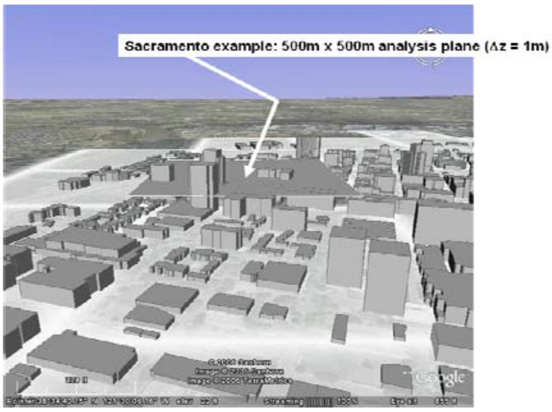
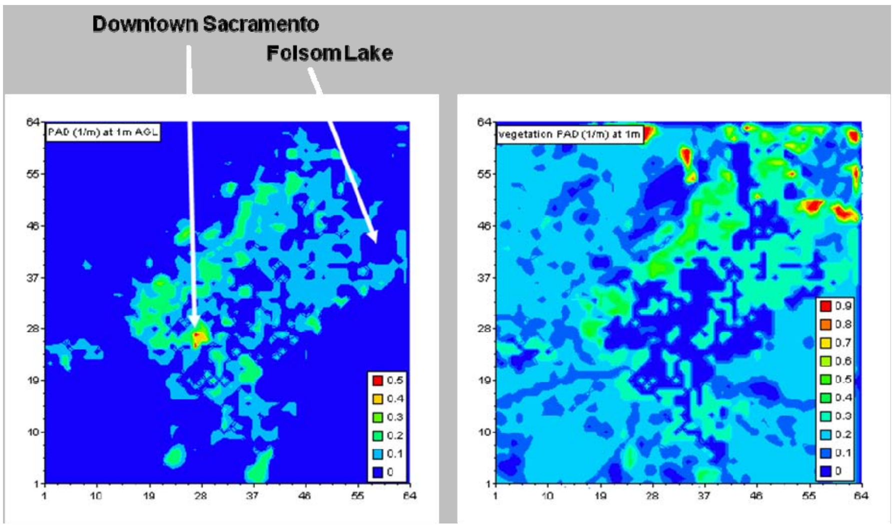


Figure 4. PAD (plan-area density) function (m^2m^{-3}) for the Sacramento uMM5 domain. The example shows cross sections at 1m AGL for buildings (left) and vegetation canopy (right).

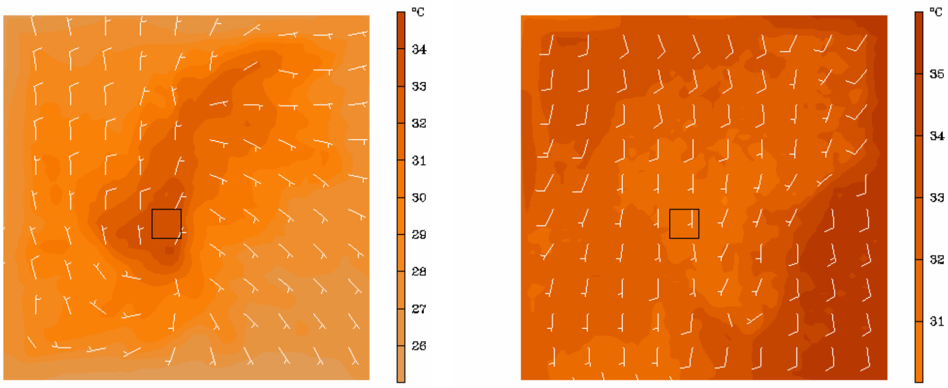


Following the stages of model set-up and configuration, and development of all needed input parameters, a base-case meteorological and photochemical scenario was developed for each domain. A performance evaluation exercise was then carried out. This was followed by the simulation of perturbation scenarios for regions and domains of interest. One scenario assumes albedo increases and the other involves increased canopy cover. In this paper, modeling results for Sacramento are presented as an example from simulations of various regions in California. In the rest of this paper, the focus of the meteorology discussion is on temperature whereas the focus of the photochemistry discussion is on the ozone concentrations field. For a full discussion of results, other domains, and study details, refer to Taha (2005, 2007, 2008a,b,c).

Base Case

The meso-urban simulations of the base-case scenario in the Sacramento region (Sacramento uMM5 domain introduced earlier) produce a generally repetitive diurnal profile whereby a UHI starts small (~1ºC) at 1500 LST, grows to about 2-4ºC by 1800, peaks around 2100 (at up to 6ºC), then begins to decrease so that it is at 2-3ºC (up to 5ºC) by 0000, and continues to get smaller until, between 0900 and 1200 LST of the next day, there is no UHI during early morning hours and then the urban area becomes 1-2ºC cooler than the surrounds by mid-morning to mid-day. Finally at around 1500 of the next day, the UHI appears again (1ºC) and the cycle is repeated through the episode. Of course the temperature field and magnitudes of the UHI are different from day to day, but the aforementioned profile is relatively representative. As discussed earlier, the meso-urban model is able to capture fine-resolution meteorological phenomena of interest that were not reproducible with mesoscale simulations. For example, and as seen in **Figure 5**, the model captures a well-defined 5ºC UHI at 0000 LST August 1st and a cool island at 1200 LST (up to 2ºC cooler than surrounds) on August 2nd, the latter due to shadowing, thermal mass, and canyon effects in the urban areas. For a visual reference of the aerial extent of these heat and cool islands, compare the temperature fields in **Figure 5** with urbanization extent shown in **Figure 4**.

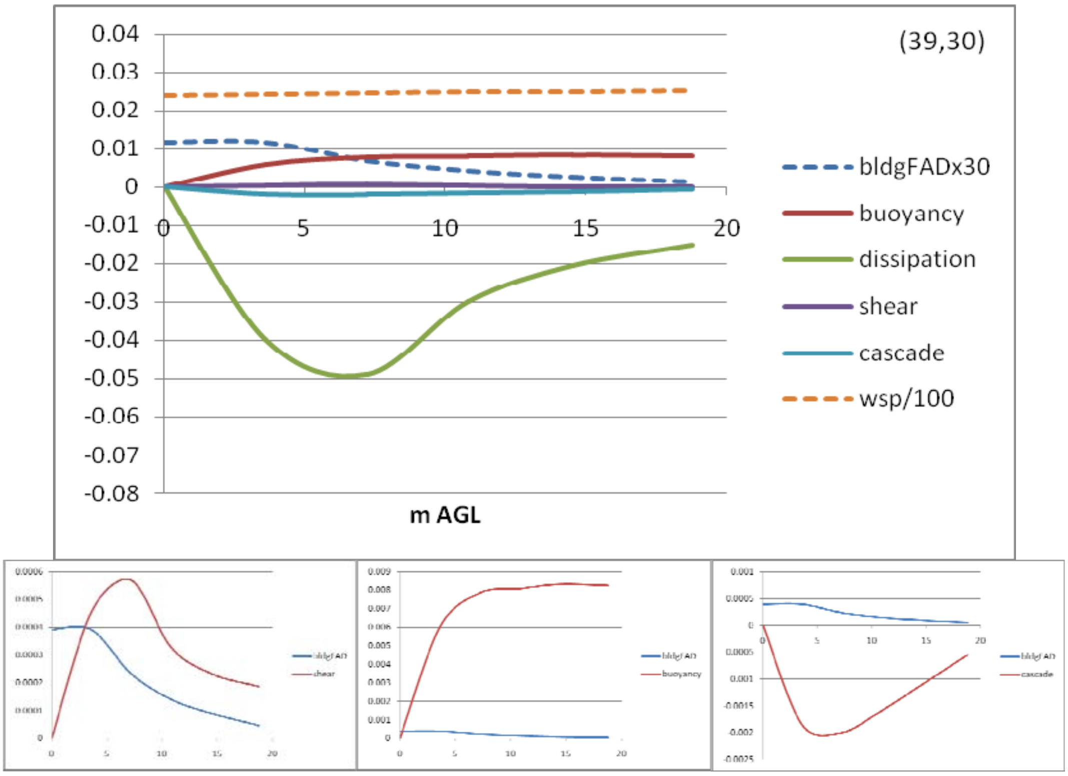
Figure 5. Left: uMM5-simulated urban heat island of 5ºC at 0000 LST August 1st. Right: a uMM5-simulated cool island of 2ºC at 1200 LST August 2nd in the Sacramento area. The inscribed square shows the relative location of high-rise buildings in Downtown Sacramento.



The simulations also capture the fine-resolution divergence/convergence features of the flow that were not detectable in mesoscale modeling, as well as the slower wind over urban areas (due to drag and roughness). For example, the urban-area winds can be slower by 2-3 ms^{-1} compared to upwind or surrounding areas during the early morning hours.

The uMM5's ability to simulate the fine-resolution *vertical* profiles of meteorological fields, e.g., in the UCL, is improved over that of the mesoscale model. **Figure 6** shows an example of selected simulated TKE budget terms at 1400 LST August 1st in an arbitrary location in Sacramento (this location is a residential-commercial area with a canopy-layer top at 18m AGL). In the figure, production terms are positive and dissipation terms are negative and the hour at 1400 was chosen as it generally represents the warmer part of the day (and unstable conditions). The vertical profiles of shear and buoyancy production of TKE, as well as other terms, follow the vertical changes in obstacles' shapes, e.g., in this case, the profiles of building frontal area density (FAD), and that shear production of TKE generally peaks at or slightly higher than the elevation where an abrupt decrease in FAD exists (critical FAD level) which generally represents the top of most buildings in the grid cell being examined. Similarly, buoyant production of TKE also generally follows the vertical FAD profiles of buildings and vegetation and increases from the surface up to the critical FAD level and then remains roughly constant throughout the rest of the UCL. The accelerated cascade dissipation term of TKE also is largest at and slightly above the critical FAD level. But while buoyancy is sustained above the critical FAD level, the accelerated cascade term decreases with height as FAD decreases.

Figure 6. TKE budget components for a location in the Sacramento modeling domain at 1400 LST

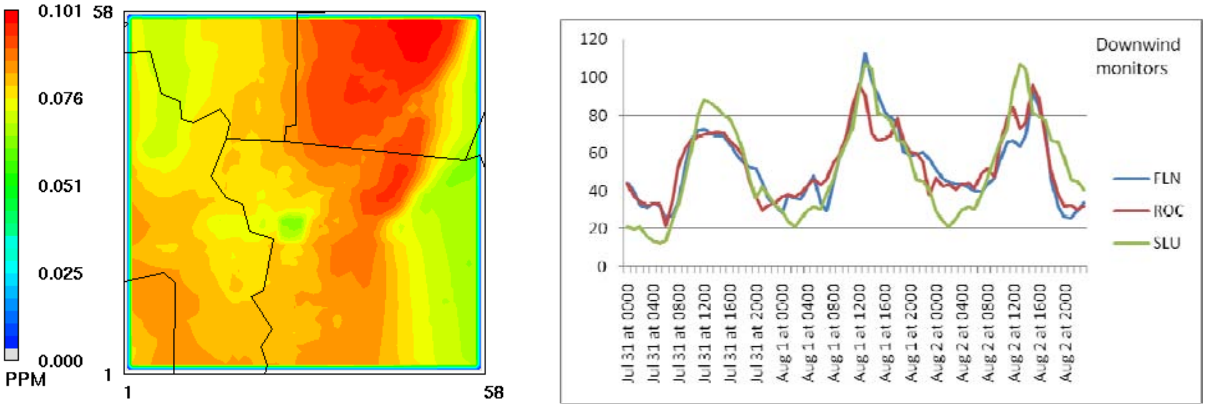


Shear Buoyancy Cascade

The simulated vertical profiles of temperature within the UCL (not shown) capture the effects of land-cover variations within the domain. For example, the simulations show that an area with vegetation canopy cover can be up to 2ºC cooler than other, less vegetated areas. The simulated heat fluxes in the UCL indicate Bowen ratios $\beta > 20$, $\beta \sim 3.5$, and $\beta \sim 1.3$ respectively for high-rise, resdiential, and forested areas in Sacramento. These ratios are generally consitent with observed and documented values in such land covers (e.g., Oke 1987).

The base-case simulations of the Sacramento 1-km photochemical modeling domain (which roughly corresponds to the uMM5 grid) show the peak concentrations consistently downwind of the downtown area, which is expected because of the transport and chemistry time scales. The high ozone is displaced to the southeast of the domain on July 31st, to the east on August 1st, and to the northeast on August 2nd (**Figure 7** shows the latter). The 1-km domain's simulated peaks are respectively 96, 117, and 101 ppb on those three days and are relatively more accurate (closer to observations in this domain) than those obtained from the coarser mesoscale simulations. Model performance evaluations (Taha 2005,2007) show that both paired and unpaired accuracies of the peak meet the EPA-recommended performance benchmarks. However while the model captures reasonably well the downwind elevated concentrations, its performance is relatively poorer in capturing the observed concentrations near and downwind of the downtown area (mid-domain region) where it underestimates the local peaks. **Figure 7** shows, as an example, the simulated ozone concentrations field at 1400 on August 2nd, when the simulated peak was 101 ppb, and as time series at three monitors of interest in the eastern portion of the domain for July 31st through August 2nd.

Figure 7. Left: simulated ozone concentration field (ppm) at 1400 on August 2nd in the Sacramento 1-km domain. Right: simulated ozone (ppb) at three monitors in the domain for three days of interest (July 31st through August 2nd). Monitor locations: Folsom/Natoma, Rockling, and Sloughhouse.



Heat Island Control

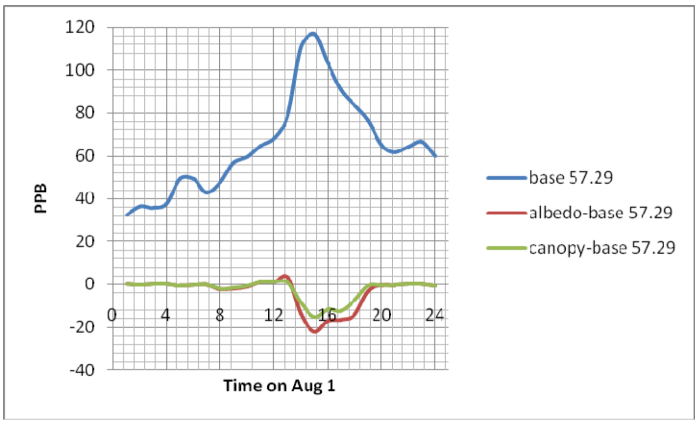
For the perturbation scenarios (discussed in detail in Taha 2005,2007), model results show that during nighttime hours, increased surface albedo and canopy cover have no effects, but that during the day, they have a significant impact on air temperature. In addition, they show that the "cooler" air can be advected downwind and thus can also impact areas beyond the modified urban regions (e.g., where surface albedo or canopy-cover was increased). In the Sacramento uMM5 domain, air temperature can be reduced (in the increased-albedo scenario) by up to 2.5ºC at 1100 LST July 31st, 2ºC at 1200 LST August 1st, and 3ºC at 1300 LST August 2nd. The associated reductions in surface temperature are up to 7ºC at 1100 LST July 31st, 10ºC at 1200 LST August 1st, and 7ºC at 1300 LST August 2nd. The increase in canopy-cover has generally the same impact directionality on air and surface temperatures as increased albedo but with relatively lower magnitudes. In this scenario, the largest reductions in air temperature reach up to 1.5ºC, 1.5ºC, and 2.5ºC respectively at 1100 LST July 31st, 1300 LST August 1st, and 1300 August 2nd. The associated (time-coincident) reductions in surface temperature are 4ºC at 1100 LST July 31st, 5.5ºC at 1300 LST August 1st, and 4ºC at 1300 August 2nd.

In terms of air quality, the simulations indicate that during the episode days of interest, ozone concentrations can be decreased by up to 16-26 ppb in the high-albedo scenario and by up to 15-19 ppb in the increased-canopy scenario. These occur in relatively small areas in the domain, typically 1-2 km^2 or slightly larger. Such large reductions are captured by the model because of the fine resolution simulation capabilities relative to coarser and more convectional simulations, e.g., at the mesoscale, where the perturbations are averaged over larger areas. Thus fine-resolution simulations are a useful tool in "zooming into" the coarse-grid simulated fields to detect and capture the fine-resolution details that are important for analysis and planning purposes (e.g., urban planning and SIP credit modeling).

However, the more representative air-quality changes are those of lowering the concentrations over the larger areas in the domain. Decreases of 5-14 ppb in the high-albedo scenario and 5-10 ppb in the increased canopy scenario are more representative of the sub-regional impacts of these strategies in Sacramento. On one day of the episode, some negative impacts also occurred upwind (to the west) of the areas experiencing decreased concentrations. The increases can reach up to 11 ppb in the high-albedo scenario and up to 5 ppb in the increased-canopy scenario. However, the area impacted by increased concentrations is much smaller than that impacted by decreased concentrations and the increases are short-lived.

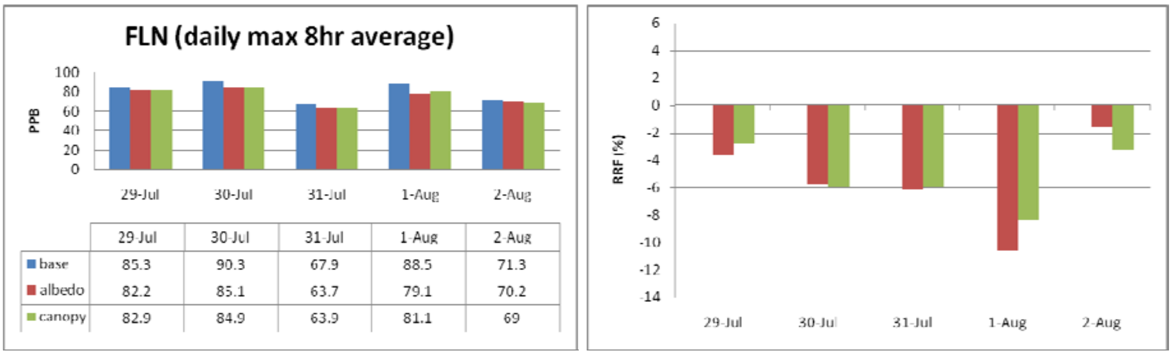
In general, the modeling suggests that the effects of changes in canopy cover (changes assumed in this modeling approach) are similar to or smaller than those of increased urban albedo. At the times and locations of the simulated daily ozone peaks, albedo increase is 20% to 100% more effective than increased canopy cover in terms of impacts on the peak concentrations when paired in space and time. However, if only pairing in space is considered, i.e., at the peak's location but regardless of the *time*, then both strategies can have a similar effectiveness. The simulations also suggest that while these strategies can have different local impacts (mid domain and in urbanized areas) their effects become more similar downwind of urban Sacramento in some cases. **Figure 8** shows an example of the relative impacts of increased albedo and canopy cover on ozone concentrations at a selected downwind location, in this case where the simulated peak concentration on August 1st occurred. While the high-albedo scenario can decrease the local peak by up to 22 ppb, the increase in canopy cover decreases it by up to 15 ppb.

Figure 8. Blue line: August 1st, simulated peak (117 ppb at location 57,29). Bottom of figure: changes in [O3] from UHI control; red: from albedo increase, green: from canopy cover increase



Analysis of the 8-hour average ozone shows that except for one instance in the Sacramento domain (at the Rocklin monitor location), the impacts of UHI control in all locations and days are a decrease in the daily maximum 8-hour average. The RRF analysis shows that the daily maximum 8-hour average can be decreased by anywhere between 4 and 14% across the episode days with the largest impacts seen on July 31st and August 1st. While the effects of increased albedo are generally larger than those of increased canopy cover, the difference is not particularly large and, in some cases, increased canopy cover is more effective. The latter situation is noticeable at the S13 monitor location, for example, which is closer to the downtown area. **Figure 9** exemplifies this discussion for a monitor location at Folsom/Natoma in the eastern (downwind) part of the domain.

Figure 9. Left: simulated daily maximum 8-hour average ozone at the Folsom/Natom monitor location. Right: reduction (%) in daily maximum as RRF.



Regulatory Aspects

Modeling of urban heat island mitigation over the years has served as a basis for introduction of this strategy in various frameworks of the regulatory environment. Results from several studies, and as in the examples shown here, indicate that the overall impact of urban heat island mitigation is a reduction in ground-level ozone in urban areas where this strategy is implemented. Thus several organizations have expressed interest in either further evaluating or demonstrating the benefits of UHI mitigation. For example, various facets of the UHI mitigation concept have been considered, informally at least, by the US EPA, Air Resources Board, and several California air-quality management districts, as well as various environmental organizations in several regions of the U.S.

As a most recent example, the Sacramento Metropolitan AQMD (SMAQMD) has initiated an urban forest program (Urban Forest For Clean Air (UFFCA) Demonstration Project) that consists of two major components: 1) replacement of high-emitting species with a low-emitting mix, and 2) increasing the net urban forest cover using low emitters of biogenic volatile organic compounds (BVOC). The first component has impacts on emissions only while the second has impacts on both meteorology and emissions. Of course, both pathways directly and indirectly impact the photochemical production of ground-level ozone and air quality.

If successful, the UFFCA will introduce one aspect (urban forest) of heat island mitigation as a voluntary control measure into the regional SIP (State Implementation Plan) of the Sacramento Federal Non-Attainment Area (SFNA). The models used in the UFFCA are those developed by Taha (2005,2007) in addition to public domain ones such as the MM5 / WRF models as well as CMAQ / CAMx and corresponding emission models. In addition, Taha (2007,2008a) also further developed the UCP MM5 of Dupont et al. (2004) creating a newer version that has enhanced capabilities for studying UHI mitigation (Taha 2008c).

References

Anderson J.R., Hardy, E.E., Roach, J.T., Witmer, R.E., 2001. A land use and land cover classification system for use with remote sensor data. USGS Professional Paper No. 964. U.S. Government Printing Office, Washington DC.

Dudhia J., 1993. A non-hydrostatic version of the Penn State/NCAR mesoscale model: Validation tests and simulation of an Atlantic cyclone and cold front. Monthly Weather Review 121, 1493-1513.

Dupont S., Otte T., Ching J., 2004. “Simulation of meteorological fields within and above urban and rural canopies with a mesoscale model (MM5)”. *Boundary-Layer Meteorology*, Vol. 113, 111-158.

Grell G.A., Dudhia J., Stauffer D.R., 1994. A description of the fifth generation PSU/NCAR mesoscale modeling system (MM5). Technical Note NCAR/TN—379+STR, NCAR.

Oke T.R., 1987. Boundary-Layer Climates. Methuen & Co. Ltd., London.

Taha, H. 2008a. "Episodic performance and sensitivity of the urbanized MM5 (uMM5) to perturbations in surface properties in Houston TX". *Boundary-Layer Meteorology*, Vol. 127, No. 2 (May 2008), pp. 193-218. doi:10.1007/s10546-007-9258-6.

Taha, H. 2008b. "Urban surface modification as a potential ozone air-quality improvement strategy in California: A mesoscale modeling study". *Boundary-Layer Meteorology*, Vol. 127, No. 2 (May 2008), pp. 219-239. doi:10.1007/s10546-007-9259-5.

Taha, H. 2008c. "Meso-urban meteorological and photochemical modeling of heat island mitigation". *Atmospheric Environment*, Vol. 42, No. 38 (December 2008), pp. 8795-8809. doi:10.1016/j.atmosenv.2008.06.036.

Taha, H. 2007. "Urban surface modification as a potential ozone air-quality improvement strategy in California -- Phase 2: Fine-resolution meteorological and photochemical modeling of urban heat islands", Final report prepared by Altostratus Inc. for the California Energy Commission, Sacramento, California, PIER Environmental Research.

Taha, H. 2005. "Urban surface modification as a potential ozone air-quality improvement strategy in California -- Phase 1: Initial Mesoscale Modeling", Final report prepared by Altostratus Inc. for the California Energy Commission, Sacramento, California, PIER Environmental Research.